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Health Risks of Rainwater Consumption: A Study of Microbiological and Heavy Metal Exposure in Island Areas

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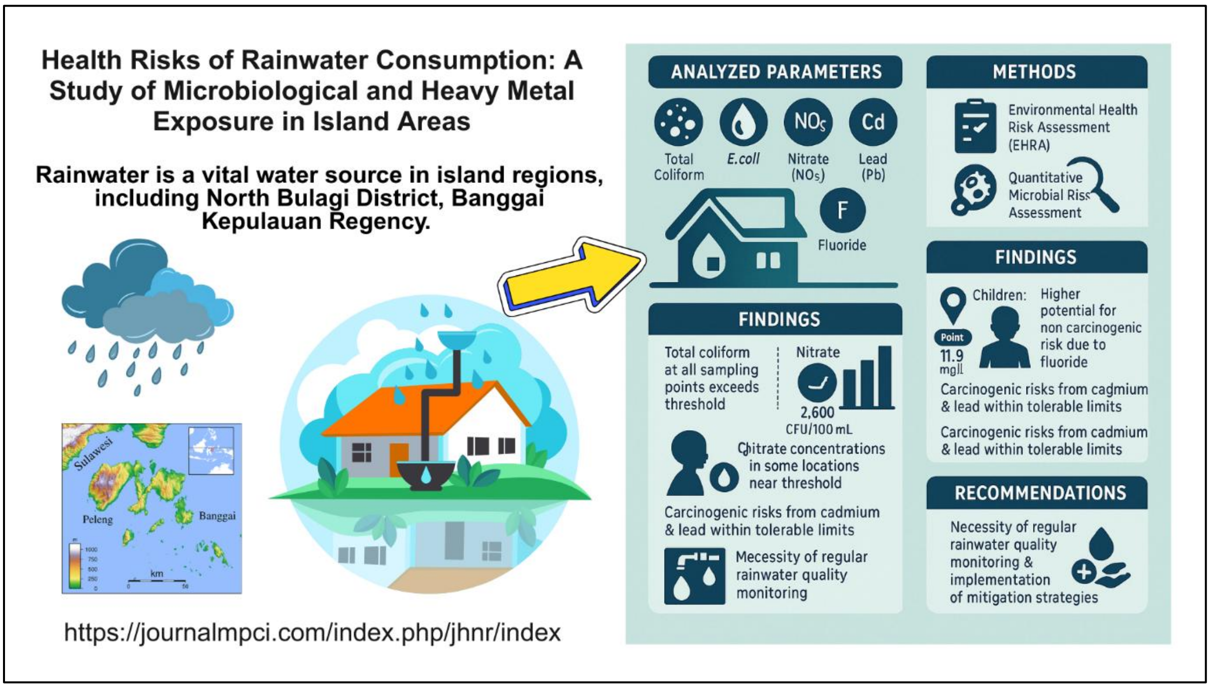
ABSTRACT

Rainwater is a vital water source in island regions, including North Bulagi District, Banggai Kepulauan Regency, Indonesia. This study aimed to evaluate the quality of harvested rainwater and assess associated health risks from microbiological and chemical contaminants. A cross-sectional design was employed, involving the collection of eight rainwater samples from household reservoirs using purposive sampling and data from 94 respondents to support an exposure assessment. The parameters analyzed included Total Coliform, *Escherichia coli*, Nitrate, Cadmium, Lead, and Fluoride. Water quality analysis was conducted following APHA standard procedures. Health risk assessments were conducted using the Environmental Health Risk Assessment (EHRA) framework for chemical exposure and Quantitative Microbial Risk Assessment (QMRA) for microbial hazards. Results showed that microbiological contamination, particularly Total Coliform, exceeded the acceptable limit at all sampling points, with the highest level recorded at Point VIII (2,600 CFU/100 mL). Most chemical parameters were within permissible levels; however, Nitrate concentrations at several locations approached the WHO guideline limit, notably at Point II (11.8 mg/L). Health risk assessment indicated a higher potential for non-carcinogenic effects among children due to Fluoride exposure (HQ > 1). Carcinogenic risks from Cadmium and Lead were within acceptable tolerable limits (ILCR < 1.0E-04). These findings underscore the importance of regularly monitoring rainwater quality and implementing mitigation strategies such as first-flush systems, filtration, and disinfection. The integrated methodological approach adopted in this study provides a robust evidence base for the formulation of effective environmental health interventions and policies, particularly in remote and island communities.

