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SOIL POLLUTION AND HEAVY METAL CONTAMINATION: INSIGHT FROM EFFLUENT DISCHARGED FROM CHALLAWA INDUSTRIAL AREA, NIGERIA

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ABSTRACT

The discharge of industrial wastewater represents a significant source of environmental pollution, particularly in developing regions where regulatory enforcement is often insufficient. This study examined the chemical characteristics of effluent discharged from three locations (LA, LB, and LC) close to the Challawa Industrial Area in Kano, Nigeria, and determined their effects on nearby soil. Effluent samples were analysed for pH, biochemical oxygen demand (BOD), phosphates (PO_4^{3-}), nitrates (NO_3^--N) and critical toxic heavy metals (HMs) such as lead (Pb), chromium (Cr), copper (Cu), Zinc (Zn) and cadmium (Cd). Simultaneously, soil samples from three locations near the discharge point were evaluated for pH, total nitrogen (TN), and total phosphorus (TP). The results revealed that effluent concentrations of HMs and nutrients far exceeded the permissible limits of the National Environmental Standards and Regulations Enforcement Agency. The Pb (90.79 mg/L), Cd (10.06 g/L), Zn (33.43 mg/L), Cr (4.49 mg/L), and Cu (12.76 mg/L) concentrations were well above the regulatory limits of 0.05 mg/L, 0.01 mg/L, 0.05 mg/L, 0.01 mg/L, and 0.02 mg/L, respectively. The Phosphate (299.74 mg/L) and nitrate (381.97 mg/L) levels also exceeded NESREA standards, indicating a significant risk of eutrophication in nearby water bodies. Regression analysis revealed that higher pH tended to increase the concentration of both nutrients, with P showing a more consistent and stronger association ($p<0.05$) than nitrogen. This study, therefore, highlight that HMs contamination is evident in the soils around the study area, posing risks to soil fertility and agricultural productivity.

Keywords: Effluent discharge, Challawa industrial area, NESREA compliance

INTRODUCTION

The discharge of industrial wastewater into the environment, particularly in developing regions, poses a significant threat to ecosystems and public health. Industrial wastewater often contains a complex mixture of organic and inorganic pollutants, including heavy metals (HMs), nutrients, and other toxic substances that remain in the environment and can cause long-term damage to soil and water resources (Schipper *et al.*, 1996; Chen *et al.*, 2005). Nigeria's fast industrialization has accelerated environmental deterioration, especially in the neighborhoods that surround industrial zones, where pollution is worsened by improper wastewater treatment (Nwankwoala and Ememu, 2018). One such area is the Challawa industrial region in Kano, which hosts a variety of industries, including textiles, tanneries, and food processing plants, which are known for generating effluents rich in pollutants that exceed regulatory limits.

Effluents from industries often contain excessive amounts of HMs such as lead (Pb), chromium (Cr), copper (Cu), Zinc (Zn) and cadmium (Cd) as well as high levels of nutrients such as phosphates (PO_4^{3-}) and nitrates (NO_3^--N) (Marcos *et al.*, 2021). These contaminants can have detrimental effects on both aquatic and terrestrial ecosystems. For example, HMs, as non-biodegradable, can build up in soil or water and pass through the food chain, harming humans, animals, and plants (Alloway, 2013). The contamination of soils by industrial effluents can also lead to altered soil chemistry, reduced agricultural productivity, and a loss of biodiversity (Rattan *et al*., 2005). Additionally, elevated concentrations of nutrients, particularly nitrogen (N) and phosphorus (P), contribute to eutrophication in water bodies, leading to algal blooms, oxygen depletion, and the death of aquatic organisms (Correl, 1998; Smith *et al.*, 2006). However, despite these aforementioned problems linked to the effluent discharge, studies that focused on the evaluation of the HMs and nutrient load associated with these industries, particularly in the Challawa industrial area, are rare.

