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Human and ecotoxicological risk assessment of heavy metals in polymer post treatment sludge from Barekese Drinking Water Treatment Plant, Kumasi

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ABSTRACT

The disposal of polymer post-treatment sludge (PTS) from Barekese Water Treatment Plants (WTPs) as organic fertilizer and aquatic feed is a common practice in Ghana, necessitating a thorough evaluation of its ecological and human health risks. This study aims to assess the suitability of PTS samples for soil amendment and fish feed, scrutinizing potential hazards to consumer health and soil. PTS samples were collected from five distinct lateral sections of three clariflocculator tanks. Potentially toxic metals such as Cd, Zn, Pb, Cu, Ni, and Cr were determined using a flame atomic absorption spectrophotometer. The mean concentration of 7.82 ± 2.43, 0.31 ± 0.021, and 0.78 ± 0.042 mg/kg for Mn, Zn, and Pb respectively. The concentrations of Ni, Cr, and Cd were below their detection limits (BDL) in all PTS samples. Upon detailed exposure assessment, ingestion emerged as the primary exposure route for both adults and children, with non-cancer risks (NCR) determined to be below 1 for both age groups. Additionally, an exploration of potential cancer risks (CR) associated with heavy metal exposure in the PTS samples revealed values below the tolerable intake levels ranging from 10^{-4} to 10^{-6} for both adults and children (10^{-8} and 10^{-9}, respectively). This study also employs various ecological indices, such as Nemerow's synthetic pollution index (PN), single factor pollution index (PI), geo-accumulation index (Igeo), contamination factor (CF), potential ecological risk index (PERI), pollution load index (PLI), polymetallic contaminant index (IPD), and ecological risk index (ERI). These indices consistently highlight a low contamination status and ecological sensitivity. Consequently, the study indicates that the presence of metals in the PTS samples does not pose a significant threat to the surrounding environment and human health. Furthermore, this research underscores the inadequacy of relying solely on regulatory limit values in assessing the health risks of waste materials. Such comprehensive assessments are crucial for safeguarding aquatic and human populations.

1. Introduction

Polymer post-treatment sludge (PTS) is a consequential byproduct generated during urban water treatment, primarily through flocculation and coagulation processes. Polymer-based coagulants have gained prominence in water treatment due to their advantages over conventional coagulants, such as lower concentration requirements, high biodegradability, reduced processing costs, and broader applicability across temperature and pH ranges [1]. Increasing polymer post-treatment sludge (PTS) production during water treatment has emerged as a pressing environmental concern since sludge disposal and management costs account for about 15–30% of the operational costs of water treatment plants (WTP) [2]. Environmental factors, technical demands, financial constraints, and local laws all play a part in sludge management and disposal procedures that enable advantageous methods to emerge as the most cost-effective choice in Ghanaian drinking water treatment plants [3]. The most common disposal processes are burning, agricultural valorization of waste, and engineered landfilling, although disposal methods vary greatly from location to location, influenced by a variety of intrinsic characteristics [4]. The agricultural utilization of sludge is mostly prevalent in Holland, China, Belgium, and Sudan while 50% of sludge is produced for agricultural utilization in Germany, Lebanon, Egypt, France, and Portugal [5,6]. Worldwide, sludge production rates vary significantly, with developing

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countries producing 100–1000 liters per capita annually, contrasting with 10,000–13,000 liters in developed nations [7]. Examples from the United Kingdom, South Africa, and the United States highlight the scale of sewage sludge generation, a trend projected to intensify with increasing industrialization [8]. Projections based on the World Urbanization Prospects indicate a threefold increase in these values over the next 30 years [9]. Increasing the amount of polymer sludges from water treatment plants for agricultural applications is advantageous and economically sound to reduce sludge treatment costs for a developing country such as Ghana. Incineration, land, and feedstock applications are advantageous examples of PTS management and disposal. The process of incineration is considered the "worst of the worst" which has adverse health consequences such as ash, increased vehicle traffic, odor, and air pollution [10]. Furthermore, recycling options for polymer sludge such as farmland application, feedstock for aquatic organisms', biogas, and agricultural use are the most environmentally and economically viable choices [11,12]. In Africa and Europe, increasing biosolids recycling for agricultural uses is a green alternative to chemical-based fertilizers that can boost soil fertility and resource recycling, and reduce unemployment for farmers, crop yields, and physical properties due to their high organic nutrient concentration [13–15]. Nevertheless, natural sludge after the treatment process in WTPs can contain pathogens such as Escherichia coli, pharmaceutical residues such as antibiotics, and heavy metals such as lead, all of which pose a risk of contamination to the soil, aquatic species, surface, and groundwater [12,16].

After conducting thorough field investigations and laboratory experiments, researchers have identified potential eco-toxicological effects associated with the land application of sludge [17]. Studies in Ghana and South Africa found high levels of toxic heavy metals like lead, cadmium, and mercury in sewage sludge, surpassing safe soil amendment limits [18,19]. In China, potentially toxic metals were reported to have accumulated in the first 20 cm depth layer of the soil after adding sludge [17,20]. The accumulated concentrations of these toxic metals in fecal sludge are caused by a variety of natural processes, involving dust, decomposing vegetation, wildfires, and rainfall transporting Fe into latrine pits. Human activities such as illegal mining, the discharge of industrial wastewater, the unregulated application of agricultural chemicals, and the disposal of hazardous waste like lead-acid batteries are also responsible for the elevated levels of heavy metals found in fecal sludge [18,19]. These metals can be absorbed by crops or aquatic species when applied onto land or used as feedstock in aquatic habitats, leading to their accumulation in the food chain. Furthermore, because of bioaccumulation, potentially hazardous heavy metals in sludge may alter the concentration of heavy metals in the soil after application [17]. Additionally, it also results in a decline in the soil's microbial diversity [17,21,22]. Thus, there should be considerable concern about the ecological implications of potentially harmful metals resulting from the land application of sludge. This raises concerns about using such sludge in agriculture and its impact on aquatic life, soil ecosystems, bacteria, plants, animals, and humans.

According to [23], sorption, inner and outer sphere complexation, and precipitation processes cause metals to accumulate in the PTS during the water treatment process at Barekese WTPs. The composition of the polymer post-treatment sludge may vary depending on the quality or characteristics of the source of water for treatment obtained directly from the river and lake sources, rainfall, and season.

Consequently, through the food chain, the risk posed due to their landscape spreading for planting should be evaluated, considering likely ecological receptors in soil and water. Food safety has become a more pressing problem, requiring a risk assessment to be conducted beforehand before applying sludge to feedstock or land. Through exposure routes such as ingestion, inhalation, and dermal contact, toxic metals in sludge can also pose significant health risks to humans, including cancer (skin, lungs, liver, bladder) and non-carcinogenic effects like gastrointestinal and kidney dysfunction, respiratory issues, diarrhea, fatigue, weakness, nausea, vomiting, and throat irritation [15,24]. Several studies attest to the bioaccumulation of potentially hazardous metals brought on by the cheaper and alternative use of sludge as organic fertilizer from WTPs, which ends up in the food chain [20,23,25]. The nature and composition of the polymer post-treated sludge, features of the sources, duration and consistency of application, soil physicochemical parameters, plant species, and management strategies all influence the degree to which the food chain becomes bioaccumulated from its use for agricultural farming [23]. Therefore, it is crucial to determine the heavy metal concentrations of polymer sludges and assess the risks before applying them to the soil and as feedstock for the aquatic community.