Key Messages:

- Rainwater in North Bulagi District is microbiologically contaminated and poses health risks, especially for children, highlighting the need for regular monitoring and treatment.
- The use of EHRA and QMRA provides a strong foundation for developing safer rainwater management policies and actions.

GRAPHICAL ABSTRACT



INTRODUCTION

Rainwater Harvesting Systems (RWHS) provide a sustainable water source, especially in areas where groundwater is contaminated by arsenic and fluoride. Although rainwater is initially pure, it can collect contaminants such as bacteria, viruses, fungi, dust, and airborne pollutants during precipitation, particularly in the early stages (1)(2)(3). RWHS methods, including rooftop and surface runoff harvesting, are widely applied in island regions to support water conservation, reduce flood risks, and ensure water availability during dry seasons (4). However, the quality of harvested rainwater is greatly influenced by air pollution from industrial emissions, traffic, and meteorological factors like wind speed and humidity (5).

Atmospheric deposition, both dry and wet, plays a major role in contaminating rainwater. Dry deposition transfers pollutants without precipitation through mechanisms such as gravitational settling and impaction, while wet deposition removes pollutants during rainfall via rainout and washout processes (6). These processes introduce nitrogen compounds, suspended solids, heavy metals, and dissolved organic carbon into storage systems. Emerging contaminants like microplastics and per- and poly-fluoroalkyl substances (PFAS) have also been detected in rainwater globally, including remote areas, posing serious long-term health risks such as reproductive disorders and cancer (7)(8). In North Bulagi District, Banggai Kepulauan Regency, harvested rainwater is the primary water source due to limited access to clean piped water. Communities in this region often collect rainwater using rooftop systems without treatment despite growing concerns over the potential health impacts of environmental pollution. Preliminary observations reported turbid water, biofilm buildup in tanks, and possible chemical residues near residential zones, indicating contamination risks.(9)

To ensure rainwater safety, appropriate treatment is essential before consumption. This includes first flush systems, chlorination, filtration, and regular cleaning of catchment and storage areas. (10) (11) In this study, the quality of harvested rainwater was assessed using parameters such as Total Coliform, *E. coli*, Nitrate (NO_3^-), Cadmium (Cd), Lead (Pb), and Fluoride (F), with risk estimated using Environmental Health Risk Assessment (EHRA) and Quantitative Microbial Risk Assessment (QMRA). These parameters were selected based on their health significance and frequent detection in rainwater systems exposed to anthropogenic and atmospheric pollution. Nitrate and Fluoride are linked to methemoglobinemia and dental/skeletal fluorosis, respectively, while Cadmium and Lead are classified as carcinogenic or

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potentially carcinogenic.(11) While previous studies have focused on chemical or microbial contamination independently, integrated health risk assessments in rainwater from island areas remain scarce. This study addresses that gap by combining chemical and microbiological analysis using two complementary assessment tools (12)(13). The EHRA and QMRA frameworks were chosen for their comprehensive and quantitative capabilities in estimating health risks from both chronic chemical exposure and pathogen ingestion, making them suitable for assessing complex environmental scenarios like rainwater use (14)(15)).

The results show that children are more vulnerable to non-carcinogenic risks from Fluoride, while carcinogenic risks from Cadmium and Lead remain within acceptable limits (16)((17). These findings emphasize the need for ongoing monitoring and effective risk mitigation strategies.