The discharge of untreated or poorly treated effluent into nearby water bodies and onto surrounding land has led to the contamination of soil and water resources in regions such as Challawa (Arise *et al.*, 2021). The health risks associated with exposure to industrial effluents containing significant amounts of HMs are linked to cancer, neurological disorders, and kidney damage (Yang *et al.*, 2019), while high levels of PO_4^{3-} and NO_3^--N have been associated with risks to humans and aquatic organisms (Tchounwou *et al.*, 2012; Sengupta *et al.*, 2015). Despite implementing environmental regulations in Nigeria, such as those enforced by the National Environmental Standards and Regulations Enforcement Agency (NESREA), industrial effluents continue to exceed permissible limits, highlighting gaps in regulatory compliance and enforcement (NESREA, 2011; Adeoluwa, 2018: Nnamani and San, 2023). Therefore, this study focused on the chemical characteristics of effluents discharged from industries in the Challawa industrial area and their impacts on nearby soils. The primary objectives of this study include a) to determine the chemical characteristics of the effluents discharged from the industries, b) to evaluate the concentrations of some HMs such as Cd, Cr, Cu, Pb, Zn and nutrients (PO_4^{3-}, NO_3^--N), in industrial effluents discharged from the Challawa industrial area, c) to assess the concentrations of some HMs such as Pb, Cu, Zn, Cd, Cr and nutrients (PO_4^{3-}, NO_3^--N), in the neighboring soil affected by the industrial effluents discharged from the Challawa industrial area. By analyzing the concentrations of key pollutants, including HMs and nutrients, and comparing these values with NESREA standards, the study will provide important insights into the extent of environmental pollution and the impact of these pollutants on the chemical properties of soils in the affected area. The findings from this study are essential for understanding the environmental risks posed by industrial effluent discharge and for developing effective mitigation strategies to protect ecosystems and public health in the region. Furthermore the study findings will contribute to the growing body of literature on industrial pollution and provide a basis for improving environmental regulations and effluent management practices.

MATERIALS AND METHODS

Study Area and Sampling

The study was conducted in a Challawa industrial region receiving effluent discharges from various industrial activities. The sampling areas were chosen based on proximity to the discharge points, with three locations (Location A: 11°53′42.0″N,8°30′36.0″E, Location B: 11°52′48.0″N,8°32′24.0″Eand Location C: 11°52′12.0″N,8°31′30.0″E) representing varying distances from the effluent source. These locations were selected to capture potential spatial variations in pollution intensities.

Effluent Sampling and Analysis

Effluent samples were collected at discharge points in sterile polyethylene containers. Sampling was performed in triplicate (3) at each site to ensure the reliability of the results. Samples were transported to the laboratory in ice-filled coolers and analyzed within 24 hours to minimize the degradation of volatile compounds. The pH of the effluent was measured using a calibrated pH meter (APHA, 2012), while Total dissolved solids (TDS) and electrical conductivity (EC) were measured using a conductivity meter (ASTM D1125-14) and gravimetric method (APHA, 2012), respectively. The biochemical oxygen demand (BOD) was measured using the standard five-day method (APHA, 2012). Briefly, the effluent samples were incubated for five days at 20°C, and oxygen levels were measured before and after incubation to calculate BOD values. The nutrient which includes sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), phosphate (PO_4^{3-}), and nitrate (NO_3^--N) were measured using ion chromatography following established methods (APHA, 2012), while the PO_4^{3-} and NO_3^--N were quantified using spectrophotometric methods, with a detection limit of 0.01 mg/L. The HMs in effluent were digested using nitric acid following USEPA (2007) Method 3050B, and the concentrations of the Cd, Cr, Cu, Pb, Zn were analysed using Atomic Absorption Spectrophotometry (AAS) (Perkin Elmer Analyst 400). All samples were in triplicate to ensure accuracy, and calibration standards were prepared for each metal. The detection limits for metals were set at 0.001 mg/L.

Soil Sampling and Analysis

Soil samples were collected from the top 0-20 cm layer at the three locations (LA, LB, LC) affected by effluent discharge. Three composite samples were taken per location using a hand-held auger. Each composite sample comprised subsamples collected in a zigzag pattern to account for spatial variability (Darma *et al.,* 2022). All the samples were air-dried, ground, and sieved through a 2 mm mesh before analysis.

Soil Physicochemical Analysis

The pH and EC were measured in 1:2.5 soil-water suspensions using a pH meter and conductivity meter (Minasny *et al.,* 2011; Omale *et al.*, 2024). The texture of the soil (silt, sand and clay) was determined using the hydrometer method (Gee and Bauder, 1986). The total nitrogen (TN) and Total Phosphorus (TP) were determined using the Kjeldahl method (Bremner, 1965) and the molybdenum blue colorimetric method (Murphy and Riley, 1962), respectively. To analyze the concentration of Cd, Cr, Cu, Pb, and Zn concentrations, the aqua regia method (USEPA, 2007 Method 3051A) was used, and the concentrations of these HMs were determined using AAS.

