Journal of Environmental Science, Health & Sustainability, 2026, 2(2), 174–186
https://journals.enviromindsolutions.com/jeshs
eISSN: 3067-946X

Article

Heavy metal contamination, physicochemical properties, and environmental health risks of soils affected by rice mill effluents in Birnin Kebbi, Nigeria

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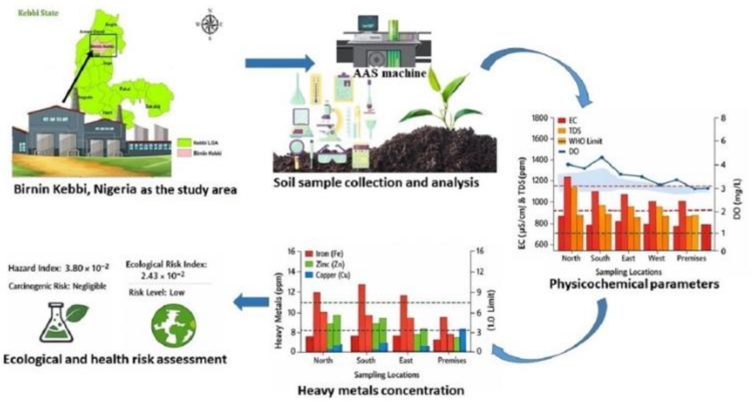
How to cite

Yahaya, T., Bello, S., Izuafa, A., Inuwa, F., Boku, U.I., Nathaniel, J., 2026. Heavy metal contamination, physicochemical properties, and environmental health risks of soils affected by rice mill effluents in Birnin Kebbi, Nigeria. Journal of Environmental Science, Health & Sustainability, 2(2), 174–186.
https://doi.org/10.63697/jeshs.2026.10075

Graphical abstract



Article info

Received: 22 December 2025
Revised: 5 February 2026
Accepted: 14 February 2026

Keywords

Soils
Heavy metals
Hazard quotient (HQ)
Public health
Rice mill effluent

Highlights

- *Soils around the Labana Rice Mill were slightly acidic with elevated electrical conductivity and total dissolved solids.*
- *Dissolved oxygen levels were low, indicating environmental stress from effluent discharge.*
- *Fe, Zn, and Cu exceeded WHO and national guideline limits, while Pb remained below detection.*
- *Health risk assessment showed low non-carcinogenic risk and negligible carcinogenic and ecological risks.*

Abstract

Rice mill effluents can degrade soil quality and introduce contaminants that pose ecological and public health risks, yet data from large-scale milling facilities in northern Nigeria remain limited. This study assessed the physicochemical characteristics, heavy metal concentrations, and associated health and ecological risks of soils surrounding Labana Rice Mill, Birnin Kebbi, Nigeria. Soil samples were collected from the mill premises and the cardinal directions (North, South, East, and West) and analyzed in the laboratory. The soils were slightly acidic, having pH values ranging between 6.20 and 6.62. Electrical conductivity (EC) exceeded the World Health Organization (WHO) guidelines (>1,500 µS/cm) in the North (1,510 µS/cm) and West (1,570 µS/cm) directions, while total dissolved solids (TDS) were also elevated in these locations (760–790 mg/L) compared to the WHO guidelines (<500 mg/L). Dissolved oxygen levels were low (2.3–2.9 mg/L) relative to WHO guidelines (6.5–8.0 mg/L), whereas temperature values (27.9–29.0°C) were within the normal ranges. Heavy metal analysis revealed elevated iron (Fe) concentrations above National Standards for Drinking Water Quality (NSDWQ) and WHO guidelines (1–

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Handling Editor: Dr. M. M. Rahman.

3 mg/L) in the South (10.90 mg/L), North (12.60 mg/L), and West (13.60 mg/L) directions. Zinc (Zn) exceeded the WHO limit (3.0 mg/L) in the South (6.90 mg/L), and copper (Cu) exceeded the NSDWQ limit (1.0 mg/L) in the same location (2.00 mg/L). Lead (Pb) was below detection limits across all sites. Non-carcinogenic health risk assessment yielded a hazard index of 3.80 × 10^{-2}, while carcinogenic risk was negligible. Ecological risk was also low (2.43 × 10^{-2}), with metal concentrations following the order: South > West > North > Premises > East. Positive correlations were observed between some physicochemical parameters and heavy metals, suggesting a common source. Although current exposure poses no immediate health risk, the detected contamination highlights the need for routine monitoring and improved pollution control measures.