Risk assessment is frequently used to estimate potential health or ecological threats as well as the likelihood of detrimental impacts on the environment [26]. The use of polymer post-treatment sludge for land application or as feedstock for fish organisms can pose an environmental risk that can be evaluated using a variety of risk assessment models, including Nemerow's synthetic pollution index, cancer and non-cancer risk, the geo-accumulation index (Igeo), the contamination factor (CF), the potential ecological risk index (PERI), the pollution load index (PLI), the metal pollution index (MPI), the polymetallic contaminant index (PmCI), the ecological risk index (ERI), the risk assessment code (RAC) [21,22,27]. These models do provide a means of estimating the environmental danger and damage of the soil resulting from subsequent PTS treatments due to metal accumulation or leaching to greater depths. The United States Environmental Protection Agency (USEPA) exposure models play a vital role in evaluating threats to human and ecological health from toxic pollutants in the environment. Limited attention has been given to evaluating the effects of the land spreading of PTS from WTPs on the human health of children and adults and ecological receptors in soil and water are relatively scarce in the literature and no information specifically is available for PTS. [15,22]. Determining the entire pollution profile of biosolids is essential to ensuring that their discharge into the environment does not harm rather than benefit the environment [28]. Ecotoxicity tests are an excellent method of determining the environmental impact of biosolids put into the soil or near aquatic habitats and examining their potential impacts on organisms. Because it is not always possible to anticipate toxicity directly from chemical data, the outcome of ecotoxicity tests on a variety of organisms can be informative for the general public [26,28].

To the best of our knowledge, there is limited research on the heavy metal profiling of polymer sludge produced by the Barekese Water Treatment Plant in Ghana and its usage in agriculture and aquatic feedstock [20]. Significantly, despite many investigations on toxic metals in sewage sludge, there is a research gap on the determination of the heavy metal concentrations, ecotoxicological effects of PTS spreading on agricultural farmlands, and associated human health risks in polymer post treated sludge production from drinking water treatment plants (WTPs) in Barekese, Ashanti Region. Furthermore, the research mentioned primarily covers regional information and does not consider geographical changes on a country scale. As a result, there are still substantial gaps in national data on heavy metal profiles of WTP sludges in different regions and WTPs in Ghana throughout the seasons of the year. The primary objectives of this study are (*i*) to bridge the research gap by determining the levels of Cd, Zn, Pb, Mn, Ni, and Cr in polymer post-treatment sludge from Barekese WTP, Kumasi, (*ii*) to assess heavy metal exposure from polymer sludge and differentiate the variation in exposure of adults and children (*iii*) to estimate potential non-carcinogenic and carcinogenic human health risks using ingestion, dermal contact and inhalation exposures to land-applied polymer sludge by children and adults, (*iv)* characterize the ecotoxicological potential associated with heavy metals in the polymer sludge. By addressing this research gap, the study contributes to a more comprehensive understanding of the risks and implications of heavy metal concentrations in polymer-based post-treatment sludge, advancing knowledge in this field and aiding in the development of effective mitigation strategies. The findings could be utilized to create a database for annual evaluation and monitoring of polymer sludge supply as a low-cost resource for soil enhancement, as well as for systematic risk assessment of biosolid discharge into the environment.

2. Materials and methods

2.1. Study area

The geographical coordinates of the Barekese Water Treatment Plant are 1" 43" 8" W and 6" 45" 6" N. The area experiences high levels of rainfall from March to July and moderate levels from September to November [29]. The Barekese waterworks facility is the main water treatment plant for the people of the Kumasi Metropolis, operated by the Ghana Water Company Limited. It is responsible for treating wastewater, groundwater, and surface water from the River Offin to supply over 5.4 million residents in the greater Kumasi area [30]. The polymer post treatment sludge from the drinking water treatment process, such as PTS, serves as a food source for fish and aquatic life on a commercial scale for human consumption. The Barekese WTPs process begins with the screening of raw water, the use of aeration to get rid of bad odor and boost oxidation, PTS coagulants are added, then the flow of water through a chamber is regulated for the treatment of water in five clariflocculator tanks with the best capacity via sedimentation/flocculation for the discharge of sludge, followed by rapid sand and carbon filtration, chlorine dosing and distribution to homes. The technical parameters of the installation, such as capacity, aerator efficiency, clariflocculator tank sizing, exact chemical dose, and efficient distribution systems, combined provide the community's reliable supply of high-quality drinking water. Fig. 1 shows a graphical representation of the study area located in the Atwima Nwabiagya North district of Kumasi.

2.2. Sampling

To obtain representative polymer sludge samples, five samples each were randomly collected from three clariflocculator tanks using an auger. Sludge samples were collected from five distinct lateral sections of three clarifloc tanks at a depth of 0 – 10 cm for analysis (n=15) in April 2021. Each sample was a composite of five grabs (250 g) from each tank to capture the overall sludge quality and average the heterogeneity of polymer post treated sludge within the treatment plant. These samples were promptly transferred into wide mouth plastic bottles to prevent metal loss. To ensure the samples' integrity, the bottles were precleaned with 0.1 M HNO_3 and double-rinsed with deionized water. Subsequently, the samples were refrigerated at -4°C overnight before undergoing sample digestion at the Department of Chemistry, Kwame Nkrumah University of Science and Technology.

2.3. Sample preparation

The sludge sample was filtered into three 100 mL Erlenmeyer flasks using a funnel and Whatman 125 mm filter paper. Triplicate sample preparations were performed throughout the analysis. The filtered sample residue was left to dry on a filter paper at a constant weight at 105 °C. One gram of PTS sample was introduced into a digestion tube, and 15 mL of concentrated HNO_3 was added and allowed to stand overnight in each tube. The mixture was boiled until the brown fume ceased. It was cooled to ambient temperature and filtered into a 100 mL volumetric flask. The solution was then topped up to the mark with deionized water.

2.4. Instrumental analysis

The digested sludge samples were analyzed for the concentrations of some targeted metals (Zn, Ni, Cd, Mn, Cr, and Pb) using a flame atomic absorption spectrophotometer (FAAS) (Agilent nov 400 P, Germany). To

