Journal of Health and Nutrition Research
Vol. 5, No. 2, 2026, pg. 960-974, https://doi.org/10.56303/jhnresearch.v5i2.1519
Journal homepage: https://journalmpci.com/index.php/jhnr/index

e-ISSN: **2829-9760**

Environmental Assessment of Cadmium in Paddy Soils and Rice Grains Adjacent to Limboto Lake: Bioaccumulation and Non-Carcinogenic Health Risks

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ARTICLE

Submitted: 03 June 2026

Accepted: 21 July 2026

Published: 01 August 2026

Keywords:
Bioaccumulation, Cadmium, Non-Carcinogenic Health Risks, Paddy Soil, Rice Grains

ABSTRACT

Cadmium (Cd) in agroecosystems poses risks to environmental quality, food safety, and public health because of its persistence and toxicity. This study assessed Cd concentrations in paddy soils and rice grains around Limboto Lake, Indonesia, evaluated soil contamination status, determined Cd transfer from soil to rice, and estimated potential health risks associated with rice consumption. A descriptive quantitative study was conducted at three rice-growing sites adjacent to the lake. Composite soil and rice grain samples were analyzed using Atomic Absorption Spectrophotometry (AAS). Soil contamination was evaluated using the Contamination Factor (Cf) and Geoaccumulation Index (Igeo), Cd transfer using the Bioaccumulation Factor (BAF), and health risks using the Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ). Soil pH ranged from 3.5 to 5.0, indicating acidic to very acidic conditions that may enhance Cd mobility and bioavailability. Cd concentrations ranged from 0.23–0.29 mg/kg in soils and 0.0019–0.0024 mg/kg in rice grains, both below environmental and food safety standards. Cf indicated moderate contamination, whereas Igeo classified the soils as unpolluted to moderately polluted, reflecting differences in the sensitivity and calculation approaches of the two indices. BAF values <1 indicated that although pH increases mobility, the current concentrations do not lead to significant bioaccumulation. EDI and THQ were below the safety threshold, indicating no significant non-carcinogenic health risk from current rice consumption. Although rice remains safe for consumption, persistent Cd occurrence in soils and rice suggests a potential long-term environmental concern if accumulation continues. Therefore, regular monitoring and soil management, including liming to increase soil pH, are recommended to reduce Cd mobility and maintain food safety in the Limboto Lake agroecosystem.

Key Messages:

- This study demonstrates that hydrological connectivity and sediment transport between the Limboto Lake and surrounding paddy fields influence Cd distribution, providing evidence for riparian agricultural.
- Although pH increases mobility, the current concentrations do not lead to significant bioaccumulation.
- The findings provide scientific evidence to support sustainable agricultural management and restoration of the nationally prioritized Limboto Lake under Presidential Regulation No. 60 of 2021, including liming for soil pH adjustment and long-term environmental monitoring.

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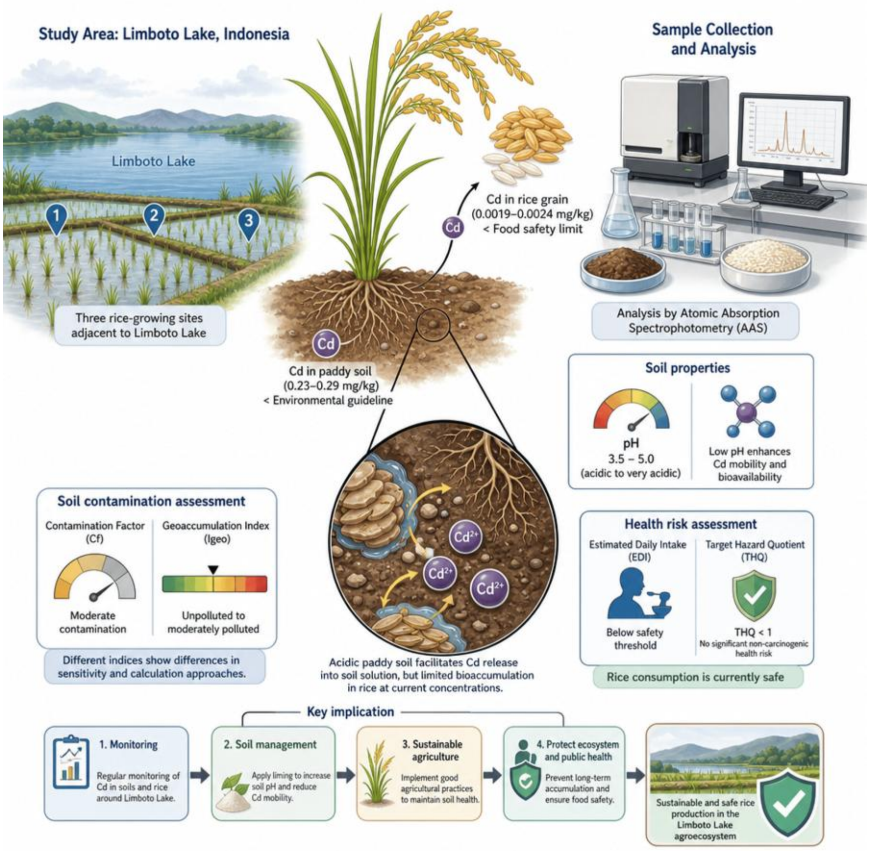
GRAPHICAL ABSTRACT



INTRODUCTION

Heavy metal contamination has become a major environmental issue due to its persistence, toxicity, and ability to accumulate in ecosystems and food chains. Among various heavy metals, cadmium (Cd) is considered one of the most hazardous pollutants because it is highly toxic even at low concentrations, non-biodegradable, and capable of bioaccumulation and biomagnification in living organisms (1). Cd can enter the environment through both natural processes, such as rock weathering, and anthropogenic activities, including industrial processes, mining operations, domestic waste disposal, and agricultural practices involving phosphate fertilizers and pesticides (2). Once released into aquatic environments, Cd tends to bind with suspended particles and accumulate in sediments, where it may persist for long periods and pose ecological risks (3).