Quality Control and Assurance

To ensure the reliability of the results, strict quality control measures were implemented throughout the sampling and analysis process. Blanks and standard reference materials were analysed alongside the samples to check for contamination and accuracy.

Data Analysis and Compliance with Regulatory Standards

Results were reported as means ± standard deviations, and all measurements were performed in triplicate ($n = 3$). Data were statistically analysed using ANOVA with Origin Pro. Software (2024b) to assess significant differences in pollutant concentrations across the locations. Marginal regression were performed to investigate relationships between pH and total P and N in the soil. Statistical significance was determined at $p < 0.05$. The measured parameters were compared with the National Environmental Standards and Regulations Enforcement Agency (NESREA) limits to assess the environmental compliance of the effluent discharges.

RESULTS AND DISCUSSION

Chemical characteristics of the effluent

Effluent discharge containing high levels of HMs, nutrients, and other pollutants poses serious environmental and public health risks. Table 1 presents the chemical parameters of effluent discharged to the environment compared to the National Environmental Standards and Regulations Enforcement Agency (NESREA, 2011; Nnamani and San, 2023) criteria. The effluent's pH (7.21) falls within the acceptable range (6.5–8.5) of NESREA standards, indicating that it is neither too acidic nor too alkaline. The pH of effluent plays a significant role in influencing not only the water quality of receiving bodies but also the biological and chemical features of the surrounding soil and ecosystems (Uwadiae and Agagbo, 2018; Yang *et al.,* 2019). This indicated that the pH range from this study generally support a good number of aquatic species and is not detrimental to biological activities (Harrison, 1999; Uwadiae and Agagbo, 2018).

Biochemical Oxygen Demand (BOD) is a critical parameter in water quality assessment. It measures the amount of dissolved oxygen required by aerobic microorganisms to break down organic material in water (Chris-Otubor and Olorunfemi, 2015). The BOD of the effluent (145.34 mg/L) is considerably higher than the allowed limit of 50 mg/L (Table 1). High BOD is a significant indicator of organic pollution and poses serious threats to water quality and aquatic ecosystems. This finding is similar to the finding in which elevated BOD from industrial waste serves as a primary concern due to oxygen depletion, leading to hypoxia or anoxia, capable of disrupting aquatic life and surrounding ecosystems (Maddah, 2022). Moreover, the effects of high BOD extend to public health and economic sectors like fisheries and the overall sustainability of natural water resources.

The concentrations of Cd (10.06 mg/L), Cr (4.49 mg/L), Cu (12.76 mg/L), Pb (90.79 mg/L), and Zn (33.43 mg/L) all exceed NESREA limits (Table 1). Elevated concentrations of HMs in effluent can have a variety of sources and serious implications for both environmental and human well-being. Heavy metals such as Cr, Cu, Zn, Cd and Pb are highly toxic at elevated levels and can cause long-term contamination of water, soil, and biota (Schipper *et al.,* 1996). Previous studies have demonstrated that the contamination of water bodies and soils with toxic HMs such as Cr, Cu, Zn, Cd and Pb could lead to severe ecological degradation, including reduced biodiversity, disruption of food chains, and toxicity to plants, animals, and humans (Zhou *et al.,* 2018). These metals may have harmful effects on human health and the environment, including reduced plant growth, neurological cancer, and human organ damage.

Elevated PO_4^{3-} and NO_3^- concentrations in the effluent are significant environmental concerns, particularly to soil health and ecosystems. Generally, these nutrients, primarily from agricultural runoff, industrial wastewater, and municipal sewage, can significantly impact soil and surrounding ecosystems (Correll, 1998). The PO_4^{3-} concentration from this study is alarmingly high (299.74 mg/L) compared to the NESREA standard of 3.5 mg/L (Table 1). These elevated concentrations could be linked to the increased activities of these industries and could lead to eutrophication in water bodies, causing excessive algae growth and depleting oxygen for aquatic life. Additionally, the nitrate (NO_3^--N) levels (381.97 mg/L) are extremely high compared to the standard (10 mg/L, Table 1). According to a similar study, it's demonstrated that excessive PO_4^{3-} and NO_3^- pollution can lead to eutrophication and contamination of groundwater, potentially causing health risks like methemoglobinemia (Marcos *et al.,* 2021). A study by Smith *et al.* (2006) demonstrated that high concentrations of nutrients, particularly PO_4^{3-} and NO_3^- are known to accelerate eutrophication, leading to "dead zones" in aquatic ecosystems where oxygen is depleted, affecting aquatic life.