METHODS

This study employed a cross-sectional design using the Environmental Health Risk Assessment (EHRA) and Quantitative Microbial Risk Assessment (QMRA) approaches to evaluate health risks from chemical and microbial contaminants in rainwater. The study was conducted in North Bulagi District, Banggai Kepulauan Regency, where rainwater is widely used as a primary drinking water source. Eight rainwater samples were collected purposively from rooftop harvesting tanks in households located in areas with different land use characteristics: three from residential zones, two from agricultural areas, two near small-scale industrial facilities, and one near a local transport hub. Rainwater was sampled during the rainy season (November–December), specifically during the first 15–20 minutes of moderate to heavy rainfall, following the standard first-flush diversion protocol to better assess potential contamination (11). Samples consisted of eight rainwater samples, collected from locations with varying land uses (residential, agricultural, and near industrial or transport zones). A total of 94 human subjects (47 children ≤12 years and 47 adults ≥18 years) were selected using purposive sampling, based on the criterion of consuming untreated rainwater. The sample size was determined through total sampling of all individuals in the study area who met the inclusion criteria, namely regular consumption of untreated harvested rainwater as their main drinking source. Informed consent was obtained from all participants, and the study received ethical approval from the relevant ethics committee.

All water samples were analyzed in a certified environmental health laboratory. Microbiological parameters—Total Coliform and Escherichia coli—were tested using the membrane filtration method (Standard Methods 9222B and 9222D, APHA 2017). Chemical parameters were analyzed as follows: Nitrate (NO_3^-) using spectrophotometry (Method 4500-NO_3^-), Cadmium (Cd) and Lead (Pb) using Atomic Absorption Spectrophotometry (AAS), and Fluoride (F) using ion-selective electrode analysis. Results were compared with the WHO (2017) and Indonesian National Standard (SNI) No. 8220:2017 for drinking water. To assess exposure variables, a structured questionnaire was administered, covering daily water intake, duration of exposure (years of consuming rainwater), and frequency (number of drinking events per day). The questionnaire was adapted from the USEPA Exposure Factors Handbook (2011) and previous research by Ahmed et al. (2010), with contextual modifications validated through expert review and pre-testing in a pilot group.

CODE OF HEALTH ETHICS

Ethical clearance was granted by the Health Research Ethics Committee of Public Health Hasanuddin University Approval No: 485/UN4.14.1/TP.01.02/2024.

RESULTS

Concentration of Microorganism Exposure in PAH

The laboratory test results from the Makassar Central Health Laboratory (BBLK) for the water quality parameters (rainwater) measured during the study, specifically the microbiological parameters, were compared against the Drinking Water Quality Standards as stipulated in the Regulation of the Minister of Health of the Republic of Indonesia No. 2 of 2023, and are detailed in Figure 1 below.