The presence of Cd in the environment is of particular concern because of its adverse effects on human health. Chronic exposure to Cd has been associated with kidney dysfunction, liver damage, respiratory disorders, bone demineralization, and increased risk of cancer (4,5). Human exposure mainly occurs through food consumption, especially crops cultivated in contaminated soils. Rice grains (*Oryza sativa* L.), one of the most important staple foods worldwide, is known to accumulate Cd more efficiently than many other cereal crops due to its cultivation under flooded conditions that influence metal mobility and uptake (6). Consequently, Cd contamination in rice grains has become a significant food safety concern in many agricultural regions.

One ecosystem potentially affected by Cd contamination is Limboto Lake, the largest lake in Gorontalo Province, Indonesia. The lake plays a crucial role in supporting irrigation systems, fisheries, and local socioeconomic activities. However, the environmental quality of Limboto Lake has deteriorated considerably over recent decades due to severe sedimentation, watershed degradation, and pollutant inputs from surrounding anthropogenic activities (7). As a result of these environmental pressures, the Indonesian government has designated Limboto Lake as one of the fifteen national priority lakes requiring restoration under Presidential Regulation No. 60 of 2021 concerning the Rescue of National Priority Lakes. The implementation of this restoration program requires scientific evidence not only on aquatic environmental quality but also on contaminant transfer into surrounding agricultural ecosystems that

https://doi.org/10.56303/jhnresearch.v5i2.1519

directly support local food production. Therefore, information on Cd contamination in paddy soils and rice grains is essential to support restoration planning, environmental monitoring, and food safety management within the Limboto Lake watershed.

Previous studies have reported the presence of heavy metals, including Cd, in several environmental compartments of Limboto Lake. Findings reported in 2020 indicated Cd concentrations of 0.0069 ppm in lake water and 0.0181 ppm in Nile tilapia (*Oreochromis niloticus*), both of which remained below applicable regulatory standards. However, Cd concentrations in sediments reached 5.935 ppm, substantially exceeding the sediment quality guideline established by the Canadian Council of Ministers of the Environment (CCME) of 0.6 ppm (8). Similar findings were reported with higher concentrations of Cd in sediments compared to water and fish tissues, highlighting the role of sediments as the primary reservoir of heavy metal contamination within the lake ecosystem (9).

The accumulation of Cd in lake sediments raises concerns regarding its potential transfer to adjacent agricultural areas. Paddy fields surrounding Limboto Lake are hydrologically connected to the lake system and may be influenced by seasonal flooding, sediment transport, and irrigation practices. During periods of increased water levels and hydrodynamic disturbance, contaminated sediments may be redistributed from the lake to surrounding agricultural lands, resulting in the accumulation of Cd in paddy soils (10). Furthermore, the extensive use of phosphate-based fertilizers such as NPK fertilizers may contribute additional Cd inputs into agricultural soils because phosphate rocks naturally contain Cd as an impurity (11,12). In addition, agricultural soils surrounding Limboto Lake are generally characterized by acidic conditions, which can increase Cd mobility and bioavailability by enhancing its solubility in the soil solution. Under such conditions, even relatively low total Cd concentrations may become more readily available for plant uptake, increasing the potential for transfer into food crops.

Cd accumulated in paddy soils may subsequently be absorbed by rice plants through root uptake mechanisms. Due to its chemical similarity to essential nutrients such as zinc (Zn), iron (Fe), and calcium (Ca), Cd can enter plant tissues through nutrient transport pathways and be translocated to aerial parts, including rice grains (13). The presence of Cd in rice grains is particularly important because rice constitutes the primary staple food for most Indonesian populations, and long-term dietary exposure may pose risks to public health (14).

Although numerous studies have investigated Cd contamination in the water, sediments, and aquatic organisms of Limboto Lake (8,9), no study has comprehensively evaluated Cd distribution within the soil–rice system surrounding the lake, including its transfer from paddy soils to rice grains and the associated human health risks. This knowledge gap is particularly important because previous studies have demonstrated elevated Cd concentrations in lake sediments, while the surrounding agricultural soils are characterized by acidic conditions that may enhance Cd mobility and bioavailability. Consequently, the absence of data on Cd accumulation in paddy soils and rice grains may conceal a potential hidden public health concern, despite environmental contamination appearing limited based solely on water quality assessments. Scientific evidence addressing Cd transfer within agricultural systems is therefore needed to support environmental monitoring, food safety protection, and evidence-based implementation of the Limboto Lake restoration program.

This study aimed to evaluate Cd distribution within the soil–rice system in agricultural areas surrounding Limboto Lake by determining Cd concentrations in paddy soils and rice grains (*Oryza sativa* L.), assessing soil contamination status, quantifying Cd transfer through the bioaccumulation factor under local soil conditions, and estimating the potential non-carcinogenic health risks associated with rice consumption. The findings are expected to improve understanding of Cd behavior in the Limboto Lake agroecosystem and provide scientific evidence to support environmental monitoring, soil management, food safety protection, and the implementation of restoration strategies for the nationally prioritized Limboto Lake.

METHODS

This study employed a descriptive quantitative approach to identify Cd concentrations in paddy soils and rice grains cultivated in agricultural areas surrounding Limboto Lake, Gorontalo Province, Indonesia. The study was conducted in January 2026 during the harvesting season. Sampling stations was

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carried out at three locations situated within the lakeside agricultural zone of Limboto Lake, namely Station I (Bolihuangga), Station II (Hunggaluwa), and Station III (Dutulanaa) in Limboto District, Gorontalo Regency. The geographic coordinates of all sampling stations were recorded using a handheld Global Positioning System (GPS) receiver and are presented in Table 1 and Figure 1 together with the corresponding sampling locations.