1 Introduction

Rice is a staple food for approximately 4 billion people worldwide, playing a crucial role in food security and agriculture (Mishra et al., 2022). It is cultivated in over 100 countries, with Asia accounting for 90% of global production (Fukagawa and Ziska, 2019). In Africa, rice production totals 10 million metric tons, with Nigeria contributing 50% (around 3 million metric tons) of this amount (Ibrahim et al., 2025). From a dietary perspective, rice is the most important grain globally, providing about 20% of the world's nutritional energy supply (Zafar and Jianlong, 2023; Duan et al., 2024), and contributing approximately 10.5% to the average caloric intake in Nigeria (Ahmed et al., 2025). Rice is rich in essential vitamins, minerals, and bioactive compounds such as phytic acid, phenols, sterols, flavonoids, terpenoids, anthocyanins, tocopherols, tocotrienols, and oryzanol (Baptista et al., 2024). Economically, the rice value chain significantly contributes to global economies through income for farmers, traders, laborers, and tax revenue for governments. The total global trade value of rice is USD 28.4 billion, derived from 700 million metric tons of trade (Odewole et al., 2024). In Nigeria, the rice market is substantial, estimated at between USD 1.5 billion and USD 3.85 billion, and is projected to grow at 10% annually due to high demand (around 7 million tons annually) (Belewu et al., 2025). However, the rice production process also contributes to environmental pollution, which may have negative implications for human health.

The rice milling process, which transforms paddy into polished rice, is a crucial step in rice production. However, it generates substantial effluents that can have serious environmental and health consequences (Mohidem et al., 2022). These effluents are typically characterized by high levels of organic matter, nutrients, and various contaminants (Kumar and Deswal, 2021). They often have elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which can deplete oxygen levels in receiving water bodies (Lokman et al., 2021). This depletion can harm aquatic organisms, including fish, invertebrates, and vital microbial communities, leading to reduced biodiversity and altered ecosystem dynamics (Larance et al., 2025). Additionally, the nutrient load in rice mill effluents can stimulate excessive algal growth, resulting in eutrophication, a process that further degrades water quality and disrupts aquatic habitats. If these effluents enter the food chain or drinking water supply, they can also pose risks to human health (Tiwari and Pal, 2022). The impact of rice mill effluents on soil is equally concerning. When discharged onto agricultural fields, these effluents can alter soil chemistry, affect nutrient availability and disrupt microbial activity (Nwankwo et al., 2025). Rice mill effluents may also contain heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), and arsenic (As) (Yahaya et al., 2021). These metals are toxic and have been linked to various health issues, including respiratory, genetic, and hematological diseases, as well as skin, eye, and brain damage.

Heavy metals contaminate soil, water, and air, disrupting ecosystems by interfering with nutrient cycles, reducing soil fertility, and damaging microbial communities (Yahaya, 2020). In plants, they can cause stunted growth, reduced yields, and metabolic damage by competing with essential nutrients, inducing oxidative stress, and disrupting enzyme functions. Ultimately, these metals can enter the food chain, posing significant risks to human health (Yahaya et al., 2022). Given these health and environmental concerns, regular monitoring of rice mill effluents is essential to protect the health of workers, nearby residents, and the broader ecosystem.

Labana Rice Mill, located in Birnin Kebbi, Nigeria, is one of the largest and fastest-growing rice mills in the country. It employs hundreds of workers and makes significant contributions to both the local and national economy. However, the mill releases pollutants into the surrounding environment, highlighting the need for continuous monitoring of toxic substances around the facility. A review of the literature indicated that, aside from studies by Yahaya et al. (2019) and Yahaya et al. (2021), the effluents from this facility have not been evaluated in recent years. Therefore, it is crucial to assess the safety of the effluents released by the mill. Soil, being a primary reservoir for pollutants, serves as an important environmental matrix for evaluating pollutant levels and associated risks.

This study aimed to assess the physicochemical parameters and heavy metal concentrations in soil samples collected around Labana Rice Mill. Additionally, the potential health risks posed by heavy metals in these soil samples were evaluated.

2 Materials and methods

2.1 Description of the study area

The Labana Rice Mill is located along the Kebbi-Argungu Motorway in Birnin Kebbi, Kebbi State, Nigeria (**Figure 1**). Birnin Kebbi is situated in the northwest of the country at latitude 12° 27' 57.8808" N and longitude 4° 11' 58.2864" E. The state is bordered by Katsina and Zamfara States to the west, Sokoto State to the north, Niger State to the south, and shares an international border with the Niger Republic to the east. The major ethnic groups in the state include the Hausa, Fulani, and Zuru, alongside non-natives such as the Yoruba, Igbo, Edo, and Nupe. The region's vegetation is predominantly grassland, with scattered shrubs and trees. The climate is marked by high temperatures, often exceeding 40°C during hot weather, and a prolonged dry season from October to May (Yahaya et al., 2022). However, during the Harmattan season (November to March), temperatures can drop below 20°C. The majority of the state's population are farmers and livestock breeders, with rice farming being particularly prominent.

Rice cultivation thrives in Kebbi due to favorable conditions such as high temperatures, abundant sunshine that supports multiple harvests, fertile alluvial soils in the Fadama areas, and access to water resources, especially through irrigation during the dry season. The abundance of paddy rice has contributed to the establishment of several rice mills, including Labana Rice Mill. This mill is one of the largest rice processing facilities in Nigeria, engaging in processes such as parboiling, milling, polishing, and packaging. These operations generate significant amounts of effluent and solid waste, which are often discharged into nearby drainage systems and surrounding farmlands. Such discharges may contain elevated levels of physicochemical pollutants and heavy metals from machinery wear, lubricants, fuel combustion, and other industrial inputs, posing potential health and environmental risks to surrounding communities.