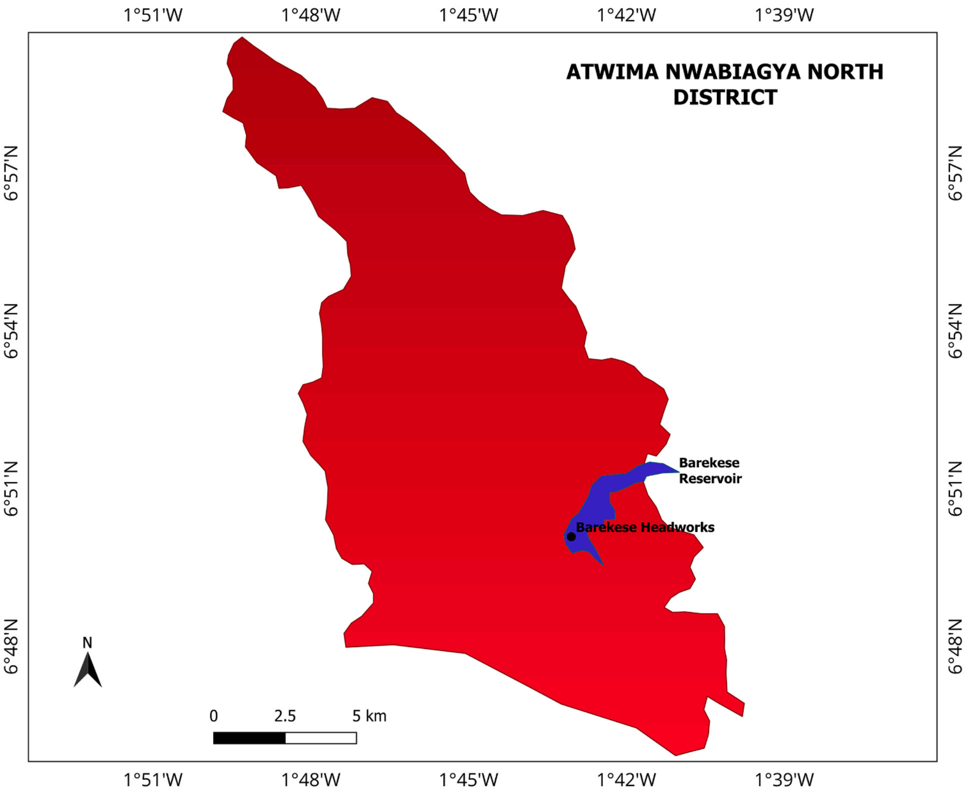

Fig. 1. Map of study area.

assess the reliability and reproducibility of the analysis, the FAAS operating conditions for the determination of potentially toxic metals in PTS where the LOD and precision percentage for Cd (0.08 mg/kg), Zn (0.11 mg/kg, ±0.47%), Pb (0.19 mg/kg, ±0.03%), Mn (0.59 mg/kg, ±0.27%), Ni (1.15 mg/kg), and Cr (1.16 mg/kg).

2.5. Quality control

Deionized water was used throughout the experiment to prepare solutions. Reagent blank measurements were used to control background contamination. The analytical validity and reliability of the data were ascertained by calculating the mean and standard deviation of the triplicate measurements.

2.6. Human health risk assessment

The human health risk evaluation was used to evaluate possible future hazards to public health and the likelihood that toxic metals in a polluted area will have negative consequences on the lives of the exposed [31]. These evaluations were represented by the average daily dose, ADD (exposure assessment), CR (cancer risk assessment), and non-carcinogenic risk assessment NCR. Ingestion, dermal adsorption, and inhalation are the important pathways that are considered concerning toxic elements in polymer PTS for public health [15,32]. Mn, and Zn are classified by USEPA as non-carcinogenic toxic metals whereas Pb, Ni, Cr, and Cd are categorized as toxic and carcinogenic metals [15,33,34].

2.6.1. Average daily dose

To evaluate the hazards to public health posed by toxic elements in polymer post-treatment sludge through ingestion, dermal contact, and inhalation, the average daily dosage (ADD) (mg/kg/day) of toxic elements was calculated using Eqs. 1 to 3 [15,35]. Using Eq. 4, the cumulative ADD for each element was calculated.

$$ADD_{ingest} = \frac{Cs \times IRingest \times EF \times ED}{BW \times AT} \times CF \tag{1}$$

$$ADD_{Inhale} = \frac{Cs \times InhR \times EF \times ED}{BW \times AT \times PEF} \tag{2}$$

$$ADD_{Dermal} = \frac{Cs \times SA \times EF \times ED \times AF \times ABS \times CF}{BW \times AT} \tag{3}$$

$$ADDtotal = \Sigma\ (ADD_{ingest} + ADD_{Inhale} + ADD_{Dermal}) \tag{4}$$

where *ADD ingestion is the average daily dose for ingestion, in mg/kg/day*

ADD inhalation denotes the average daily dose for inhalation measured in mg/kg/day

ADD dermal is the average daily dose, for skin contact measured in mg/kg/day

Cs is the concentration of heavy metals in post-treatment sludge measured in mg/kg

Iringest is the ingestion rate of heavy metals which is 100 mg/day for adults and 200 mg/day for children

InhR is the inhalation rate which is 7.6 m^3*/day for children and 20* m^3*/day for adults*

EF stands for exposure frequency, using 350 days yearly

ED represents exposure duration, with adults exposed for 30 years and children for 6 years

BW stands for average body weight, which for adults is 70 kg and for children is 16 kg

AT (ED × 365 days) is the average time in days, it's 2190 days in a year for children and 10,950 days every year for adults

SA is the area of exposed skin (5700 cm^2 *for adults and 2800* cm^2 *for children)*

CF is a unity conversion factor of 1×10^{-6} *kg/mg*

PEF is the particle emission factor, 1.36 × 109 m^3*/kg, which represents the PTS-to-air particulate emission factor*

AF is the adherence factor (0.07 $mg{\cdot}cm^{-2}$ */ day for adults and 0.2* $mg{\cdot}cm^{-2}$ */ day for children)*

ABS is an abbreviation for skin absorption fraction at 0.001 for each toxic metal

2.6.2. Non-carcinogenic risk

The unitless hazard quotient (HQ) was used to assess non-cancer risk (NCR). It is the fraction of a toxic element's ADD through an exposure route to the reference dose (RfD) for each metal using Eq. 5 [31]. HQ > 1 indicates a high risk of harmful non-cancer adverse impacts on human health. HQ is the highest value below which the exposed person is not subject to any adverse health consequences.

$$HQ = \frac{ADD}{RfD} \tag{5}$$

The chronic *oral reference doses (RfD)* (mg/kg/day) for Ni, Pb, Zn, Cd, Mn, and Cr are presented in Table S1.

The hazard index (HI) in Eq. 6, which represents the cumulative hazard quotients (HQs) for every toxic metal, was utilized to examine the risk of non-cancer impacts characterized by a combination of toxic metals [15,31,32].

$$HI = \Sigma\ (HQ_1 + HQ_2 + HQ_3 \ldots\ldots\ldots\ldots + HQn) \tag{6}$$

An HI < 1, signifies no non-cancer adverse impacts present. Non-carcinogenic health hazards are indicated by HI >1 [31].

2.6.3. Carcinogenic risk

Cancer risk (CR), also known as carcinogenic risk, is the incremental chance that a consumer may develop cancer due to exposure to cancer-causing heavy metals during their entire lifespan [31,32]. The cancer risk for the heavy metals of interest was calculated using Eq. 7. The Pb ingestion pathway was used [32].

$$CR = ADD\ x\ SF \tag{7}$$

The *carcinogenic slope factor (SF)* measures the risk of cancer in humans and determines the dosage at which a consumer is likely to develop cancer in any part of the body. A cancer risk of less than 10^{-6} for a single heavy metal is considered negligible and can be disregarded. However, a risk greater than 10^{-4} is considered highly unacceptable and a cause for alarm.

2.7. Ecological risk assessment

The ecological risk assessment in this study was characterized by Nemerow's synthetic pollution index (PN), single factor pollution index (PI), the geo-accumulation index (Igeo), the contamination factor (CF), the potential ecological risk index (PERI), the pollution load index (PLI), the metal pollution index (MPI), the polymetallic contaminant index (IPD), and the ecological risk index (Eri).