Table 1. Geographic Coordinates of the Sampling Stations Surrounding Limboto Lake

Sampling Station	Station Name	Latitude	Longitude
Station I	Bolihuangga	0.61583	122.96611
Station II	Hunggaluwa	0.61194	122.97167
Station III	Dutulanaa	0.61000	122.99167

This study was designed as an environmental baseline assessment focusing on representative agricultural areas located within the riparian zone of Limboto Lake. Three sampling stations were purposively selected to represent the major rice-growing areas directly adjacent to the lake, where potential Cd transfer from lake sediments to agricultural soils is most likely to occur. At each sampling station, subsamples collected from five sampling points were homogenized to produce one composite soil sample and one composite rice sample for laboratory analysis. Therefore, each reported Cd concentration represents the analytical result of a single composite sample from each station. Composite sampling was employed to reduce spatial variability within each field and to provide representative estimates of Cd concentrations at each station.

The study population comprised all paddy fields located within the riparian zone surrounding Limboto Lake. Samples consisted of paddy soil and rice grains collected from three sampling stations. Cadmium analysis was performed by the UPTD Balai Laboratorium Kesehatan Masyarakat Provinsi Gorontalo using Atomic Absorption Spectrophotometry (AAS) following SNI 06-6992.4:2004 for soil samples and SNI 6128:2020 for rice samples. The laboratory operated under the quality management system of the Indonesian Health Laboratory Accreditation Committee (KALK) during the study period.

The agricultural areas selected for this study are located within the riparian zone surrounding Limboto Lake and are potentially influenced by seasonal hydrological fluctuations. Although Limboto Lake is not directly used as an irrigation water source, periodic flooding and lake overflow events may inundate adjacent paddy fields and facilitate the transport of lake sediments into agricultural lands. Considering that previous studies have reported elevated Cd concentrations in Limboto Lake sediments, such hydrological processes may contribute to the transfer and accumulation of Cd in paddy soils surrounding the lake.

For paddy soil sampling, five sampling points were established diagonally in an X-shaped pattern within a single paddy field at each station to represent field conditions. Soil samples were collected from a depth of 0–20 cm. Approximately 100 g of soil was collected from each point and combined into a composite sample (±500 g), which was homogenized. Subsequently, approximately 100 g of the composite sample was retained for laboratory analysis.

Rice grain samples were collected from the same paddy fields used for soil sampling. Approximately 500 g of harvested paddy grain originating from 25–30 rice clumps was collected at each station. The grains were sun-dried for 3–4 days, manually dehulled, homogenized, and subsampled to obtain approximately 100 g of rice grains for laboratory analysis. Sampling procedures followed SNI 19-0428-1998 (15) regarding solid sampling methods.

Prior to soil sampling, soil pH was measured at each sampling point using an Intelligent Soil Test device. Measurements were performed at the same locations where soil samples were collected. The pH values obtained from the five sampling points at each station were averaged to represent the soil acidity condition of the station. Soil pH categories were interpreted according to the standards issued by the Indonesian Center for Soil and Fertilizer Standard Testing (16).

Cd concentrations in paddy soil samples were analyzed using an Atomic Absorption Spectrophotometer (AAS; DF-AAS01, PT. DIFOTEK, Indonesia) following the Indonesian National Standard (SNI) 06-6992.4:2004 (17) concerning sediment analysis through acid digestion and AAS determination. Cd concentrations in rice grain samples were analyzed using the same instrument in accordance with SNI 6989-84:2019 (18) for dissolved and total metal determination by flame atomic absorption

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spectrophotometry.

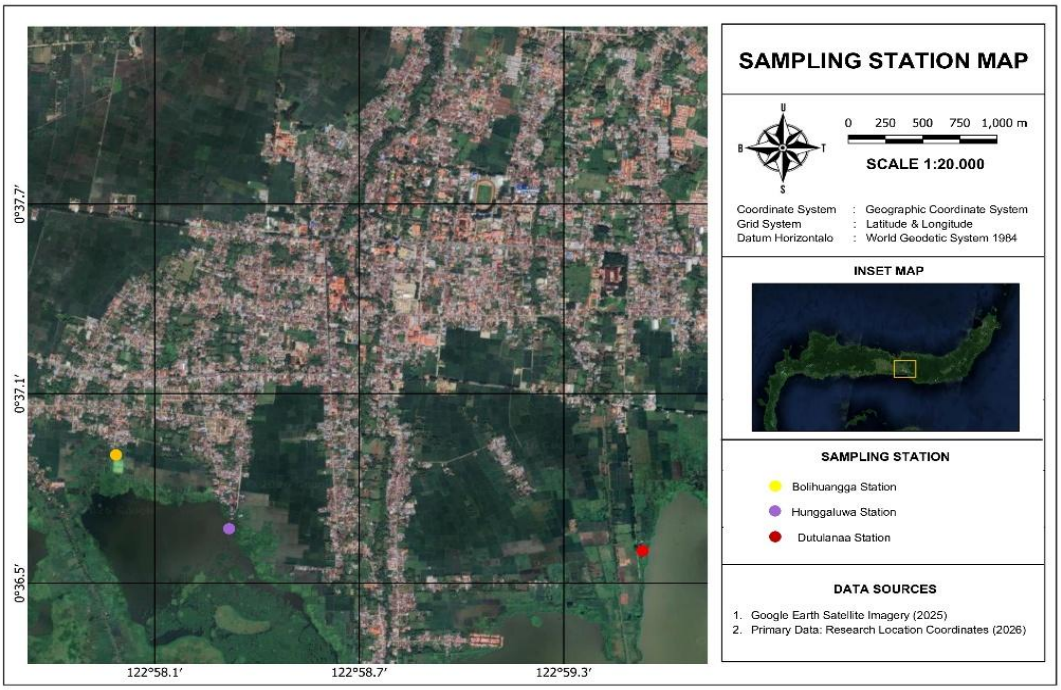

Figure 1. Sampling Station

The resulting Cd concentrations were expressed in ppm for paddy soil samples and mg/kg for rice grain samples. Soil Cd concentrations were compared with the sediment quality guideline established by the Canadian Council of Ministers of the Environment (CCME) (19), whereas rice grains Cd concentrations were evaluated against the maximum permissible limit specified in SNI 6128:2020 (20). Next, to assess the level of Cd contamination in paddy soils and to evaluate the degree of anthropogenic enrichment, the contamination factor (Cf) and geoaccumulation index (Igeo) were applied. These indices were used as environmental risk assessment tools to quantify soil contamination relative to natural background conditions.