2.2 Sample collection and preparation

Soil samples were collected weekly for three consecutive weeks from the northern, southern, eastern, and western axes of Labana Rice Mill, as well as within the mill premises,

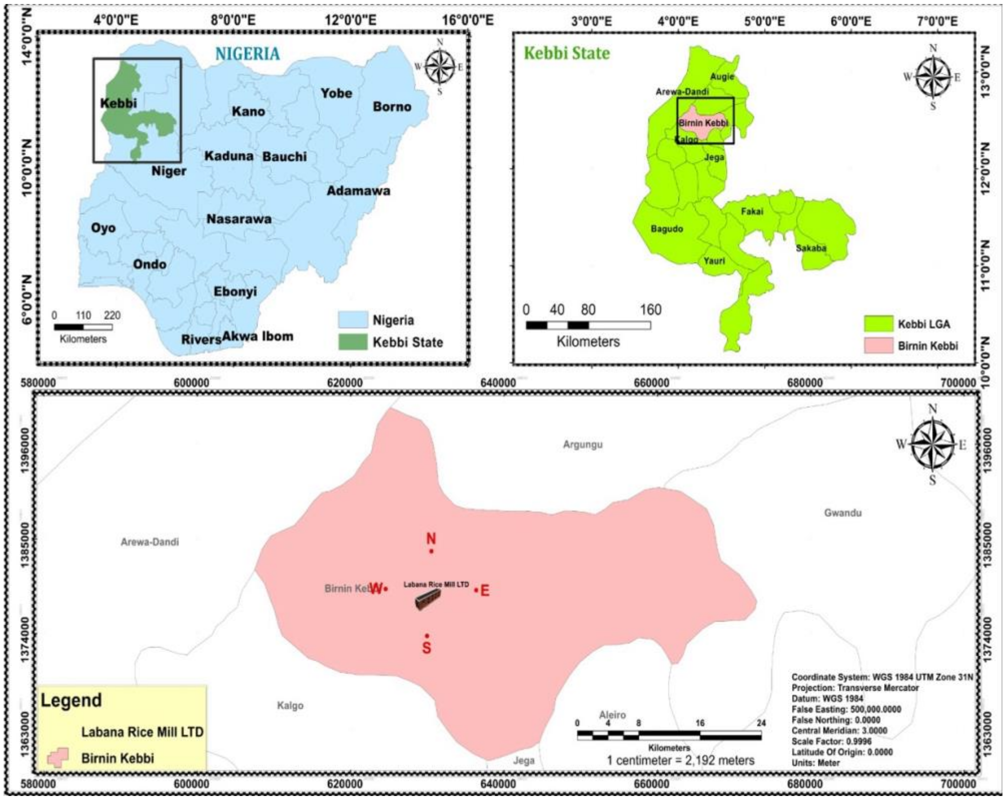

Figure 1. *Map showing location of the study site.*

between August and September 2025. The northern and eastern axes are the effluent discharge points of the mill, the southern is the entrance, and the western is the packaging unit. During each sampling event, three samples were taken per axis at 5 m intervals, yielding nine samples per axis and a total of 45 samples. Samples were randomly collected at a depth of 0–10 cm (Yahaya, 2020) into clean, pre-sterilized polyethylene bags, labelled, and transported to the laboratory, where they were stored at 4°C before analysis (APHA, 2017). The samples were then air-dried at room temperature (28°C) for 5 days, and later oven-dried until constant weights were attained. Thereafter, the samples were gently crushed with a mortar and pestle and sieved through a 2-mm mesh to remove debris and homogenize the material prior to digestion.

2.3 Determination of physicochemical parameters

The physicochemical parameters of the soil samples were analyzed following the protocols of the American Public Health Association (APHA, 2017). Time-sensitive parameters such as pH, temperature, and electrical conductivity (EC) were measured onsite using a portable pH meter (CA 10101), a digital thermometer (K-Life DT-01), and a conductivity meter (CA 10141). In the laboratory, total dissolved solids (TDS) were estimated from EC readings (Barroso et al., 2023). Dissolved oxygen (DO) was determined using the Winkler titrimetric method (Carvalho et al., 2021), chemical oxygen demand (COD) by the dichromate oxidation method (von Mühlen et al., 2022), and biological oxygen demand (BOD) after 5 days of incubation at 20°C (Sen et al., 2025).

2.4 Heavy metal analysis

The samples were digested following APHA (2017) to convert heavy metals into soluble forms suitable for atomic absorption spectroscopy analysis. A 1.0 g portion of each sieved soil sample was placed in a digestion flask, followed by the addition of 10 mL HNO_3 and 2 mL $HClO_4$. The mixture was heated under a fume hood at 150°C until a clear solution was obtained. The digest was then cooled, filtered, and diluted to 50 mL with deionized water. Four heavy metals – lead (Pb), zinc (Zn), iron (Fe), and copper (Cu) – frequently documented in the literature as being associated with rice milling activities were selected for analysis.