2.7.1. Single factor pollution index (PI)

To analyze the contamination of a single heavy metal, the single-factor pollution index (PI) was created and employed. Expressed in terms of a single heavy metal, PI represents the pollution level of that particular heavy metal in the PTS. It was assessed to express the pollution level by comparing it with standard values. It can be described as the subsequent Eq. 8.

$$PI = \frac{C_S}{S_i} \tag{8}$$

where,

"Si" denotes the limit standard (mg/kg) for the ith (individual) heavy

metal,

"Ci" represents its concentration in polymer post-treatment sludge (mg/kg).

"PI" is the corresponding single-factor pollution index.

The Class II of Quality Control of Imported Organic Fertilizers is used as a reference for "Si", with the following standard values for Mn, Zn, Pb, Cd, Ni, and Cr: 400, 300, 100, 300, 50, and 100 mg/kg, respectively [21,36,37]. According to the pollution index (PI) value, the contamination level of heavy metals can be classified into five grades: no contamination ($PI \leq 1.0$), low contamination ($1.0 < PI \leq 2.0$), moderate contamination ($2.0 < PI \leq 3.0$), strong contamination ($3.0 < PI \leq 5.0$), and very strong contamination ($PI > 5.0$) [21].

2.7.2. *Nemerov's synthetic pollution index*

To evaluate the overall synthetic pollution caused by heavy metals, the synthetic pollution index (PN) by Nemerow was utilized. The equation for PN is as follows:

$$\mathrm{PN} = \sqrt{\frac{(\mathrm{Pimean})^2 + (P\mathit{i}\mathrm{max})^2}{2}} \tag{9}$$

where

PI mean is the mean value of the single-factor pollution index for each individual (ith) potentially toxic metal,

PI max is the maximum value of the single-factor pollution index for each individual (ith) potentially toxic metal.

Based on the PN value, the pollution level can be classified into five categories: safe/clean ($PN \leq 0.7$), warning limit of pollution ($0.7 < PN \leq 1.0$), slight pollution ($1.0 < PN \leq 2.0$), moderate pollution ($2.0 < PN \leq 3.0$), and heavy pollution ($PN > 3.0$).

2.7.3. *Geoaccumulation index (Igeo)*

The geoaccumulation index (Igeo) is a reference tool for estimating the level of elemental pollution in soil by assessing the environmental contamination state through a comparison with geochemical background concentrations [27]. The geoaccumulation index (Igeo) for metals in the PTS sample was determined using a specific expression in Eq. 10.

$$\mathrm{Igeo} = \log_2\left(\frac{\mathrm{Cn}}{1.5\mathrm{Bn}}\right) \tag{10}$$

Where

Cn is the measured concentration of the examined metal in the sample,

Bn is the geochemical background concentration/value or reference value of the metal (n) obtained within our region.

The values for Bn of the metals (mg/kg) in Kumasi were; Cd = 0.01, Ni = 4.28, Pb = 7.91, Cr = 4.67, Zn = 7.49, and Mn = 158.68 [38,39]. The factor of 1.5 is used to account for the possible variations in background values for a given metal in the environment as well as very small anthropogenic influences [27]. Igeo values were classified into seven grades: (< 0 practically unpolluted), (0–1 unpolluted to moderately polluted), (1–2, moderately polluted), (2–3 moderately to strongly polluted), (3–4 strongly polluted), (4–5, strongly to extremely polluted), and (> 5, extremely polluted).

2.7.4. *Contamination factor (CF)*

Metal contamination in the polymer post-treatment sludge (PTS) is quantified using a contamination factor (CF), which is computed as follows in Eq. 11 [27]:

$$\mathrm{CF} = \frac{\mathrm{Cn\ PTS\ sample}}{\mathrm{Bn\ shale}} \tag{11}$$

where

Bn represents the geochemical baseline value of the specified metal

The Cn sample shows the metal concentration in the PTS sample.

Based on CF readings, sediments are graded into four categories: CF <1 denotes little pollution, 1≤ CF <3 denotes moderate contamination, 3≤ CF <6 significant contamination, and CF ≥6 denotes very high contamination [27].

2.7.5. *Polymetallic contamination index (IPD)*

This index provides an overall measure of pollution levels for each potentially toxic heavy metal contaminant in each sample [23]. The IPD is calculated in Eq. 12, by summing up the contamination factors (Cf) for a specific heavy metal (Pb, Zn, Ni, Cr, Cd, and Mn) across all the samples (from the first sample, X=1, to the nth sample, X=n).

$$\Sigma^{n}_{x=1} Cf_x \tag{12}$$

Polymetallic contamination index (IPD) classifications of contamination classes are as follows: ($IPD < 5$, low), ($5 \leq IPD < 10$, moderate), ($10 \leq IPD < 20$, considerable), and ($IPD \geq 20$, high) [23].

2.7.6. *Pollution load index (PLI)*

The Pollution Load Index (PLI) serves as an integrated method for evaluating the pollution level of various contaminants in Polymer Treatment Sludge (PTS). It assesses the overall sludge quality by taking into account the combined impact of multiple metals analyzed in PTS, as indicated by Eq. 13 [23,27]. PLI is defined as the nth root of the multiplications of the contamination factor (CF) of metals as calculated in Eq. 13.

$$\mathrm{PLI} = (CF_{Pb} \times CF_{Zn} \times CF_{Mn})^{\frac{1}{n}} \tag{13}$$

where

n is the total number of metals (Pb, Zn, Mn) considered.

A PLI value greater than 1 means polluted sludge for soil application, whereas a PLI value less than 1, indicates no pollution [27].

2.7.7. *Ecological risk index (Er_I) and potential ecological risk index (PERI)*

The toxicity risk and overall ecological sensitivity of Pb, Mn, and Zn were evaluated by calculating the ecological risk index (Eri) and potential ecological risk index (PERI) associated with these pollutants [23]. Eqs. 14 and 15 can be used to calculate the Eri for a single element and the PERI for a multi-element, thus a cumulative number of all heavy metals found in the sludge samples [23].

$$\mathrm{Eri_x} = \mathrm{Tr_x} \times \mathrm{Cf_x} \tag{14}$$

$$\mathrm{PERI} = \sum_{x=1}^{n} Eri_x \tag{15}$$

where Tr_x and Cf_x stand for an individual element sedimentological toxic response factor and contamination factor, respectively. The Tr_x for Pb, Mn, Zn, Cr, Ni, and Cd are 5, 1, 1, 2, 6, and 30.

The degree of pollution is as follows: Low risk when Eir < 40, moderate risk when Eir is within the range of 40–80, considerable risk when Eir is within the range of 80–160, high risk when Eir is within 160–320 and extreme risk when Eir > 320 [23]. The risk level is low when PERI is less than 150, medium when $150 \leq PERI < 300$, high when $300 \leq PERI < 600$, and extremely high when PERI is greater than 600 [23].

3. Results and discussion

3.1. *Toxic metals concentration in polymer post-treatment sludge*

The concentrations of toxic metals and their respective USEPA required thresholds for the polymer post treatment sludge (PTS) are summarized in Table 1.

The average concentrations of toxic metals in PTS were arranged in ascending order as follows: Ni, Cr, and Cd were the least abundant, while Zn, Mn, and Pb were more prevalent, with Pb being the most abundant.

Table 1
Toxic metals (mg/kg) in polymer post treatment sludge from Barekese WTPs.