Cf was calculated as the ratio between the measured Cd concentration in soil and its background concentration using the following equation (Formula 1).

$$C_f = \frac{C_{soil}}{C_{background}} \ldots\ldots\ldots\ldots \text{(Formula 1)}$$

where:

Cf = contamination factor

C_{soil} = Cd concentration in paddy soil (mg/kg)

$C_{background}$ = background Cd concentration in natural soil (mg/kg)

In this study, background concentration of 0.1 mg/kg was adopted based on values reported in previous studies on natural soil Cd levels (21). Cf values were classified to determine the level of Cd contamination in paddy soils. The classification system used in this study was as follows: Cf < 1 indicates low contamination; 1 ≤ Cf < 3 indicates moderate contamination; 3 ≤ Cf < 6 indicates considerable contamination; and Cf ≥ 6 indicates very high contamination (22).

In addition, Igeo was used to evaluate the degree of Cd enrichment in soils considering natural geochemical variability, calculated using the following equation (Formula 2).

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \ldots\ldots\ldots\ldots \text{(Formula 2)}$$

where:

Igeo = geoaccumulation index

C_n = measured Cd concentration in soil (mg/kg)

B_n = geochemical background value of Cd in soil (mg/kg)

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1.5 = constant factor accounting for natural lithogenic variability in soil

The resulting Cf and Igeo values were used to classify the level of soil contamination and to provide a quantitative basis for environmental risk assessment of Cd in the study area. Igeo were classified to assess the degree of Cd pollution in paddy soils based on established geochemical criteria. The classification is as follows: Igeo ≤ 0 indicates unpolluted conditions; 0 < Igeo ≤ 1 indicates unpolluted to moderately polluted; 1 < Igeo ≤ 2 indicates moderately polluted; 2 < Igeo ≤ 3 indicates moderately to strongly polluted; 3 < Igeo ≤ 4 indicates strongly polluted; 4 < Igeo ≤ 5 indicates strongly to extremely polluted; and Igeo > 5 indicates extremely polluted conditions (23).

The bioaccumulation factor (BAF) was calculated to evaluate the ability of rice plants to accumulate cadmium (Cd) from paddy soils. BAF was determined as the ratio between Cd concentration in rice grains and Cd concentration in paddy soil (Formula 3). A higher BAF indicates a greater capacity of the plant to absorb and accumulate Cd from the surrounding soil environment.

$$BAF = \frac{C_{rice}}{C_{soil}} \text{............ (Formula 3)}$$

where:
BAF = bioaccumulation factor
C_{rice} = Cd concentration in rice grains (mg/kg)
C_{soil} = Cd concentration in paddy soil (mg/kg)

The BAF was used to assess the ability of rice plants to accumulate cadmium from paddy soils. BAF greater than 1 indicates a high accumulation capacity, whereas BAF less than 1 indicates a relatively low transfer of Cd from soil to rice grains (24).

A screening-level health risk assessment was conducted to provide a preliminary estimate of potential non-carcinogenic health risks associated with Cd exposure through rice consumption. Because primary survey data on rice consumption patterns among local residents were unavailable, the assessment employed default national exposure parameters commonly used in environmental health risk assessment studies. Consequently, the estimated risks should be interpreted as screening-level estimates rather than site-specific population risk. Default exposure parameters were adopted, including a rice ingestion rate of 0.256 kg/day (25), an average body weight of 55 kg (26), and an oral reference dose of 1E-3 mg/kg BW/day for Cd (27). The estimated daily intake (EDI) was calculated using the following equation (Formula 4).

$$EDI = \frac{C \times IR}{BW} \text{ .... (Formula 4)}$$

where:
EDI = estimated daily intake (mg/kg BW/day)
C = Cd concentration in rice grains (mg/kg)
IR = rice grains ingestion rate (kg/day)
BW = body weight (kg)

The target hazard quotient (THQ) was calculated to estimate the potential non-carcinogenic health risk associated with Cd exposure (Formula 5). The use of default exposure parameters introduces uncertainty because actual rice consumption rates and body weight of the local population may differ from the adopted national values. Therefore, the estimated EDI and THQ should be interpreted as conservative screening indicators rather than precise estimates of individual exposure. THQ below 1 indicates that adverse non-carcinogenic health effects are unlikely, whereas a THQ value greater than 1 suggests a potential health concern (26).

$$THQ = \frac{EDI}{RfD} \text{ .... (Formula 5)}$$

where:
THQ = target hazard quotient
RfD = oral reference dose for Cd (mg/kg BW/day)

Data were analyzed descriptively using univariate analysis. Cd concentrations, soil pH, BAF, and health risk assessment were summarized for each sampling station and presented in graphical and tabular

https://doi.org/10.56303/jhnresearch.v5i2.1519

form. The measured Cd concentrations were then compared with the applicable environmental and food safety standards to assess their compliance with regulatory limits.

RESULTS

Soil pH, Cd in Paddy Soil, and Cd in Rice Grains

Soil pH was measured to characterize the acidity conditions of paddy soils at the three sampling stations surrounding Limboto Lake. The average soil pH values obtained at each station are presented in Figure 2. Based on Figure 2, the results of soil pH measurements from the three sampling stations surrounding Limboto Lake indicate that all locations had acidic soil conditions (4,17 ± 0,76). The highest pH was observed at Station III (pH 5.0), while the lowest pH was recorded at Station II (pH 3.5). According to the Indonesian Center for Soil and Fertilizer Standard Testing, pH 3.5 and 4.0 are classified as very acidic, whereas a pH 5.0 is classified as acidic. These findings indicate that the paddy soils at all three stations were characterized by relatively high acidity levels.