Table 1: Chemical Characteristics of the Effluent Discharged to the Study Areas

Parameters	Mean	NESREA STD.
pH	7.21±0.2	6.5-8.5
EC (ds/m)	2.1±8.1	0.7
TDS (mg/L)	455.17±16.5	450
TSS	151.41±7.2	500
BOD (mg/L)	145.34±5.7	50
Cl^- (mg/L)	152.38±5.12	
Mg^{2+} (mg/L)	38.35±2.1	
Ca^{2+} (mg/L)	79.23±1.34	
Na^+ (mg/L)	144.5±2.17	
HCO_3^- (mg/L)	529.11±11.34	
PO_4^{3-} (mg/L)	299.74±10.06	3.5
NO_3^--N (mg/L)	381.97±25.28	10
Cd (g/L)	10.06±0.09	0.01
Cr (g/L)	4.49± 0.02	0.05
Cu (g/L)	12.76±0.21	0.01
Pb (g/L)	90.79± 0.16	0.05
Zn (g/L)	33.43± 0.04	0.02

Note: EC; Electrical conductivity: TDS; Total dissolve soild: TSS; Total Suspended Solids: BOD; Biological oxygen demands: Na; Sodium: Ca; Calcium: Mg; Magnesium: Cl; Chlorine: Cr; Chromium: Cu: Copper Cd; Cadmium: Pb: Lead: Zn: Zinc

Chemical characteristics of the soil

The chemical properties of soils from the three different locations affected by effluent discharge (LA, LB, and LC) as compared to the NESREA standard are presented in Table 2. The soil pH is relatively neutral, with slight variations across the locations (6.59, 6.55, and 6.51), which suggests that the effluent discharge has not significantly acidified or alkalinized the soils. This pH range is considered ideal for many biological and chemical processes in soil ecosystems. This result is in line with earlier research showing that soil pH decreases with distance and is higher at the point of industrial effluent discharge (Tabassum *et al.,* 2016). Given the soil-neutral pH condition, the soil may provide a balanced environment that promotes plant growth, microbial activity, availability of nutrient, and general soil health.

Table 2: Chemical Characteristics of the Soil affected by the effluent discharge

Parameters	LA	LB	LC
pH	6.59±0.60	6.55±0.30	6.51±0.20
EC (dS/m)	4.76±0.13	4.91±0.22	5.23±0.25
Sand	28.45±2.23	28.00±3.04	27.81±1.02
Silt	18.55±1.45	17.58±1.09	17.04±3.13
Clay	47.88±1.33	46.72±1.61	45.11±1.88
Total N (mg/kg)	62.09±9.03	75.23±5.45	89.47±7.34
Total P (mg/kg)	113.56±11.32	166.91±13.88	186.98±6.45

Note: LA; Location A: LB; Location B: LC; Location C: EC; Electrical conductivity: N; Nitrogen: P; Phosphorus

Effect of the effluent discharged on the Heavy metals and Nutrients

The concentrations of Cd, Pb, Cu, Cr and Zn in the study areas were compared to NESREA standards (Fig. 1b). The high levels of these metals far exceed regulatory limits, emphasizing the hazardous impact of the effluent on the environment and potential risks to human health. The contamination of soils with HMs could result to their bioaccumulation in the trophic level and cause chronic health problems in the exposed populations (Darma *et al.,* 2022). These findings are consistent with a study by Arise et al. (2021), in which elevated HMs were observed in the industrial layout of Challawa. Excessive levels of HMs in the soil pose significant risks to soil health, plant productivity, human health, and the environment. These metals can bioaccumulate in plants and animals, leading to chronic toxicity and long-term environmental degradation. In terms of human health, long-term exposure to HMs particularly Cd, Cr, Zn and Pb has been connected to various diseases, including cardiovascular problems, neurological disorders and cancer (Tchounwou *et al.,* 2012). Therefore, the fact that these HMs were found in the soil of the studied area above permissible levels underscores the pressing need for enhanced wastewater treatment and more stringent adherence to environmental regulations.