Sample	Pb	Ni	Mn	Cr	Zn	Cd
A	0.74	BDL	9.39	BDL	0.34	BDL
B	0.77	BDL	9.04	BDL	0.29	BDL
C	0.82	BDL	5.02	BDL	0.30	BDL
Min	0.74	N/A	5.02	N/A	0.29	N/A
Max	0.82	N/A	9.39	N/A	0.34	N/A
Mean	0.78	N/A	7.82	N/A	0.31	N/A
Deviation	0.04	N/A	2.43	N/A	0.02	N/A
USEPA	300	420	N/A	1200	2800	39
LOD	0.19	1.15	0.59	1.16	0.11	0.08

BDL: Below detection limit; N/A: Not available; LOD (mg/kg): Limit of detection.

The concentrations of Ni, Cr, and Cd were below detection limits (BDL) and were also lower than USEPA guideline limits which shows a promising alternative for soil conditioning (Table 2).

In this study, the average lead (Pb) concentration in PTS was 0.78 ± 0.042 mg/kg, with a range of 0.74–0.82 mg/kg. The results of our study indicated lower concentrations of lead (Pb) in sludge compared to the (USEPA) limit of 300 mg/kg [15,32,40]. In contrast, a higher mean Pb concentration of 50 mg/kg was found in sewage sludge from WTPs in Taiyuan, China [15]. A recent study in South Africa reported a low mean Pb concentration of 0.099 mg/kg in sewage sludge from municipal WWTPs, aligning with the results of our study [32]. The recent phase-out of lead-based fuel and water mains in Ghana could account for the lower concentrations [15,19,32].

In this study, the average Zn concentration in PTS was 0.31 ± 0.021 mg/kg, with a range between 0.29 and 0.34 mg/kg. The USEPA limit of 2800 mg/kg for Zn in sludge [15,32] was lower than our findings. The zinc concentration of sewage sludge in China and South Africa was 93.64 and 1752 mg/kg respectively, which was greater than the findings of our study [15,19]. The presence of Zn in PTS could be attributed to the use of brass as a rust-proof cleaning agent in homes and WTPs. Furthermore, because zinc is a constituent of galvanized steel such as water distribution pipes, its presence in treatment plants may be due to corrosion [19]. There is currently no established health-based recommended value for zinc, as there are no recognized diseases associated with elevated doses of zinc in water supply systems [32].

This study revealed a mean concentration of 7.82 ± 2.43 mg/kg for manganese, with concentrations ranging from 5.02 to 9.39 mg/kg. It is worth noting that there seems to be no maximum amount of Mn in biosolids because it represents a valuable micronutrient for plants, birds, and animals, and poses a low hazard to the environment [26,41]. Our findings indicated a lower mean concentration of Mn, compared to sewage sludge in Poland which documented concentrations between 65.43 and 224.19 mg/kg [26]. Concentrations of Mn in PTS at Barekese WTP may be attributed to the utilization of brown calcitic lime in drinking water treatment, which contains higher amounts of Mn than white lime owing to its low manganese content [42]. Nonetheless, untreated raw water also significantly contributed to the overall Mn concentration.

3.2. *Average daily dose*

Table 2 displays the mean, 95% lower and upper confidence limits, and total exposure (ADDtotal) to all three pathways (oral intake, dermal exposure, and inhalation) of toxic metals. This was determined to identify the most significant exposure pathway of PTS to human health among adults and children derived from exposure pathways in comparison to their oral reference dose. No exposure assessment was performed for Ni, Cd, or Cr because they were below the detection limits. The order of heavy metals, derived from their average values (95% UCL and LCL), can be ranked as follows: Mn > Pb > Zn. For adults and children, Mn and Pb had the highest ADD levels, followed by Zn. This finding corroborates earlier research by showing that exposure to PTS has a greater negative impact on children than on adults [15,20,31]. This observation may be because children have lighter bodies and engage more frequently in outdoor activities than adults [20,31,43]. In comparison with skin contact and PTS inhalation, the threat of exposure to toxic metals through dietary means was the highest, which is in agreement with earlier research [15,19,20,31,40]. Inhalation and dermal routes were relatively minor pathways for both children and adults in this study. In comparison, the ADD values (Table 2) obtained were lower than the Rfd values (Table S1) for the various exposure routes in both adults and children

Table 2
Average Daily Dose (ADD) (mg/kg/day) of toxic metals in the PTS from the Barekese Water Treatment Plant, Kumasi.

Heavy metal	Sample	Adults				Children			
		ADDingest	ADDdermal	ADDinhale	ADDtotal	ADDingest	ADDdermal	ADDinhale	ADDtotal
Pb	**A**	1.01×10^{-6}	4.03×10^{-9}	1.48×10^{-10}	1.01×10^{-6}	8.83×10^{-6}	2.47×10^{-8}	2.47×10^{-10}	8.86×10^{-6}
	B	1.06×10^{-6}	4.22×10^{-9}	1.56×10^{-10}	1.06×10^{-6}	9.26×10^{-6}	2.59×10^{-8}	2.59×10^{-10}	9.29×10^{-6}
	C	1.12×10^{-6}	4.48×10^{-9}	1.65×10^{-10}	1.13×10^{-6}	9.83×10^{-6}	2.75×10^{-8}	2.75×10^{-10}	9.86×10^{-6}
	Mean	1.06×10^{-6}	4.24×10^{-9}	1.56×10^{-10}	1.07×10^{-6}	9.31×10^{-6}	2.61×10^{-8}	2.60×10^{-10}	9.33×10^{-6}
	Min	1.01×10^{-6}	4.03×10^{-9}	1.48×10^{-10}	1.01×10^{-6}	8.83×10^{-6}	2.47×10^{-8}	2.47×10^{-10}	8.86×10^{-6}
	Max	1.12×10^{-6}	4.48×10^{-9}	1.65×10^{-10}	1.13×10^{-6}	9.83×10^{-6}	2.75×10^{-8}	2.75×10^{-10}	9.86×10^{-6}
	95% UCL	1.21×10^{-6}	4.81×10^{-9}	1.77×10^{-10}	1.21×10^{-6}	1.06×10^{-5}	2.96×10^{-8}	2.95×10^{-10}	1.06×10^{-5}
	95% LCL	9.21×10^{-7}	3.67×10^{-9}	1.35×10^{-10}	9.25×10^{-7}	8.06×10^{-6}	2.26×10^{-8}	2.25×10^{-10}	8.08×10^{-6}
Mn	**A**	1.29×10^{-5}	5.13×10^{-8}	1.89×10^{-9}	1.29×10^{-5}	1.13×10^{-4}	3.15×10^{-7}	3.14×10^{-9}	1.13×10^{-4}
	B	1.24×10^{-5}	4.94×10^{-8}	1.82×10^{-9}	1.24×10^{-5}	1.08×10^{-4}	3.03×10^{-7}	3.03×10^{-9}	1.09×10^{-4}
	C	6.88×10^{-6}	2.74×10^{-8}	1.01×10^{-9}	6.90×10^{-6}	6.02×10^{-5}	1.68×10^{-7}	1.68×10^{-9}	6.03×10^{-5}
	Mean	1.07×10^{-5}	4.27×10^{-8}	1.57×10^{-9}	1.07×10^{-5}	9.37×10^{-5}	2.62×10^{-7}	2.62×10^{-9}	9.39×10^{-5}
	Min	6.88×10^{-6}	2.74×10^{-8}	1.01×10^{-9}	6.90×10^{-6}	6.02×10^{-5}	1.68×10^{-7}	1.68×10^{-9}	6.03×10^{-5}
	Max	1.29×10^{-5}	5.13×10^{-8}	1.89×10^{-9}	1.29×10^{-5}	1.13×10^{-4}	3.15×10^{-7}	3.14×10^{-9}	1.13×10^{-4}
	95% UCL	1.90×10^{-5}	7.57×10^{-8}	2.79×10^{-9}	1.90×10^{-5}	1.66×10^{-4}	4.65×10^{-7}	4.64×10^{-9}	1.66×10^{-4}
	95% LCL	2.44×10^{-6}	9.75×10^{-9}	3.59×10^{-10}	2.45×10^{-6}	4.12×10^{-6}	5.99×10^{-8}	5.98×10^{-10}	2.14×10^{-5}
Zn	**A**	4.71×10^{-7}	1.88×10^{-9}	6.92×10^{-11}	4.72×10^{-7}	3.46×10^{-6}	1.15×10^{-8}	1.15×10^{-10}	4.13×10^{-6}
	B	3.95×10^{-7}	1.58×10^{-9}	5.81×10^{-11}	3.97×10^{-7}	3.55×10^{-6}	9.68×10^{-9}	9.66×10^{-11}	3.47×10^{-6}
	C	4.06×10^{-7}	1.62×10^{-9}	5.97×10^{-11}	4.07×10^{-7}	3.71×10^{-6}	9.94×10^{-9}	9.92×10^{-11}	3.56×10^{-6}
	Mean	4.24×10^{-7}	1.69×10^{-9}	6.23×10^{-11}	4.25×10^{-7}	3.46×10^{-6}	1.04×10^{-8}	1.04×10^{-10}	3.72×10^{-6}
	Min	3.95×10^{-7}	1.58×10^{-9}	5.81×10^{-11}	3.97×10^{-7}	4.12×10^{-6}	9.68×10^{-9}	9.66×10^{-11}	3.47×10^{-6}
	Max	4.71×10^{-7}	1.88×10^{-9}	6.92×10^{-11}	4.72×10^{-7}	4.60×10^{-6}	1.15×10^{-8}	1.15×10^{-10}	4.13×10^{-6}
	95% UCL	5.25×10^{-7}	2.10×10^{-9}	7.73×10^{-11}	5.28×10^{-7}	2.82×10^{-6}	1.29×10^{-8}	1.28×10^{-10}	4.61×10^{-6}
	95% LCL	3.22×10^{-7}	1.29×10^{-9}	4.74×10^{-11}	3.23×10^{-7}	4.12×10^{-6}	7.89×10^{-9}	7.88×10^{-11}	2.83×10^{-6}