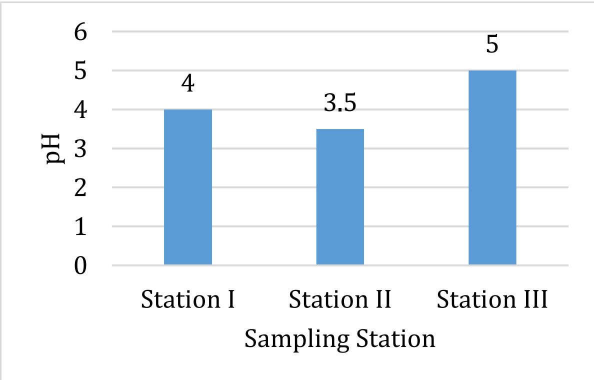

Figure 2. Soil pH at the Sampling Stations

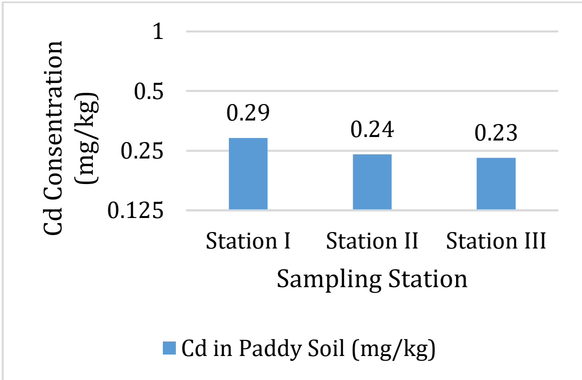

Figure 3. Cd Concentration in Paddy Soil

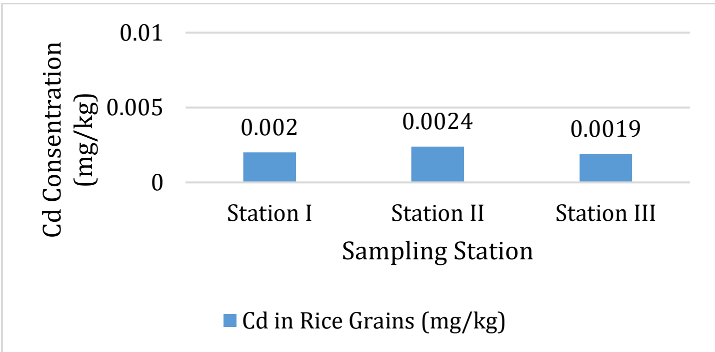

Figure 4. Cd Concentration in Rice Grains

Cd concentrations in paddy soil were determined to assess the level of environmental contamination in agricultural areas surrounding Limboto Lake. The measured Cd concentrations at each sampling station are presented in Figure 3. Based on Figure 3, Cd concentrations in paddy soil samples collected from agricultural areas surrounding Limboto Lake were relatively low and showed only slight variation among the sampling stations (0,25 ± 0,03 mg/kg). The highest Cd concentration was observed at Station I (0.29 mg/kg), while the lowest concentration was recorded at Station III (0.23 mg/kg). When compared with the sediment quality guideline established by the CCME of 0.6 mg/kg, the Cd concentrations measured at all three stations were below the permissible limit. These findings indicate that the Cd concentrations in paddy soils at the study sites complied with the applicable environmental quality standard.

Cd concentrations in rice grains were analyzed to evaluate the potential transfer of Cd from paddy soil to edible plant tissues. The results are presented in Figure 4. Based on Figure 4, the concentrations of Cd in rice grain samples collected from the three sampling stations were relatively low and showed only

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slight variation among the stations (0,0021 ± 0,0003 mg/kg). The highest Cd concentration was observed at Station II (0.0024 mg/kg), while the lowest concentration was recorded at Station III (0.0019 mg/kg). These findings indicate that the rice grain samples collected from the study area were safe for consumption with respect to Cd contamination, as all measured concentrations were below the maximum permissible limit specified by SNI 6128:2020.

Bioaccumulation and Non-Carcinogenic Health Risks

Cf was used to assess the level of Cd contamination in paddy soils relative to natural background concentrations. This index provides a quantitative measure of soil contamination intensity across sampling stations. The results of the Cf analysis showed values ranging from 2.30 to 2.90 across the sampling stations. The highest Cf was observed at Station I (Cf 2.90), while the lowest Cf was recorded at Station III (Cf 2.30). Based on the classification criteria, all sampling stations fall within the moderate contamination category (1 ≤ Cf < 3), indicating that Cd contamination is present at a consistent moderate level across the study area.

Table 2. Bioaccumulation and Non-Carcinogenic Health Risks

Sampling Station	pH	Paddy Soil Cd (mg/kg)	Rice Grains Cd (mg/kg)	Cf	Igeo	BAF	THQ	Interpretation (Cf; Igeo; BAF; THQ)
Station I	4.0	0.29	0.0020	2.90	0.95	0.0069	0,00931	Moderate contamination; Unpolluted to moderately polluted; No significant bioaccumulation; Not a risk
Station II	3.5	0.24	0.0024	2.40	0.68	0.0100	0,01117	Moderate contamination; Unpolluted to moderately polluted; No significant bioaccumulation; Not a risk
Station III	5.0	0.23	0.0019	2.30	0.61	0.0083	0,00884	Moderate contamination; Unpolluted to moderately polluted; No significant bioaccumulation; Not a risk

Igeo was applied to evaluate the degree of Cd enrichment in paddy soils by considering natural geochemical background variations. This index provides an indication of the extent of anthropogenic influence on soil contamination. Igeo ranged from 0.61 to 0.95 across all sampling stations. The highest Igeo was recorded at Station I (Igeo 0.95), while the lowest Igeo was recorded at Station III (Igeo 0.61). According to the Igeo classification, all sampling locations fall within the category of unpolluted to moderately polluted (0 < Igeo < 1), indicating a low to moderate level of cadmium enrichment in paddy soils.