The total N (62.09–89.47 mg/kg) and P (113.56–186.98 mg/kg) in the soil are elevated, indicating nutrient enrichment from the effluent (Table 2, Figure 2c). The finding is similar to a study that indicated an increased concentration of N and P due to industrial effluent discharge (Sengupta *et al.,* 2015). Excessive N and P amounts in the soil can have immediate and long-term adverse effects on soil health**,** plant growth**,** and the surrounding environment (Marcos *et al.,* 2021). Although N and P are necessary for plant growth, high concentrations of these nutrients can upset the delicate nutrient balance in the soil, causing nutrient runoff into surrounding water bodies and exacerbating eutrophication (Sengupta *et al.,* 2015; Marcos *et al.,* 2021). This process can lead to algae blooms, oxygen depletion and the death of aquatic organisms, further damaging the ecosystem.

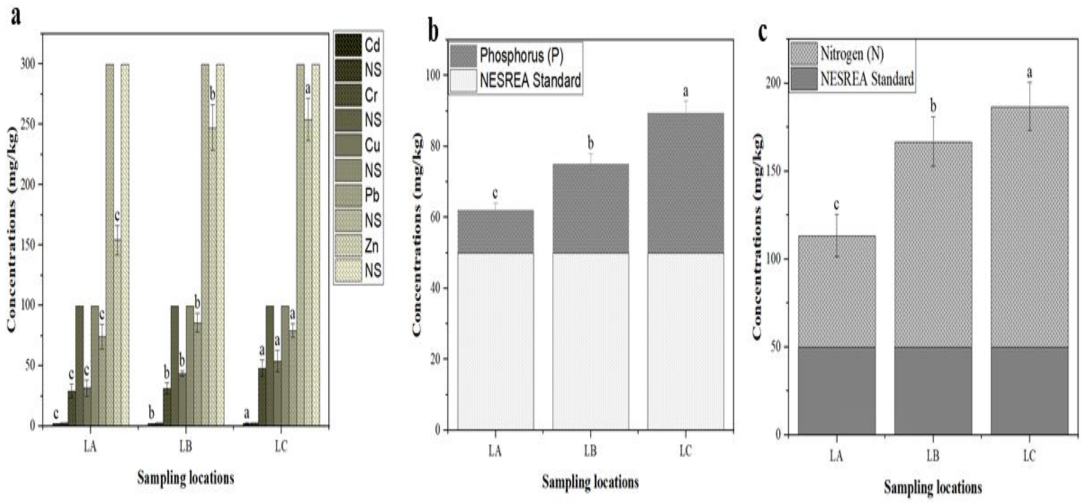

Figure 1: Effect of the effluent discharge on the (**a**) Total concentration of Cd, Cr, Cu, Pb and Zn (**b**) Total Phosphorus (TP) and (**c**) Nitrogen (TN) in the study areas as compared to the NESREA Standard

Relationship between pH and increased nutrients in the soil

A higher pH tends to increase the concentration of both nutrients, with P showing a more consistent and stronger relationship than nitrogen. Across all three location (LA, LB, LC), there is a clear positive correlation between pH and P levels, with LB showing the strongest correlation. The regression results show a clear relationship between pH and total P and N concentrations in the soils receiving effluent discharge (Figure 2a-d). This is consistent with previous study suggesting more P availability due to a higher pH in the soils, increasing the risk of P runoff into surface water bodies (Minasny *et al.,* 2011). The relationship between pH and elevated N and P in the soil is crucial for understanding how these nutrients behave, their availability to plants, and their potential environmental impact. Soil pH can directly influence the availability, mobility, and transformation of N and P and the interactions with other soil components (Sengupta *et al.,* 2015). This association is capable of causing eutrophication, a process where excess nutrients stimulate algae growth, depleting oxygen levels and harming aquatic ecosystems. Therefore, pH management is crucial to avoid the excessive mobilization of these nutrients, which can lead to environmental degradation through eutrophication**,** nitrate leaching**,** and contamination of water resources.