The concentrations of the heavy metals were determined using an Atomic Absorption Spectrophotometer (UNICAM Model 969). Standard stock solutions (1,000 mg/L) were serially diluted to prepare working standards, and calibration curves were generated for each metal. Blanks were analyzed to correct for background interference. All analyses were performed in triplicate to ensure accuracy and reproducibility.

2.5 Quality assurance and quality control

A quality assurance and quality control procedure were implemented for all physicochemical and heavy-metal analyses. Instrument calibration was performed with multi-element standard solutions spanning the concentration ranges of the samples, and calibration curves ($R^2 \geq 0.995$) were verified at the beginning and after every ten samples. Method blanks, duplicate samples, and spiked recoveries were included in each analytical batch to assess contamination, precision, and accuracy. Limits of detection and quantification were calculated as three and ten times the standard deviation of procedural blanks, respectively, and all reported concentrations were above the quantification limits.

2.6 Human health risk assessment

The health risks of heavy metals in the soil samples were estimated from their carcinogenic and non-carcinogenic risks. Human health risk was evaluated for a conservative child-exposure scenario, assuming incidental ingestion of contaminated soil as the primary exposure pathway. This route is particularly relevant for children because of frequent hand-to-mouth behavior during outdoor play near the mill. Adults may be exposed to heavy metals in the soil when the soil contaminate drinking water or enter food chain. Additionally, dry soil particles may be airborne and inhaled by adults and children.

The non-carcinogenic risks were estimated from their chronic daily intakes (CDI), hazard quotient (HQ), and hazard index (HI) as outlined in equations 1, 2, and 3 (USEPA, 2022).

$$\mathrm{CDI} = \frac{C \times IR \times EF \times ED}{BW \times AT} \qquad (1)$$

Where: C = contaminant concentration (mg/kg); IR = ingestion rate (1×10^{-4} kg/day child); EF = exposure frequency (365 days/year). ED = exposure duration (70 years). BW = body weight (15 kg). AT = averaging time (ED × 365 non-carcinogenic).

$$\mathrm{HQ} = \frac{CDI}{RfD} \qquad (2)$$

Where RfD is the oral reference dose (mg/kg/day). RfD for Fe, Cu, Zn, and Pb is 0.7, 0.04, 0.3, and 0.004 (mg/kg BW/day), respectively (USEPA, 2022).

$$HI = \sum_{i=1}^{n} HQI \qquad (3)$$

$HQ < 1$ = safe, and $HI < 1$ = safe (USEPA, 2022).

The carcinogenic risk (CR) of the heavy metals was calculated using equation 4 (USEPA, 2022).

$$CR = CDI \times SF \qquad (4)$$

Where SF is the cancer slope factor (mg/kg/day). According to USEPA (2022), SF of Pb is 0.00000243. Other heavy metals (Fe, Cu, and Zn) analyzed are not carcinogenic, so they have no SF. CR that falls between 1×10^{-6} to 1×10^{-4} is acceptable (USEPA, 2022).

2.7 Ecological risk assessment of the heavy metal

The ecological risks (Er) of heavy metals in the soil were estimated using equation 5 (Hakanson, 1980).

$$Er = Tr \times \frac{C}{Si} \qquad (5)$$

Potential Ecological Risk Index (PERI) $= \sum E_r^i$

Where T^{i}_{r} = toxic response factor of each heavy metal (Fe = 1, Cu = 6, Zn = 1, and Pb = 5). Ci = measured concentration; Si = background or reference value (mg/kg) of each heavy metal (Fe = 15,000, Cu = 35, Zn = 100, Pb = 35 mg/kg). PERI <150 = low risk (acceptable).

2.8 Pollution indices

In addition to ecological risk, several pollution indices were used to characterize heavy-metal contamination in the soils (Hakanson, 1980). The contamination factor (CF) was calculated as shown in equation 6.

$$CF = C_i / B_i \qquad (6)$$

Where C_i is the measured concentration and B_i is the background or reference value of metal i.

Geoaccumulation index (I_{geo}) was calculated from equation 7.

$$I_{geo} = \log_2 [C_i / (1.5\ B_i)] \qquad (7)$$

Enrichment factor (EF) was obtained using equation 8.

$$EF = \frac{(Ci / Cref)}{(Bi / Bref)} \qquad (8)$$

Using Fe as the reference element. These indices, together with the ecological risk factor (Er) and potential ecological risk index (PERI), were interpreted using commonly applied classification schemes to distinguish low, moderate, and high contamination classes.

2.9 Correlation analysis

Pearson's correlation coefficient (r) was used to assess the linear relationship between physicochemical parameters and heavy metal concentrations. The coefficient was calculated as per the equation 9.

$$r = \frac{\sum(Xi - \bar{X})(Yi - \bar{Y})}{\sqrt{\sum(Xi - \bar{X})^2 (Yi - \bar{Y})^2}} \qquad (9)$$

2.10 Data analysis

Data obtained were analyzed using Microsoft Excel and SPSS (Version 25). Descriptive statistics such as mean, range, and standard deviation were calculated. Pearson correlation analysis was applied to examine relationships between physicochemical parameters and heavy-metal concentrations. In addition, principal component analysis (PCA) with varimax rotation was performed on standardized variables to identify potential pollution sources. Components with eigenvalues greater than 1 were retained, and variables with loading coefficients ≥ |0.6| were considered significant contributors to each component.