BAF was calculated to evaluate the transfer of Cd from paddy soil to rice grains. The BAF ranged from 0.0069 to 0.0100 across the three sampling stations. Station II exhibited the highest BAF (BAF 0.0100), whereas the lowest BAF was recorded at Station I (BAF 0.0069). All BAF were below 1, suggesting a relatively low capacity of rice plants to accumulate Cd from paddy soils into rice grains.

To evaluate the potential health risks associated with Cd exposure through rice grains consumption, the EDI and THQ were calculated using default exposure parameters. The EDI of Cd through rice grains consumption ranged from 0.00000884 to 0.00001117 mg/kg BW/day. The highest EDI was observed at Station II (0.00001117 mg/kg BW/day), corresponding to the highest Cd concentration detected in rice grains. Similarly, the highest THQ was recorded at Station II (0,01117), whereas the lowest

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THQ was observed at Station III (0,00884). All THQ were substantially below the safety threshold of 1, indicating that rice grains consumption from the study area is unlikely to pose significant non-carcinogenic health risks under the assumed exposure conditions.

DISCUSSION

Soil Acidity and its Influence on Cd Availability

Soil pH is a key environmental factor that regulates the mobility, solubility, and bioavailability of heavy metals in agricultural ecosystems (28). The results of this study showed that soil pH at the sampling stations ranged from 3.5 to 5.0, indicating acidic to very acidic soil conditions. Station II exhibited the lowest pH (pH 3.5), and the highest pH at Station III (pH 5.0). According to the Indonesian Center for Soil and Fertilizer Standard Testing, soils within this pH range are classified as acidic and may influence the behavior and availability of trace metals, including Cd.

The influence of soil acidity on Cd availability has been widely reported in environmental studies. Under acidic conditions, increased concentrations of hydrogen ions (H^+) compete with metal cations for adsorption sites on soil particles, thereby reducing metal retention and enhancing the release of Cd into the soil solution. Consequently, Cd becomes more soluble and readily available for plant uptake. In contrast, higher soil pH promotes metal adsorption and precipitation processes, reducing Cd mobility and limiting its transfer to plants. Therefore, soil acidification is generally associated with increased Cd bioavailability and a greater risk of accumulation in agricultural crops (29).

The findings of this study support this mechanism. Although the highest Cd concentration in paddy soil was observed at Station I (0.29 ppm), the highest Cd concentration in rice grains was recorded at Station II (0.0024 mg/kg). A decrease in soil pH from 5.0 at Station III to 3.5 at Station II was accompanied by an increase in Cd concentration in rice grains from 0.0019 mg/kg to 0.0024 mg/kg. This pattern suggests that total Cd concentration in soil alone does not fully determine Cd accumulation in rice grains. Instead, soil pH appears to play a critical role in controlling the fraction of Cd that remains bioavailable and accessible for plant uptake.

The effect of soil acidity is further reflected in the BAF obtained in this study. Station II exhibited the highest BAF (BAF 0.0100), despite having lower soil Cd concentrations than Station I. This finding indicates that acidic soil conditions may enhance Cd uptake efficiency by increasing metal solubility and root absorption. Similar observations have been reported in previous studies, where lower soil pH was associated with increased Cd accumulation in rice grains tissues due to enhanced metal mobility in the rhizosphere.

The acidic soil conditions observed in the agricultural areas surrounding Limboto Lake may also be influenced by local environmental characteristics. These areas are located within the lake's riparian zone and are periodically affected by hydrological fluctuations, including seasonal flooding and sediment deposition. Such processes may alter soil chemical properties and influence the distribution and availability of heavy metals. Although the Cd concentrations measured in both paddy soil and rice grains remained below the applicable quality standards, the combination of acidic soil conditions and the presence of Cd indicate a potential pathway for contaminant transfer within the rice agroecosystem.

Overall, the findings highlight the importance of soil pH as a controlling factor in Cd bioavailability and accumulation in rice grains cultivated around Limboto Lake. The observed relationship between lower soil pH, higher Cd concentrations in rice grains, and elevated BAF suggests that soil acidity may contribute more strongly to Cd uptake than the total concentration of Cd present in the soil. Therefore, soil pH should be considered an important indicator when evaluating the environmental behavior and potential risks of Cd contamination in agricultural areas adjacent to Limboto Lake.

Cd Contamination in Paddy Soils Surrounding Limboto Lake

The presence of Cd in paddy soils surrounding Limboto Lake reflects the combined influence of lake-derived sediment deposition and long-term anthropogenic inputs within the watershed system. Soil Cd concentrations showed a spatial gradient across sampling stations, with the highest level recorded at Station I (0.29 mg/kg), followed by Station II (0.24 mg/kg) and Station III (0.23 mg/kg). This pattern indicates heterogeneous Cd distribution governed by local hydrodynamic conditions and sediment

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transport processes rather than uniform background accumulation.

Cf analysis confirmed moderate Cd contamination across all stations, indicating that soil Cd levels are consistently elevated above natural background concentrations. In parallel, Igeo classified all sites as unpolluted to moderately polluted, suggesting a low to moderate degree of geochemical enrichment. The agreement between Cf and Igeo results indicates that Cd contamination is present at an early to intermediate stage of environmental alteration, without reaching severe pollution conditions.

Although both indices evaluate soil contamination, they differ in their conceptual basis. The contamination factor (Cf) directly compares measured Cd concentrations with the background concentration, making it more sensitive to relatively small increases above natural levels. In contrast, the geoaccumulation index (Igeo) incorporates a correction factor (1.5) to account for natural lithogenic variability, resulting in a more conservative assessment of contamination status. Consequently, the moderate contamination indicated by Cf and the unpolluted to moderately polluted classification obtained from Igeo should not be interpreted as contradictory findings but rather as complementary evidence that Cd enrichment has occurred while geochemical alteration remains relatively limited. From a watershed management perspective, this condition represents an early warning stage in which preventive measures can be implemented before more severe contamination develops.