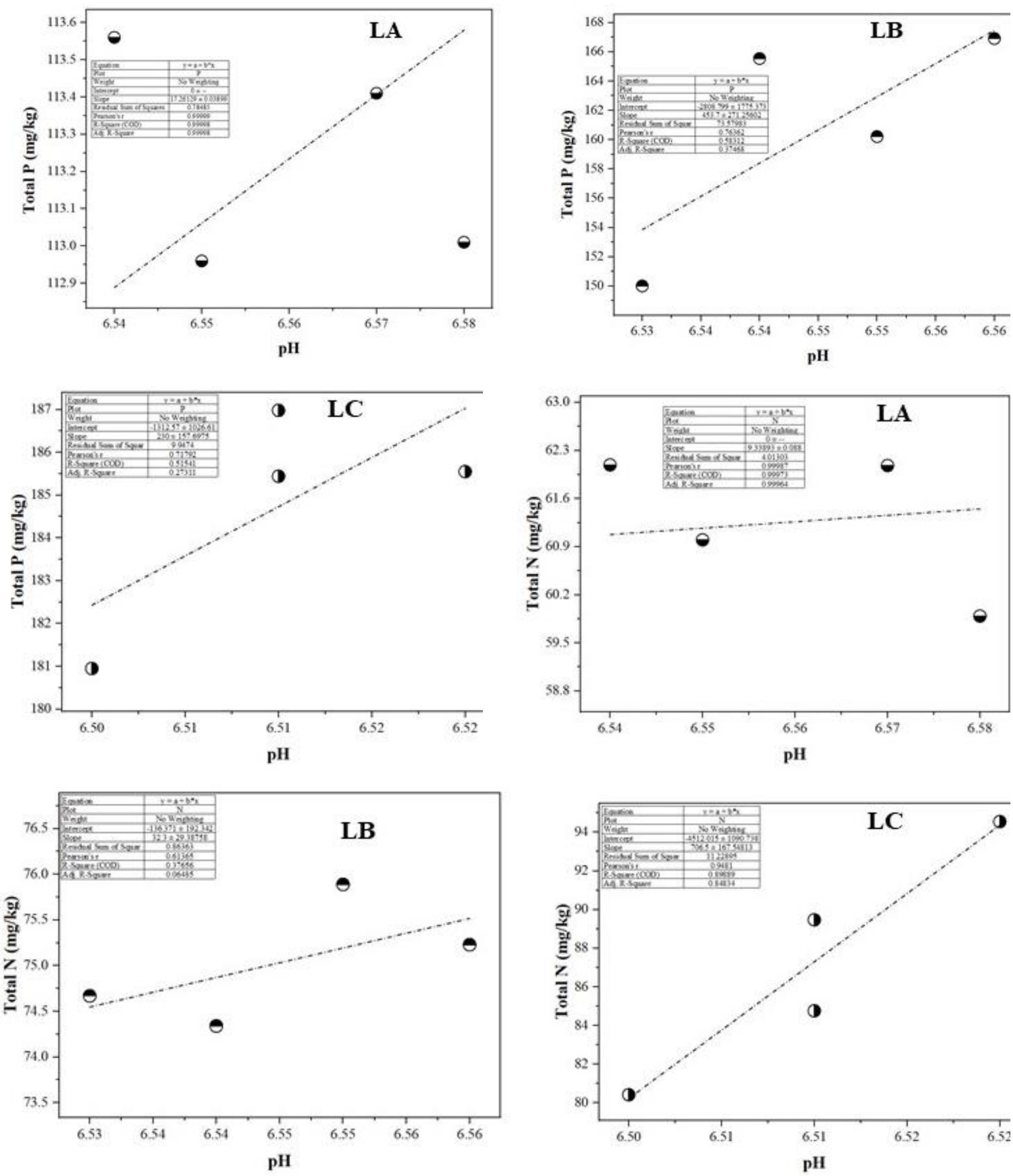

Figure 2: Relationship between of the effluent discharge on the total phosphorus (TP) and nitrogen (TN) in the study areas.

CONCLUSION

The results demonstrate significant loads of HMs nutrients in the soil around the vicinity of the Challawa industrial area, and this could be linked to the discharge of effluents with high levels of pollutants into soils and water bodies. The observed HMs contamination and nutrient enrichment suggest a risk of long-term ecological damage and public health issues. Regression analysis suggests that pH plays a role in controlling nutrient concentrations (P and N) in the soil, which is influenced by effluent discharge, particularly phosphorus. The study, therefore, provides an insight into the baseline information regarding the HMs concentration and nutrients in the effluent discharged from the industries into the soil around the Challawa industrial area. Therefore, implementing more stringent effluent treatment processes and monitoring systems is essential to mitigate the impacts of industrial pollution on the environment. Furthermore, managing pH in treatment systems and effluent streams could be critical in reducing nutrient pollution and preventing downstream environmental impacts like eutrophication. In addition, analysis, including the role of other variables such as organic matter content, temperature, and redox potential, may provide a more comprehensive understanding of nutrient dynamics in effluent-impacted soils

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