3 Results

3.1 Physicochemical parameters of the soil samples

The pH values ranged from 6.20 to 6.62, indicating slightly acidic to near-neutral conditions (**Table 1**). Electrical conductivity (EC) was highest at the northern (1,510 µS/cm) and western (1,570 µS/cm) sites, slightly exceeding WHO guideline values. Total dissolved solids (TDS) showed a similar trend, with elevated values at the northern (760 mg/L) and western (790 mg/L) locations. Dissolved oxygen (DO) ranged from 2.3 to 2.9 mg/L, lower than the values (6.5–8 mg/L) recommended by the WHO. The temperatures (27.9–29.0°C) were within the typical range for tropical environments.

3.2 Concentrations of heavy metals in soil samples

Iron concentrations showed the highest levels across all sites, with the west (13.6 ± 0.25 mg/L), north (12.6 ± 0.31 mg/L), and south (10.9 ± 0.28 mg/L) exceeding WHO guideline values (**Table 2**). Cu and Zn concentrations were generally within WHO permissible limits, except for Zn at the south site (6.90 ± 0.30 mg/L), which was slightly elevated. Pb concentrations were below detection limits in all samples.

Table 1. *Physicochemical parameters of soil samples obtained around Labana Rice Mills. The values were expressed as mean ± SD (n = 9).*

Sampling sites	pH	EC (µS/cm)	TDS (mg/L)	DO (mg/L)	Temp (°C)
Premises	6.57 ± 0.10	713 ± 10.5	354 ± 6.2	2.8 ± 0.2	27.9 ± 0.4
North	6.20 ± 0.09	1,510 ± 15.2	760 ± 10.4	2.5 ± 0.3	28.5 ± 0.3
West	6.22 ± 0.08	1,570 ± 12.8	790 ± 8.6	2.3 ± 0.2	28.5 ± 0.3
South	6.62 ± 0.07	480 ± 7.9	240 ± 5.0	2.6 ± 0.2	28.5 ± 0.3
East	6.55 ± 0.09	670 ± 8.5	433 ± 6.1	2.9 ± 0.2	29.0 ± 0.3
WHO (2024)	6.0–8.5	<1,500	<500	6.5–8	<35°C

3.3 Health and ecological risk assessment

The potential non-carcinogenic and carcinogenic health risks, along with the ecological risks from heavy metals in the soil, are summarized in **Table 3**. These values were calculated based on the mean concentrations of the heavy metals. For non-carcinogenic risk, the individual HQ values for all heavy metals were below the threshold of 1.0. The cumulative HI value was 0.038, which is also below 1.0, indicating that there is no immediate non-carcinogenic health risk from exposure to the soil. The carcinogenic risk from Pb, the only carcinogenic heavy metal among the heavy metals tested, was negligible, as Pb concentrations were below detection limits. The potential ecological risk index is 0.306, which is considered very low. The Er values for each individual heavy metal were also very low.

3.4 Pollution indices

The calculated CF, Igeo, and EF values indicated generally low to moderate contamination for most heavy metals, with higher CF and EF values for Zn at the southern location (**Table 4**). This pattern is consistent with the elevated Zn concentration along with the low potential ecological risk index suggesting low overall ecological risk.

A composite contamination index was calculated for each location based on the concentrations of the four heavy metals relative to their WHO guideline values. The southern location was the most contaminated, with contamination index of 224.58, but largely driven by the high Zn concentrations. The western and northern zones were also highly contaminated, with contamination indices of 197.92 and 189.17, respectively. On the other hand, rice mill premises and east of the mill are moderately contaminated (46.58 and 61.25, respectively).

3.5 Principal component analysis

The PCA reduced the dataset into three principal components with eigenvalues >1, jointly explaining 99.03% of the total variance. The PC1 (53.6%) was strongly influenced by pH and DO, with negative contributions from EC, TDS, and Fe, representing a salinity–dissolved oxygen gradient (**Fig. 2**). The PC2 (31.45%) was dominated by Cu and Zn loadings alongside moderate Fe and DO loadings, indicating a heavy metal pollution index. The third

Table 2. *Concentrations of heavy metals in soil samples collected around Labana Rice Mills. The values were expressed as mean ± SD (n = 9). BDL = below detection limits.*

Sampling site	Fe (mg/L)	Cu (mg/L)	Zn (mg/L)	Pb (mg/L)
Premises	2.44 ± 0.12	1.50 ± 0.08	1.30 ± 0.06	BDL
North	12.6 ± 0.31	1.60 ± 0.09	2.40 ± 0.10	BDL
West	13.6 ± 0.25	1.50 ± 0.07	2.10 ± 0.09	BDL
South	10.9 ± 0.28	2.00 ± 0.12	6.90 ± 0.30	BDL
East	4.74 ± 0.20	0.90 ± 0.05	0.30 ± 0.02	BDL
WHO (2024)	1–3	4.0	3.0	0.01
NSDWQ (2007)	0.3	1.0	3.0	0.01