The spatial distribution of Cd is primarily controlled by flood-mediated sediment deposition from Limboto Lake. During inundation events, fine-grained, metal-associated sediments are transported and deposited onto adjacent paddy fields, particularly in low-lying depositional zones such as Station I. These particles exhibit high adsorption capacity for Cd, resulting in localized enrichment. Consequently, paddy fields function as secondary sinks for sediment-bound heavy metals within the fluvial–lacustrine system.

Under flooded rice cultivation conditions, reducing soil environments further influence Cd mobility by promoting the release of Cd from sediment-bound phases into soil pore water. This enhances its bioavailable fraction and facilitates redistribution within the topsoil layer (30). In addition, long-term agricultural practices, particularly phosphate fertilizer application, may contribute to cumulative Cd input, although its influence is likely secondary compared to sediment-driven sources in this system (31).

Despite moderate contamination levels, the persistence of Cd in flood-affected soils indicates a dynamic system where deposited metals can be periodically remobilized under changing redox and pH conditions. This maintains Cd availability within the soil environment and sustains its potential transfer into the agricultural food chain. Overall, Cd contamination in paddy soils surrounding Limboto Lake is governed by sediment-driven inputs modulated by flood dynamics and soil geochemical processes. The observed moderate contamination levels highlight a transitional environmental condition that links natural hydrological processes with anthropogenic influence, forming a continuous pathway for downstream transfer into rice cultivation systems.

Cd Accumulation and Bioaccumulation in Rice Grains

The presence of Cd in rice grains collected from all sampling stations confirms the successful transfer of Cd from contaminated paddy soils into the edible portion of rice plants, representing the final stage of contamination in the soil–plant–food chain within the Limboto Lake agricultural ecosystem. The spatial distribution of Cd in rice grains closely follows the pattern observed in paddy soils pH, where higher concentrations are found in areas with lower soil pH levels, particularly at Station II. This spatial consistency indicates a direct and continuous soil-to-rice transfer pathway driven by environmental contamination in the study area.

The accumulation of Cd in rice grains is primarily controlled by its bioavailable fraction in the rhizosphere rather than total soil concentration. In flooded paddy systems, acidic soil conditions combined with reducing environments enhance Cd solubility in pore water, increasing its availability for root uptake (32). These conditions facilitate Cd mobility from soil solution into plant roots, making rice highly responsive to changes in environmental Cd bioavailability.

At the physiological level, Cd uptake occurs through transport pathways shared with essential micronutrients such as Zn^{2+}, Fe^{2+}, and Mn^{2+}. Due to its similar ionic properties, Cd is absorbed by root transporters and partially translocated to above-ground tissues, including grains. Although rice plants possess partial exclusion and sequestration mechanisms, their efficiency is limited under continuous

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exposure conditions, resulting in detectable Cd accumulation in edible grains (33).

To further evaluate the efficiency of Cd transfer from soil to rice grains, the BAF was calculated as the ratio between Cd concentration in rice grains and Cd concentration in soil. The obtained BAF across all sampling stations were consistently below unity (BAF < 1), indicating limited transfer efficiency from soil to rice grains. However, the presence of Cd in rice despite low BAF confirms that Cd mobility remains active within the system, sustained by continuous environmental availability in flooded paddy conditions.

Spatial variation in BAF reflects differences in soil chemistry and hydrological influence, particularly soil pH and water saturation levels. Sites with more acidic conditions and higher moisture content tend to exhibit relatively higher BAF due to increased Cd solubility and mobility in pore water. This demonstrates that Cd uptake is strongly governed by environmental bioavailability rather than total soil Cd concentration alone. From an ecological perspective, the combined accumulation and bioaccumulation results indicate that the Limboto Lake paddy ecosystem operates as a regulated but continuous transfer system. While Cd is not efficiently accumulated at high levels (BAF < 1), the persistent movement of Cd into rice grains represents a sustained exposure pathway that is environmentally significant.

Overall, the findings demonstrate that Cd transfer from soil to rice grains is an ongoing and environmentally regulated process driven by soil geochemistry and flood-induced mobility in the Limboto Lake paddy system. Although bioaccumulation efficiency remains low (BAF < 1), the consistent detection of Cd in rice grains confirms a sustained exposure pathway from environmental compartments to the human food chain. This indicates that the system represents a low-efficiency but continuous transfer model, where long-term dietary exposure rather than acute toxicity becomes the primary concern for public health.

Environmental and Human Health Implications

The presence of Cd across paddy soils and rice grains in the Limboto Lake agricultural system indicates a continuous and functionally connected contamination pathway linking sediment dynamics, soil processes, and food production. This integrated system demonstrates that Cd contamination in the study area is not an isolated environmental phenomenon, but rather a watershed-scale process governed by hydrological transport and biogeochemical cycling.

From an environmental perspective, the paddy fields surrounding Limboto Lake act as a secondary sink for Cd derived from lake sediments. Repeated flood events facilitate the deposition of fine sediment particles enriched with heavy metals into agricultural soils, resulting in gradual and cumulative enrichment over time. This process establishes a long-term contamination baseline in the soil, particularly in areas with strong hydrological connectivity to the lake system. The environmental risk is further intensified by the dynamic geochemical behavior of Cd under flooded rice cultivation conditions. Alternating redox states and acidic soil environments enhance Cd mobility and sustain its bioavailability across cropping cycles (34). This ensures that Cd remains continuously accessible for plant uptake, even in the absence of additional external inputs. As a result, the system operates as an active biogeochemical pathway that perpetuates internal recycling of Cd within the soil–water–plant continuum.

From a food safety perspective, the detection of Cd in rice grains confirms a direct dietary exposure route for the local population. Although the measured concentrations may not indicate acute toxicity, the chronic nature of rice consumption introduces a long-term exposure scenario. Given the well-documented bioaccumulative behavior of Cd in the human body, particularly in renal tissues, even low-level continuous intake may result in progressive health effects over time.