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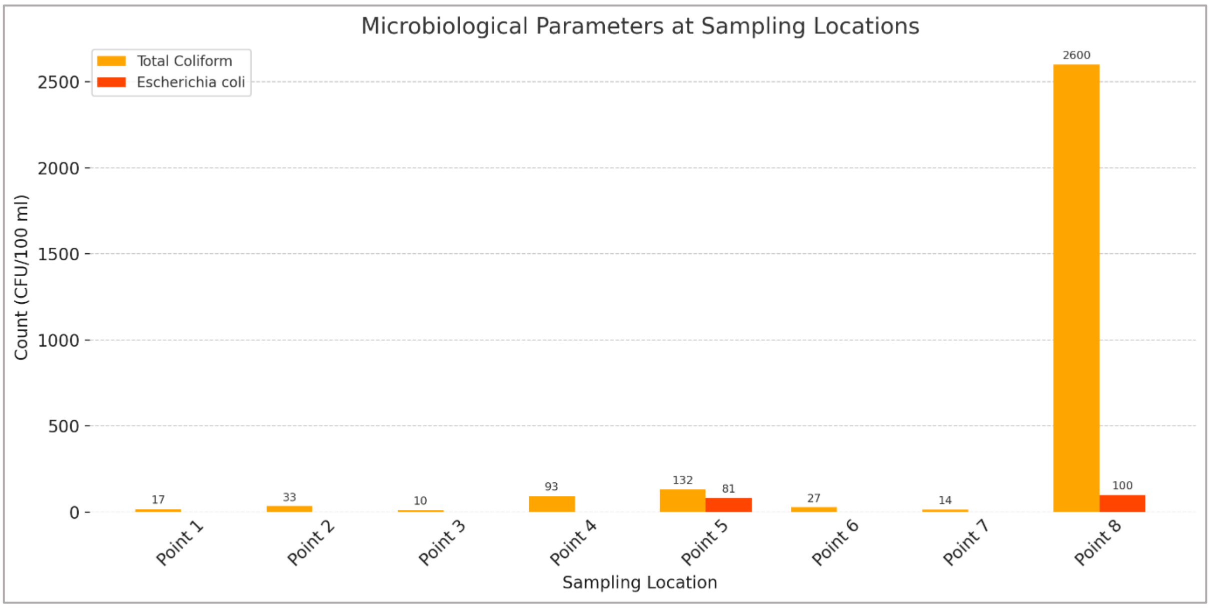

Figure 1. Comparison of Rainwater Microbiological Quality at Sampling Points

Most points met the E. coli quality standard (0 CFU/100 ml), except Points V and VIII, which showed contamination. Total Coliform levels exceeded the standard at Points IV, V, and especially VIII (2,600 CFU/100 ml), indicating significant pollution likely caused by domestic waste or surface runoff.

Concentration of Chemical Exposure (pH, Nitrate (NO_3), Cadmium (Cd), Lead (Pb), Fluoride (F)) in Rainwater Storage.

The laboratory test results from the Makassar Central Health Laboratory (BBLK) for the water quality parameters (rainwater) measured during the study, specifically the chemical parameters pH, Nitrate (NO_3), Cadmium (Cd), Lead (Pb), and Fluoride (F), are detailed in Table 2 below.