Table 3. *Non-carcinogenic, carcinogenic, and ecological risks of heavy metals in soil obtained from Labana Rice Mills.*

Heavy metals	CDI	HQ	CR	Er
Fe	1.18×10^{-4}	1.68×10^{-2}	0.0	5.31×10^{-4}
Cu	1.97×10^{-5}	1.97×10^{-2}	0.0	2.12×10^{-2}
Zn	3.47×10^{-5}	2.58×10^{-3}	0.0	2.60×10^{-3}
Pb	0.0	0.0	0.0	0.0
Total		$3.80x10^{-2}$	0.0	$2.43x10^{-2}$

component (PC3; 13.97%) was primarily dominated by temperature, reflecting an independent thermal influence.

3.6 Correlation analysis

The data showed significant positive correlations between some physicochemical parameters (EC and TDS) and heavy metals (Fe, Cu, and Zn), suggesting a common source related to rice-mill effluent despite variable salinity-metal links (**Table 5**). The PCA loadings corroborate this: PC2 highlights Cu/Zn/Fe pollution factors linked to milling activities, while PC1 reflects opposing salinity-oxygen baselines.

Table 4. *Contamination factor (CF), geoaccumulation index (Igeo), and enrichment factor (EF) for Fe, Cu, and Zn in soils.*

Location	Heavy metals	CF	Igeo	EF
Premises	Fe	0.000	-12.258	1.0
	Cu	0.043	-10.732	10.61
	Zn	0.013	-11.442	3.269
North	Fe	0.001	-11.290	1.0
	Cu	0.046	-10.688	9.986
	Zn	0.024	-10.913	5.28
West	Fe	0.001	-11.221	1.0
	Cu	0.043	-10.726	10.05
	Zn	0.021	-11.029	4.777
South	Fe	0.001	-11.400	1.0
	Cu	0.057	-10.555	12.95
	Zn	0.069	-10.138	15.92
East	Fe	0.000	-11.965	1.0
	Cu	0.026	-10.982	9.434
	Zn	0.003	-12.795	1.049

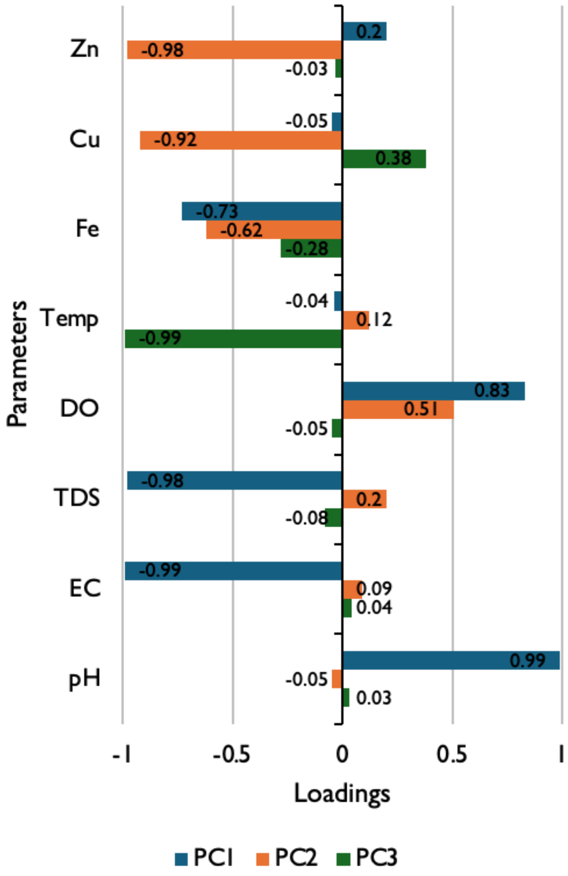

Figure 2. *The varimax-rotated loadings of physicochemical parameters and heavy metals on principal components.*

4 Discussion

The physicochemical characteristics of the soil samples showed slightly acidic pH values (6.2–6.62), which, according to Xia et al. (2024), support nutrient availability and microbial activity. This mild acidity, observed at the northern, western, and southern axes, may result from organic acids or chemical residues in the effluents (Kandagatla et al., 2023). Similar pH ranges in rice mill effluents have been reported by Nabayi et al. (2021), while Hassan et al. (2016) and Erhuen et al. (2024) documented more acidic conditions in soils and water bodies receiving rice mill discharge. Electrical conductivity was elevated in samples from the northern (1,510 ± 15.2 μS/cm) and western (1,570 ± 12.8 μS/cm) axes, indicating high concentrations of dissolved organic and inorganic substances, particularly soluble salts. This aligns with findings by Afrad et al. (2020) and Nabayi et al. (2021), though Islam et al. (2020) and Singh and Bajpai (2025) reported acceptable EC levels in similar settings. Total dissolved solids were similarly elevated in the western (790 ± 8.6 mg/L) and northern (760 ± 10.4 mg/L) axes, reflecting the expected