95% UCL and LCL = 95% upper and lower confidence interval

3.3. Carcinogenic and non-carcinogenic risks

For both adults and children, estimates for non-carcinogenic risk (HQ, and HI) in PTS through oral, inhalation, and dermal routes are shown in Table 3 and Table 4. The mean, 95% LCL, and UCL values of HQ and HI were calculated in Table 3 and Table 4. The results indicate that both HQ and HI values were less than one (HQ and HI < 1) in all samples, suggesting no adverse health impacts related to the use of PTS samples through the food chain. These findings are in agreement with previous studies conducted in Turkey and China [20,43,44].

The carcinogenic risks (CR) from Table 4 in both children (10^{-8}) and adults (10^{-9}) were less than the tolerable intake value between 10^{-4} to 10^{-6} for heavy metals in PTS [32]. The outcomes of this study showed no adverse cancer effects in children and adults. The bioaccumulation of hazardous metals in humans varies with size, age, food source, and feeding habitat, therefore this level of risk is not guaranteed to stay constant. Based on the health risks for both adults and children, the agricultural use of polymer post treatment sludge from Barekese WTPs was safer to use.

3.4. Ecological risk of heavy metals in polymer post treatment sludge

The assessment of Nemerow's synthetic pollution index (PN), single factor pollution index (PI), geo-accumulation index (Igeo), contamination factor (CF), potential ecological risk index (PERI), pollution load index (PLI), polymetallic contaminant index (IPD), and the ecological risk index (Eri) shown in Table 5 were estimated to evaluate the status of environmental health risk related to toxic metal concentration in the polymer post treatment sludge.

The single factor pollution (PI) for Zn, Pb, and Mn in polymer post treatment sludge was 0.001, 0.01, and 0.02 respectively (Table 5). The PI of all metals was below one indicating low contamination risk in PTS when used as an alternative for fertilizer in soils and feedstock for fishes. The overall pollution caused by every single element in the order of Zn, Mn, and Pb was extremely low enough to cause threats to sediments and fish.

Nemerow's synthetic pollution index (PN) provides an assessment of the cumulative effect of all toxic metals in PTS from Barekese owing to the harm they can cause to an ecosystem when they exceed 0.7. The PN obtained is shown in Table 5. The PN for Zn, Pb, and Mn was 0.09, 0.24, and 0.4 in PTS sludge for soil reconditioning. The PN obtained in our study was less than 0.7 which was considered safe for agricultural purposes.

The geo-accumulation index (Igeo) was assessed to identify the extent of risk heavy metals present in PTS can cause when utilized for agricultural fertilizers. The negative Igeo values obtained in this study were in the order of Zn (-5.93) $<$ Mn (-4.93) $<$ Pb (-3.93) as shown in Table 5. The negative Igeo values indicate high sludge quality and a low degree of contamination of heavy metals examined in the PTS. Based on the Igeo values, the agricultural practices of PTS can be considered as the most viable option.

The contamination factor (CF) of Pb, Zn, and Mn was 0.10, 0.05, and 0.04 as shown in Table 5. The CF obtained was below one indicating an extremely low contamination status for all toxic metals in all PTS samples. This means PTS samples when applied to farmlands will pose negligible adverse effects.

The pollution load index (PLI), provides the combined effect of all hazardous metals and shows the overall levels of heavy metal toxicity in the PTS sample when applied on land or used as feedstock for fish. The PLI obtained was 2.79×10^{-4} as shown in Table 5 which was lower than 0. The PLI values obtained in this study were below the background values. The PLI indicated that the entire pollution of the PTS sample area showed no pollution status.

The polymetallic contamination index (IPD) obtained was in the order of Zn (0.12) $<$ Mn (0.15) $<$ Pb (0.29) as shown in Table 5. In this study, the calculated IPD values for Pb, Mn, and Zn fall within the low contamination range of 5, suggesting that the PTS sample has relatively low pollution levels for these specific heavy metals.

The ecological risk index (Eri) values for Pb, Mn, and Zn (0.49, 0.05, 0.04, respectively) represent the ecological risk associated with each potentially toxic metal in Table 5. The Eri values obtained in this study were less than 40 indicating a low degree of contamination for that singular heavy metal in all PTS samples.

The PERI value (0.58) is an overall risk index that considers the combined risk of all heavy metals examined in Table 5. In this study, the PERI value obtained was less than 95 which generally indicated a low degree of overall risk by all the heavy metals combined.

Table 3
Carcinogenic and Non-Carcinogenic Risks via inhalation, dermal, and oral exposure of adults and children to heavy metals in PTS from the Barekese Water Treatment Plant, Kumasi.