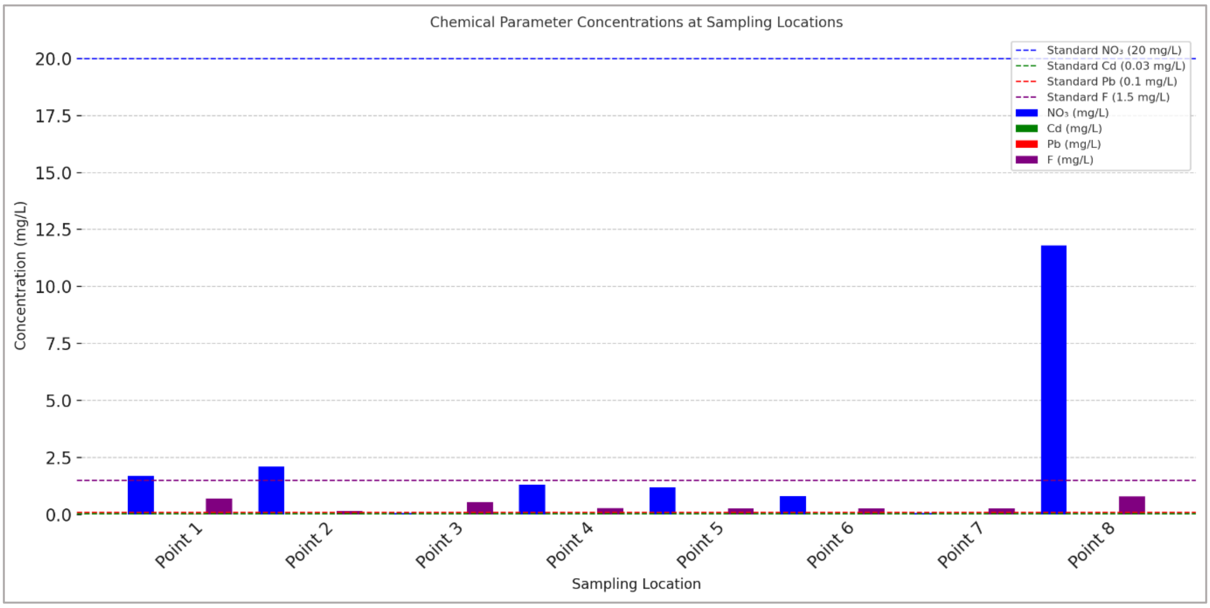

Figure 2. Comparison of Rainwater Chemical Quality at Sampling Points

Point VIII recorded the highest NO_3 (11.8 mg/L) and F (0.8 mg/L) levels, likely due to runoff or local geological conditions, but both remain below the limits. Cd and Pb levels were very low at all points, indicating minimal industrial or mining impact.

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Quantitative Microbial Risk Assessment Analysis of Total Coliform and E. coli in Rainwater Storage

Based on Table 1, the annual infection probability data (Pinf/yr Cf for coliform and Pinf/yr Ec for *E. coli*) indicate that most locations have a low annual infection risk, with Pinf/yr Cf ranging between 10^{-5} to 10^{-6}, as observed at Points I, II, III, VI, and VII, reflecting relatively safe water conditions. Point IV has a Pinf/yr Cf of 6.30E-05, which is slightly higher but still falls within the low-risk category. Meanwhile, Point V recorded a Pinf/yr Cf of 8.27E-05 and a Pinf/yr Ec of 4.73E-05, indicating an increased risk that requires attention. Point VIII presents the highest risk, with a Pinf/yr Cf reaching 1.49E-03 and a Pinf/yr Ec of 4.69E-05, suggesting a significant potential health hazard, particularly from coliform contamination

Table 1. Distribution of Risk Characterization Analysis

Point	Number of Respondents	Pinf/yr Cf	Pinf/yr Ec
I	4	1.24E-05	0.00E+00
II	22	2.24E-05	0.00E+00
III	17	7.08E-06	0.00E+00
IV	7	6.30E-05	0.00E+00
V	16	8.27E-05	4.73E-05
VI	2	1.97E-05	0.00E+00
VII	20	9.34E-06	0.00E+00
VIII	7	1.49E-03	4.69E-05

Health Risk Analysis for Chemical Exposure (Nitrate (NO_3), Cadmium (Cd), Lead (Pb), Fluoride (F)

Here are two tables that categorize the results of the health risk analysis for chemical exposure based on age groups:

Table 2. Health Risk Analysis for Children

Point	RQ Nitrate (NO_3) (mg/L)	RQ Cadmium (Cd) (mg/L)	RQ Fluoride (F) (mg/L)	RQ Lead (Pb) (mg/L)
I	5.82E-02	1.10E-02	6.76E-01	7.67E-02
II	1.05E-01	4.79E-03	4.79E-03	3.20E-02
III	2.21E-03	1.33E-06	2.43E-02	3.54E-04
IV	5.57E-02	4.11E-02	3.20E-01	1.71E-03
V	6.61E-02	5.29E-03	3.67E-01	4.22E-03
VI	2.73E-02	3.71E-03	2.58E-01	1.70E-02
VII	2.97E-03	7.60E-02	3.96E-01	2.37E-02
VIII	3.77E-05	1.21E-01	1.00E-03	1.51E-02