Table 5. *Pearson correlation coefficients between physicochemical parameters and heavy metals in soils (n = 45).*

Variables	pH	EC	TDS	DO	Temp	Fe	Cu	Zn
pH	1	-0.994	-0.984	0.768	-0.075	-0.704	0.0	0.246
EC	-0.994	1	0.986	-0.773	0.008	0.664	-0.014	-0.287
TDS	-0.984	0.986	1	-0.695	0.144	0.617	-0.164	-0.387
DO	0.768	-0.773	-0.695	1	0.086	-0.909	-0.505	-0.322
Temp	-0.075	0.008	0.144	0.086	1	0.231	-0.489	-0.093
Fe	-0.704	0.664	0.617	-0.909	0.231	1	0.494	0.465
Cu	0.0	-0.014	-0.164	-0.505	-0.489	0.494	1	0.878
Zn	0.246	-0.287	-0.387	-0.322	-0.093	0.465	0.878	1

correlation between EC and TDS. Elevated TDS in rice mill effluent typically arises from dissolved organic and inorganic materials leached during parboiling and soaking. These dissolved ions directly increase EC (Mohit and Suprita, 2022). Dissolved oxygen was low across all samples (2.3–2.9 mg/L), likely due to high TDS, microbial activity, and potential eutrophication, although biological parameters were not assessed in this study (Debassi et al., 2025). High TDS reduces DO by lowering oxygen solubility and supporting microbial decomposition that consumes oxygen (Hanjaniamin et al., 2023). Low DO in rice mill effluents is typically linked to elevated organic loads and higher temperatures that promote bacterial respiration (Dien et al., 2019). Soil temperatures across sites (27.9–29.0°C) were within WHO limits, likely due to sampling during the rainy season when higher moisture content moderates soil temperature (Zhang et al., 2022). Overall, physicochemical conditions were more degraded at the northern and western axes, likely due to their proximity to effluent discharge points.

Elevated Fe concentrations, exceeding WHO limits in all samples, may be attributed to mechanical wear of milling equipment, which releases Fe particulates through corrosion and abrasion (Oniya et al., 2018). Additional sources include the paddy rice itself, which can accumulate Fe from the soil and may be Fe-fortified, as well as water used during milling, particularly during parboiling (Yahaya et al., 2021). These observations agree with findings by Yahaya et al. (2021), and Mohidem et al. (2022), who reported elevated Fe in soils surrounding rice mills due to machinery corrosion and wastewater runoff. In contrast, Ajah et al. (2022) and Surma and Gesa (2025) reported permissible Fe levels in rice from cultivated fields and milling facilities. On the other hand, Cu, Zn, and Pb, were within permissible limits, except Zn (6.9 ± 0.3 mg/L) in samples from the southern axis. These findings are consistent with most available studies, including Bai et al. (2018), Kukwa et al. (2024), and Surma and Gesa (2025). Beyond milling operations, heavy metals in rice mill effluents may also originate from agrochemicals (fertilizers, pesticides, and herbicides), as well as from natural background levels in soils and water used for parboiling. The estimated health risks using total metal concentrations and did not directly measure oral bioaccessibility. Because only a fraction of ingested metals becomes soluble in gastrointestinal fluids, the risk values reported here may overestimate actual internal exposure. Future work should incorporate in-vitro bioaccessibility assays, such as those applied for As and other metals in contaminated soils, to provide more realistic estimates of bioaccessible doses and associated health risks as demonstrated by Fazle Bari et al. (2021).

The HI of 3.80×10^{-2} and individual HQs (Fe: 1.68×10^{-2}, and Cu: 1.97×10^{-2}) from non-carcinogenic risk assessment, which are all below the threshold (<1), indicate that exposure to the soil may not currently pose health risks. Similarly, the soil poses no CR risk as the only carcinogenic heavy metals (Pb) among the heavy metals analyzed was below detection levels. These findings indicate that, even under a conservative child-ingestion scenario, both non-carcinogenic and carcinogenic risks remain within acceptable limits. The PERI of the heavy metals was 2.43×10^{-2}, which is far below the threshold values of 150, suggesting that exposure to the heavy metals may not currently pose any ecological risks. Pollution indices further confirmed the low overall contamination status of the soils. The CF for all metals remained below 1, and I_{geo} values were strongly negative, indicating an "unpolluted" class across all sites. Nevertheless, the EF revealed a noticeable relative enrichment of Zn at the southern site, alongside moderate Cu enrichment at all locations, which mirrors the elevated Zn concentration reported for the southern site and supports the PERI results that point to low but non-negligible ecological concern in this area. The Zn enrichment may be attributed to site-specific anthropogenic activities such as increased vehicular traffic, wear of galvanized materials, corrosion of roofing sheets and pipelines, or the use of Zn-containing agrochemicals and fertilizers common in peri-urban and agricultural zones. Similar concerns regarding trace-element accumulation in soils and their transfer into crops, with associated human-health risks, have been documented in other contaminated agro-ecosystems (Ramos Ramos et al., 2025). Spatial distribution analysis showed that southern, northern, and western axes of the mill were all contaminated, suggesting uniform distribution of contaminants around the mill confirming mill emissions as the primary source.