Heavy metal	Sample I.D		Adults			Children		CRingest	
		HQingest	HQdermal	HQinhale	HQingest	HQdermal	HQinhale	Adults	Children
Pb	**A**	2.88×10^{-4}	7.74×10^{-6}	4.22×10^{-8}	2.52×10^{-3}	7.01×10^{-8}	4.75×10^{-5}	8.58×10^{-9}	7.51×10^{-8}
	B	3.02×10^{-4}	8.12×10^{-6}	4.42×10^{-8}	2.65×10^{-3}	7.35×10^{-8}	4.99×10^{-5}	9.00×10^{-9}	7.87×10^{-8}
	C	3.21×10^{-4}	8.62×10^{-6}	4.70×10^{-8}	2.81×10^{-3}	7.81×10^{-8}	5.29×10^{-5}	9.55×10^{-9}	8.36×10^{-8}
	Mean	3.04×10^{-4}	8.16×10^{-6}	4.44×10^{-8}	2.66×10^{-3}	7.39×10^{-8}	5.01×10^{-5}	9.04×10^{-9}	7.91×10^{-8}
	Min	2.88×10^{-4}	7.74×10^{-6}	4.22×10^{-8}	2.52×10^{-3}	7.01×10^{-8}	4.75×10^{-5}	8.58×10^{-9}	7.51×10^{-8}
	Max	3.21×10^{-4}	8.62×10^{-6}	4.70×10^{-8}	2.81×10^{-3}	7.81×10^{-8}	5.29×10^{-5}	9.55×10^{-9}	8.36×10^{-8}
	95% UCL	3.45×10^{-4}	5.69×10^{-5}	5.04×10^{-8}	3.02×10^{-3}	8.38×10^{-8}	5.69×10^{-5}	1.03×10^{-8}	8.97×10^{-8}
	95% LCL	2.63×10^{-4}	4.34×10^{-5}	3.85×10^{-8}	2.30×10^{-3}	6.40×10^{-8}	1.71×10^{-4}	7.83×10^{-9}	6.85×10^{-8}
Mn	**A**	2.80×10^{-4}	2.79×10^{-5}	4.40×10^{-5}	2.45×10^{-3}	7.31×10^{-5}	1.65×10^{-4}		
	B	2.69×10^{-4}	2.68×10^{-5}	4.23×10^{-5}	2.35×10^{-3}	7.04×10^{-5}	9.15×10^{-5}		
	C	1.49×10^{-4}	1.49×10^{-5}	2.35×10^{-5}	1.31×10^{-3}	3.91×10^{-5}	1.43×10^{-4}		
	Mean	2.33×10^{-4}	2.32×10^{-5}	3.66×10^{-5}	2.04×10^{-3}	6.09×10^{-5}	9.15×10^{-5}		
	Min	1.49×10^{-4}	1.49×10^{-5}	2.35×10^{-5}	1.31×10^{-3}	3.91×10^{-5}	1.71×10^{-4}		
	Max	2.80×10^{-4}	2.79×10^{-5}	4.40×10^{-5}	2.45×10^{-3}	7.31×10^{-5}	2.53×10^{-4}		
	95% UCL	4.12×10^{-4}	2.53×10^{-4}	6.49×10^{-5}	3.61×10^{-3}	1.08×10^{-4}	3.25×10^{-5}		
	95% LCL	5.31×10^{-5}	3.25×10^{-5}	8.36×10^{-6}	4.65×10^{-4}	1.39×10^{-5}	1.71×10^{-4}		
Zn	**A**	1.57×10^{-6}	3.13×10^{-8}	2.31×10^{-10}	1.37×10^{-5}	3.83×10^{-10}	1.92×10^{-7}		
	B	1.32×10^{-6}	2.63×10^{-8}	1.94×10^{-10}	1.15×10^{-5}	3.22×10^{-10}	1.61×10^{-7}		
	C	1.35×10^{-6}	2.70×10^{-8}	1.99×10^{-10}	1.18×10^{-5}	3.31×10^{-10}	1.66×10^{-7}		
	Mean	1.41×10^{-6}	2.82×10^{-8}	2.08×10^{-10}	1.24×10^{-5}	3.45×10^{-10}	1.73×10^{-7}		
	Min	1.32×10^{-6}	2.63×10^{-8}	1.94×10^{-10}	1.15×10^{-5}	3.22×10^{-10}	1.61×10^{-7}		
	Max	1.57×10^{-6}	3.13×10^{-8}	2.31×10^{-10}	1.37×10^{-5}	3.83×10^{-10}	1.92×10^{-7}		
	95% UCL	1.75×10^{-6}	2.15×10^{-7}	2.58×10^{-10}	1.53×10^{-5}	4.28×10^{-10}	2.15×10^{-7}		
	95% LCL	1.07×10^{-6}	1.32×10^{-7}	1.58×10^{-10}	9.40×10^{-6}	2.63×10^{-10}	1.32×10^{-7}		

Table 4

Hazard Indices from the Non-Carcinogenic Risks via Inhalation, dermal, and oral exposure of Adults and Children to heavy metals in PTS from the Barekese Water Treatment Plant, Kumasi.

	Adults			Children		
Sample I.D	**HIingest**	**HIdermal**	**HIinhale**	**HIingest**	**HIdermal**	**HIinhale**
A	5.70×10^{-4}	3.57×10^{-5}	4.40×10^{-5}	4.98×10^{-3}	7.32×10^{-5}	2.19×10^{-4}
B	5.73×10^{-4}	3.50×10^{-5}	4.24×10^{-5}	5.01×10^{-3}	7.05×10^{-5}	2.15×10^{-4}
C	4.72×10^{-4}	2.36×10^{-5}	2.36×10^{-5}	4.13×10^{-3}	3.92×10^{-5}	1.45×10^{-4}
Mean	5.38×10^{-4}	3.14×10^{-5}	3.67×10^{-5}	4.71×10^{-3}	6.09×10^{-5}	1.93×10^{-4}
Min	4.39×10^{-4}	2.27×10^{-5}	2.36×10^{-5}	3.84×10^{-3}	3.92×10^{-5}	1.39×10^{-4}
Max	6.02×10^{-4}	3.65×10^{-5}	4.40×10^{-5}	5.27×10^{-3}	7.32×10^{-5}	2.24×10^{-4}
95% UCL	7.59×10^{-4}	3.10×10^{-4}	6.49×10^{-5}	6.64×10^{-3}	1.08×10^{-4}	3.10×10^{-4}
95% LCL	3.17×10^{-4}	7.61×10^{-5}	8.40×10^{-6}	2.78×10^{-3}	1.40×10^{-5}	7.61×10^{-5}

Table 5

Assessment of ecological risk indices of polymer post treatment sludge.

Toxic Metal	PI	PN	Igeo	CF	IPD	PLI	Eri	PERI
Pb	0.01	0.24	-3.93	0.10	0.29	2.79×10^{-4}	0.49	0.58
Mn	0.02	0.40	-4.93	0.05	0.15		0.05	
Zn	0.001	0.09	-5.18	0.04	0.12		0.04	

3.5. Pearson correlation

Pearson's correlation was used to identify common sources and variables that affect the distribution and dispersion of pollutants in PTS, as well as their interrelations with each other [31]. Strong negative and positive connections were represented by values of −1 and +1, respectively. No linear relationship among the toxic metals is indicated by 0. If potentially toxic metals show a strong positive connection, they may indicate mutual dependency, similarity in behavior, or a common enrichment source [45].