Table 3. Health Risk Analysis for Adults

Point	RQ Nitrate (NO_3) (mg/L)	RQ Cadmium (Cd) (mg/L)	RQ Fluoride (F) (mg/L)	RQ Lead (Pb) (mg/L)
I	3.40E-02	6.39E-03	3.94E-01	4.47E-02
II	6.29E-02	2.88E-03	2.88E-03	1.92E-02
III	1.63E-03	9.77E-07	1.79E-02	2.61E-04
IV	3.46E-02	2.56E-02	1.99E-01	1.07E-03
V	3.35E-02	2.68E-03	1.86E-01	2.14E-03
VI	6.54E-03	7.67E-04	5.33E-02	3.52E-03
VII	1.05E-03	2.69E-02	1.40E-01	8.41E-03
VIII	1.18E-05	3.77E-02	3.14E-04	4.71E-03

Table 2 and Table 3 above presents the Risk Quotient (RQ) for several contaminants, including Nitrate (NO_3), Cadmium (Cd), Fluoride (F), and Lead (Pb), in two receptor groups: children and adults. The Risk Quotient (RQ) is the ratio of contaminant exposure to the reference level that does not pose a health

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risk. An RQ value greater than 1 indicates a potential health risk. Nitrate and Cadmium exhibit low RQ values at all points for both children and adults, indicating a relatively low health risk. Fluoride in children approaches the risk threshold at certain points, particularly at point 1, necessitating further monitoring to prevent significant health risks, especially fluorosis in children. Lead has a low RQ value; however, it still requires attention, as Lead is a toxic substance that, even at low concentrations, can have long-term effects, particularly on children, who are more vulnerable to Lead poisoning.

DISCUSSION

Rainwater Quality and Health Risks

Water is essential for life, and humans require at least one liter of water daily. Good water quality is crucial for maintaining health, and drinking water must meet physical, chemical, bacteriological, and radiological standards. Some dissolved chemicals in water are necessary for the body but can be harmful if they exceed safe concentrations. Studies indicate that harvested rainwater should be treated before consumption. Chlorination in storage tanks and regular cleaning of catchment surfaces and pipelines help minimize (10)(18)(11). The catchment area, such as rooftops, collects rainwater, which then flows into storage tanks. To improve quality, the first flush of rain should be discarded, as initial rainfall contains high levels of atmospheric pollutants (19)(20)(21).

Microbial and chemical contamination mechanisms are influenced by environmental deposition, roofing material, seasonal variation, and local anthropogenic activities. These mechanisms are often overlooked in island studies, despite their relevance to tropical climate dynamics and infrastructure limitations (12)(13). Microbial contamination is a significant concern, with pathogenic microorganisms present on rooftops due to airborne pollutants, bird droppings, insects, and decaying plant material (20)(10)(11)(19). In the Caribbean, a *Salmonella* outbreak was linked to bird fecal contamination in rainwater catchments (22), with similar reports from Australia where *Escherichia coli* and *Campylobacter* were found in rainwater tanks (23). Beyond biological risks, inorganic pollutants like heavy metals (e.g., lead, cadmium, and chromium) pose hazards due to corrosion of roofing materials, pipes, and storage tanks, particularly from acidic rain (24). This study emphasizes the need to align local water safety evaluations with regulatory standards such as the WHO Guidelines (2017) and Indonesia's Ministry of Health Regulation No. 2 of 2023, which stipulate 0 CFU/100 mL for *E. coli* and Total Coliform and strict thresholds for heavy metals in drinking water. The World Health Organization (25) estimates that poor water quality contributes to 25% of global deaths and illnesses. Heavy metal exposure remains a critical factor affecting drinking water safety. To assess potential health risks, an ARKL study was conducted following the 2012 Technical Guidelines from the Indonesian Ministry of Health (26).