In this context, the Limboto Lake paddy system can be characterized as an emerging environmental and public health risk area, where environmental contamination has already transitioned into a food chain exposure pathway. The combination of sediment-driven contamination, enhanced soil mobility, and plant uptake efficiency creates a persistent exposure loop that directly links environmental quality to human health outcomes.

Although THQ values below one indicate that adverse non-carcinogenic effects are unlikely under current exposure assumptions, these results should be interpreted cautiously because the present assessment represents a screening-level estimate based on default national exposure parameters. Such an approach may not fully capture the actual dietary habits of local communities, who may consume larger

https://doi.org/10.56303/jhnresearch.v5i2.1519

quantities of locally produced rice over extended periods. Furthermore, the bioaccumulative nature of Cd suggests that continuous low-dose exposure over decades could contribute to progressive renal dysfunction and other chronic health effects that are not adequately reflected by short-term screening indices alone.

The findings also highlight that effective risk management cannot rely solely on soil quality control, but must adopt a watershed-based approach. Priority should be given to monitoring sediment quality in Limboto Lake, reducing upstream contaminant inputs, and implementing agricultural practices that limit Cd mobility and uptake. Additionally, routine monitoring of Cd levels in rice grains is essential to ensure food safety and to prevent long-term accumulation in the human population. Overall, this study demonstrates that Cd contamination in the Limboto Lake region represents an integrated environmental-health issue characterized by continuous transfer from sediment to soil and ultimately to the human food chain. This reinforces the need for proactive and system-level interventions to mitigate long-term ecological and public health risks.

Potential sources of bias should also be considered when interpreting the findings. Sampling locations were intentionally selected within the riparian zone surrounding Limboto Lake because these areas are most likely to receive sediment deposition from lake flooding. Consequently, the results may represent conditions with relatively higher Cd exposure compared with paddy fields located farther from the lake. In addition, sampling was conducted during the harvesting season following the annual hydrological cycle. Seasonal flooding may alter sediment deposition, soil chemistry, and Cd mobility; therefore, Cd concentrations and transfer characteristics could differ under dry-season conditions.

This study has several limitations that should be considered when interpreting the findings. First, environmental sampling was limited to three representative stations surrounding Limboto Lake, which may not fully capture the spatial variability of Cd contamination throughout the entire agricultural area. Second, this study employed a cross-sectional design in which sampling was conducted only once during the harvesting season. Consequently, seasonal variations in hydrological conditions, sediment transport, and soil chemistry were not evaluated and may influence Cd distribution and bioavailability over time. Third, only Cd was analyzed, whereas other potentially interacting heavy metals such as Pb, Hg, As, or Zn were not included. Interactions among multiple metals may influence uptake mechanisms and associated health risks. Finally, the human health risk assessment represents a screening-level estimate based on default national exposure parameters because site-specific consumption data were unavailable. Future studies should incorporate larger spatial coverage, repeated seasonal sampling, multi-metal assessment, and locally derived exposure parameters to provide a more comprehensive understanding of heavy metal dynamics in the Limboto Lake agroecosystem.

Future longitudinal studies are needed to evaluate temporal changes in Cd accumulation and to determine the effectiveness of soil remediation practices, particularly liming for pH adjustment, in reducing Cd bioavailability. In addition, further investigations should assess the influence of seasonal flooding and sediment redistribution on Cd mobility within riparian agricultural soils surrounding Limboto Lake.

CONCLUSION

This study confirms the presence of cadmium (Cd) in both paddy soils and rice grains cultivated in agricultural areas surrounding Limboto Lake, demonstrating an active soil–plant transfer pathway within the agroecosystem. Cd was detected in all paddy soil samples, with concentrations ranging from 0.23 to 0.29 ppm, and in all rice grain samples, with concentrations ranging from 0.0019 to 0.0024 mg/kg. Although the measured concentrations remained below the applicable environmental and food safety standards, the detection of Cd in rice grains confirms the transfer of Cd from paddy soils to edible plant tissues. These findings indicate that the agricultural ecosystems surrounding Limboto Lake have been exposed to Cd contamination pathways and demonstrate the movement of heavy metals from environmental media into food crops. In addition, the higher Cd concentration observed in rice grains from Hunggaluwa despite lower soil Cd concentrations suggests that soil acidity, rather than total soil Cd concentration alone, may play an important role in regulating Cd bioavailability and uptake by rice plants.

Based on these findings, continuous monitoring of Cd contamination in agricultural soils and rice surrounding Limboto Lake is recommended to prevent long-term accumulation of heavy metals within the

https://doi.org/10.56303/jhnresearch.v5i2.1519

food chain. Efforts to promote sustainable agricultural practices, including the prudent use of phosphate-based fertilizers, should also be encouraged to minimize additional Cd inputs into agricultural lands. Further studies involving a larger number of sampling locations and additional environmental parameters, such as irrigation water quality, sediment characteristics, soil organic matter, and other factors influencing Cd mobility and bioavailability, are needed to provide a more comprehensive understanding of Cd transport and accumulation in the agricultural ecosystem surrounding Limboto Lake.

DECLARATION OF THE USING OF AI

During the preparation of this manuscript, the authors used artificial intelligence tools including ChatGPT (OpenAI) and Gemini AI to enhance clarity, language fluency, and overall readability of the text. All Al generated suggestions were critically reviewed and edited by the authors to ensure accuracy, originality, and academic integrity. The authors take full responsibility for the content of the publication.

FUNDING

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

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Gorontalo Provincial Health Laboratory and the laboratory technicians for analyzing Cd levels in soil and rice. They also thank the Limboto District Government, the Bolihuangga, Hunggaluwa, and Dutulanaa Village Governments for granting research permits. They also thank the farmers and landowners for facilitating access to the rice fields, and their supervisors for providing input on the preparation of this article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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