Table S2 presents the correlation coefficients for Ni, Cr, Cd, Pb, Mn, and Zn. Mn exhibits a moderate, positive significant correlation with Zn, while Mn and Zn exhibited a strong negative association with Pb. Moderately positive correlation values between some metals could be related to similar environmental pollution sources or accumulation trends. No relationship was observed among Ni, Cr, and Cd, suggesting that the heavy metals originated from different sources.

3.6. One sample t-test and confidence level

The single-parametric t-test was used to examine whether the average toxic metal concentrations were significantly different from their maximum permissible limits, MPL. For the one-sample t-test, a null hypothesis (H_O) was accepted as the mean value of the PTS for each heavy metal being greater than or equal to their respective permissible limits ($Ho \geq MPL$), or for the alternate hypothesis (H_A), the mean was less than the MPL ($H_A < MPL$) at a significance level of 0.05. A one-sample t-test will show whether the mean variables are significantly greater/less than their respective hypothesized permissible limits. The null hypothesis will be accepted or rejected based on the confidence levels, means, p-value, and sample t-test if $H_O \leq MPL$ and if $H_A > MPL$.

The statistical results from the one-sample t-test and 95% UCL and LCL results are displayed in Table S3.

The negative magnitude of the t-stat of −12342.48 and −162443.29 shows that the mean Pb and Zn concentration is significantly less than the MPL of 300 and 2800 mg/kg ($Ha < MPL$) for the polymer sludge samples from Table S3.

Since the negative t-stat values are less than the t-critical value of 2.92, it infers that the mean Pb and Zn of 0.78 and 0.31 mg/kg are significantly less than their MPL values ($Ha < MPL$). The low p-values of 3.28E-09 and 1.89E-11 are below the significant alpha value of 0.05 at the 95% confidence limit, signifying that the mean concentrations of Pb and Zn are significantly less than those of MPL ($Ha < MPL$).

The upper (0.88, 13.85, and 0.38) and lower (0.67, 1.78, and 0.24) confidence limits indicate that the mean concentration is significantly less than the MPLs for Pb, Mn, and Zn from the study. Based on the statistical evaluation report from the confidence interval and the ANOVA one sample T-test in Table S3, there is sufficient evidence to dismiss the null hypothesis with confidence ($Ho \geq MPL$), showing that the mean concentration of all the metals, 95% UCL and LCL, t-test results are significantly less than the USEPA threshold value.

3.7. Principal component analysis (PCA)

The application of PCA resulted in the observation of correlations and data exploration to comprehend the major variables and identify outliers. PCA was used to determine the variability within a given dataset. Strong factors (> 0.75), moderate (0.50–0.75), and weak factors (< 0.50) are the three categories of factor loadings that were used [46].

The potential sources of contaminants affecting sludge in Barekese WTPs were clarified with the aid of varimax rotation, which increased the percentage variability of the component coefficients [47]. Two factor components were detected owing to eigenvalues > 0.5, explaining 100% of the total variability. A scree plot was used to determine the number of maintained factor components (PCs) (Figure S1). The extracted loadings had no effect or did not significantly affect the heavy metals when the loading was positive or negative, respectively. As indicated in Table S4 and Figure S1, two independent factor components (F1 and F2) accounted for the complete cumulative variance.

The first factor loading (F1) displayed strong positive loading with Mn, weakly positive loadings with Zn, Ni, Cr, and Cd, and negative loading with Pb, accounting for 58.30% variability. The origin of Mn may be predominantly linked to the use of brown lime for drinking water treatment, due to the insufficient supply and cost of white lime. The second factor loading (F2) accounted for 41.70% variability and displayed strong positive loading with Zn, moderate loading with Pb, and weak loadings with Mn, Ni, Cr, and Cd. The correlation between Pb and Zn may stem from construction materials, fossil fuel combustion, dump sites, organic waste, or deteriorating road surfaces within the catchment. Nonpoint sources of origin are indicated by weak and negative factor loadings for metals.

3.8. Limitations and recommendations of the study

The study acknowledges limitations in the determination of heavy metals, indicating that only a few were analyzed. This might not reflect the overall heavy metal profile in the sludge, limiting the understanding of contaminant levels. Despite health and ecological risk assessments, the study recognizes the need for further aquatic pollution assessment using species sensitivity distribution to estimate the potential impact of polymer post-treated sludge on aquatic life accurately. To enhance the swift identification of endangered aquatic species and improve biodiversity conservation, it is crucial to implement continuous monitoring of the aquatic ecosystem in the Barekese estuary and establish a comprehensive local biotoxicological database. The recommendation to sample sludge during both dry and wet seasons highlights a limitation in the current study's seasonal representation, suggesting a potential gap in understanding the geographical distribution of contaminants from the source to the treatment chamber.

This study suggests expanding the scope of heavy metal analysis to provide a comprehensive profile. This includes assessing other contaminants and conducting physicochemical analyses to offer a broader understanding of sludge contamination at drinking water plant premises. Considering the low levels of toxic metals detected in this study and their minimal bioaccumulative potential, exploring the use of polymer post-treated coagulants for agricultural purposes and fish feedstock is recommended, particularly in response to the increasing popularity of inorganic fertilizers in Ghana. There is a recommendation to conduct a national-scale assessment of sludge from drinking water treatment plants to identify untapped waste valorization opportunities. The study proposes the use of robust instruments for analyzing heavy metals in sludge samples from drinking water treatment plants to ensure a more accurate representation of metal concentrations.

4. Conclusion

The results of this study showed that the concentrations of Pb, Zn, Mn, Ni, Cr, and Cd in polymer post treatment sludge were below the maximum allowable limits set by USEPA. The findings from this study indicate that PTS from Barekese drinking water treatment plants have low heavy metal concentrations as compared to sewage sludge discovered in other studies.

According to the exposure assessment, oral intake was the primary pathway of potentially toxic metal exposure, preceded by skin contact and inhalation in both individuals. However, the non-carcinogenic risks for both individuals were less than 1 in all samples, while the carcinogenic risk was lower than the USEPA threshold of 10^{-4} to 10^{-6}, indicating that adults and children are unlikely to experience potential adverse cancer or non-cancer health risk.

All ecological indices such as Nemerow's synthetic pollution index (PN), single factor pollution index (PI), the geo-accumulation index (Igeo), the contamination factor (CF), the potential ecological risk index (PERI), the pollution load index (PLI), the polymetallic contaminant index (IPD), and the ecological risk index (Eri) indicated low contamination status and ecological sensitivity which signified the presence of these metals in the polymer post treatment sludge samples poses an unlikely significant threat to the surrounding environment.

The one sample t-test, 95% UCL, and LCL show that the average concentrations of toxic metal are statistically less than the maximum USEPA values. Pearson correlation indicated the absence of relationship amongst the toxic metals signifying different contamination sources.

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CRediT authorship contribution statement

Samuel Owusu Nti: Writing – review & editing, Resources, Investigation. **Enock Gyabeng:** Resources, Investigation. **Boansi Adu Ababio:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Edward Ebow Kwaansa-Ansah:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Gerheart Winfred Ashong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.toxrep.2024.03.010.

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