Microbiological Contamination in Drinking Water

Microbiological contamination in drinking water, particularly from *Total Coliform* and *Escherichia coli*, poses a significant public health risk. *Total Coliform* indicates organic pollution, while *E. coli* is directly associated with fecal contamination and can cause gastrointestinal infections. According to the EPA and WHO standards, safe drinking water must have 0 CFU/100 ml of these bacteria (8)(25). Research findings in Bulagi Utara District show high microbiological contamination in several rainwater collection points. Figure 1 indicates that Point VIII recorded *Total Coliform* at 2600 CFU/100 ml and *E. coli* at 100 CFU/100 ml, exceeding WHO's safety limits. In contrast, Points I and III had significantly lower contamination levels (0 CFU/100 ml for *E. coli*). The lack of adequate filtration systems in rainwater storage is likely a key contributor to this contamination, exacerbated by open or poorly maintained reservoirs allowing pathogen intrusion via dust, animal contact, or debris. These findings align with Machdar et al. (2013), who reported similar contamination in rural areas where untreated rainwater often harbors *Total Coliform* and *E. coli*. These results underscore the urgent need for context-specific mitigation strategies such as first-flush diversion, tight-lid storage, and point-of-use treatment, particularly in island regions with high rainfall and open-roof collection practices. Communities relying on untreated rainwater face high infection risks, particularly vulnerable groups like children and the elderly. Mitigation measures, including simple water

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treatment systems and public education on water hygiene, are essential to prevent waterborne diseases, especially in regions heavily dependent on rainwater (27).

Health Risk Assessment of Chemical Contaminants in Rainwater

Research findings indicate that the Risk Quotient (RQ) values for Nitrate (NO_3), Cadmium (Cd), Lead (Pb), and Fluoride (F) in rainwater from Bulagi Utara District remain within safe limits (RQ < 1) for both children and adults. However, Fluoride in children at Point 1 approaches the risk threshold (RQ = 0.67), making it the most concerning parameter. High fluoride levels can lead to dental fluorosis, characterized by changes in tooth enamel, and skeletal fluorosis, which can cause hardening and thickening of bones (28).

Nitrate exposure remains significantly below risk levels, with a maximum concentration of 0.226 mg/L, which is well below the U.S. Environmental Protection Agency's (EPA) maximum contaminant level (MCL) of 10 mg/L. This suggests no immediate health concerns related to methemoglobinemia (29). Lead (Pb) poses a low direct risk (RQ = 0.077 at its highest); however, chronic exposure remains a significant concern due to its neurotoxic effects, especially in children. Even low levels of lead exposure have been linked to intellectual and behavioral deficits, including hyperactivity, deficits in fine motor function, hand-eye coordination, reaction time, and decreased intelligence test performance (30). Recent studies indicate that cadmium (Cd) exposure, even at low levels, can lead to kidney dysfunction and damage. Cadmium accumulates primarily in the kidneys, impairing renal function and potentially causing proteinuria. Therefore, continuous monitoring of cadmium exposure is essential to mitigate potential health risks (31)(32)(25).

Overall, rainwater in Bulagi Utara is relatively safe for drinking based on chemical parameters. However, Fluoride poses the highest potential risk, particularly for children. Proper filtration and public awareness are essential for sustainable rainwater use (33). These findings reinforce the importance of integrating chemical risk profiles into local water safety planning, prioritizing cost-effective fluoride filtration technologies such as activated alumina and bone char in at-risk communities (WHO, 2017; UNICEF, 2021).

Limitations

This study has several limitations. First, rainwater sampling was conducted only during the rainy season (November–December), which may not represent year-round water quality. Second, uncontrolled variables such as the type and condition of rooftop materials, tank cleaning frequency, and environmental exposure levels may have influenced the results. Lastly, health risk estimation relied on modeled exposure rather than direct health outcome data, which may affect risk precision.

CONCLUSION

This study confirms that rainwater in the study area faces significant challenges, especially microbiological contamination, with *Total Coliform* reaching 2,600 CFU/100 ml at Point VIII. While chemical parameters remain within safe limits, the potential for long-term accumulation of fluoride and lead requires attention. An integrated mitigation strategy involving disinfection, filtration, and source investigation is recommended. Regular monitoring and water treatment are essential to reduce health risks and support sustainable rainwater use, particularly in vulnerable island communities. These findings offer a solid foundation for future research and policy formulation in rainwater quality management.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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