Although health risk assessment of the heavy metals indicated no immediate health risks from exposure to the soil, the detection of some heavy metals and physiochemical parameters above the safe limits raises concerns. High EC can stress plants by causing osmotic imbalance, reducing nutrient uptake, inducing ion toxicity (e.g., Na^+, and Cl^-), degrading soil structure, and contributing to oxygen depletion in aquatic systems (Yahaya et al., 2021). Pearson correlation analysis revealed clear interrelationships among soil parameters near the mill. Electrical conductivity showed a strong positive association with TDS ($r = 0.99$, $p < 0.001$) and a moderate positive relationship with Fe ($r = 0.66$, $p < 0.01$), indicating that increasing salinity was accompanied by higher dissolved solids and Fe concentrations. In contrast, Fe was strongly and negatively correlated with DO ($r = -0.91$, $p < 0.001$), suggesting oxygen depletion under Fe-enriched conditions. The weak to moderate negative correlation between EC and Zn ($r = -0.29$, $p < 0.05$) implies limited co-variation between salinity and Zn levels, whereas the strong positive correlation between Cu and Zn ($r = 0.88$, $p < 0.001$) points to shared geochemical behavior or common anthropogenic inputs. Consistent with these relationships, PCA extracted three components explaining 99.03% of the total variance. The PC1 (total variance explained is 53.60%) reflected a dominant salinity–oxygen gradient, defined by positive loadings of pH and DO and negative loadings of EC and TDS. The PC2 (total variance explained is 31.45%) was governed by Fe, Cu, and Zn, highlighting a heavy-metal control, while the PC3 (total variance explained is 13.97%) was primarily associated with temperature, indicating an independent thermal influence. These results show that variability in soil quality near the mill is mainly controlled by ionic composition and oxygen dynamics, with metal enrichment and temperature contributing as secondary factors. Consumption of water with excessive dissolved salts may increase risks of cardiovascular and renal disorders (Kaur, 2019; Yahaya et al., 2023). Elevated TDS impacts crops, infrastructure, and human health, leading to saline taste, pipe scaling, skin dryness, digestive problems, kidney stones, reduced immunity, and potential increases in hypertension and heart disease due to high sodium levels (Adjovu et al., 2023). Low DO disrupts aerobic processes in soil and water, restricting root growth, reducing nutrient and water absorption, altering microbial communities, and causing hypoxia in humans, which presents with confusion, breathlessness, tachycardia, and cyanosis (Munzel et al., 2023). Elevated Fe levels further impair soil quality, plant growth, water aesthetics, and potability, and chronic exposure in humans can contribute to organ damage due to Fe accumulation (Akhtar et al., 2022).

5 Conclusion

This study evaluated the physicochemical properties, heavy metal concentrations, and potential health risks associated with soils surrounding Labana Rice Mills, Birnin Kebbi, Nigeria. The results showed that effluent discharge from the facility alters soil characteries, particularly at the northern and western axes closest to discharge points. While soil pH remained slightly acidic and within acceptable ecological ranges, elevated EC and TDS values indicate high levels of dissolved organic and inorganic pollutants. Dissolved oxygen levels were consistently low, suggesting increased microbial activity and reduced oxygen availability, which can impair soil and aquatic ecosystem function. Heavy metal analysis showed that Fe concentrations exceeded WHO limits in all locations, likely due to the corrosive activities associated with machines, contaminated process water, and natural or agricultural inputs. Although most other metals were within permissible limits, elevated Zn at the southern axis presents an additional concern. Although the health and ecological risk assessment of the heavy metals pose no immediate health risk, the detection of these metals raises ecological and public health concerns. Labana Rice Mills should implement an effective effluent treatment system. Periodic monitoring of soil, water, and effluent quality should be mandated to track changes over time and ensure compliance with national and international standards. Routine inspection and maintenance of milling equipment should be prioritized to minimize corrosion and reduce Fe contamination in the effluent. Farmers supplying the mill should be encouraged to adopt safe and regulated application of fertilizers, pesticides, and herbicides to limit heavy metal buildup in soils and runoff entering the milling process.

6 Data availability statement

The data can be made available upon request from the corresponding author.

7 Ethical statements

Ethical approval was not required for this research.

8 Conflict of interest

The authors declare that there is no conflict of interest.

9 Author contributions

T. Yahaya: Conceptualization, writing – original draft, and writing – review & editing. S. Bello: Data acquisition, formal analysis, and supervision. A. Izuafa: Software, visualization, and writing – review & editing. F. Inuwa: Data curation and validation. I. U. Boku: Investigation and formal analysis. J. Nathaniel: Writing – review & editing. All authors read and approved the final version of the manuscript for publication.

10 Copyright statement

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