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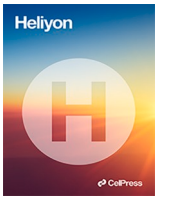

Research article

Environmental impact assessment of SONARA's oil sludge landfill in BATOKE, south-west Cameroon

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ABSTRACT

The focus of this study was to assess the environmental impact of the BATOKE oil sludge dump. A field visit was conducted to evaluate the condition of the site, followed by the sampling of oil sludge, BATOKE river water, soil, and locally grown manioc and macabo tubers. Subsequent physico-chemical characterization revealed parameters such as pH, electrical conductivity, total hydrocarbons, COD, BOD5, TSS, major cations and anions, as well as heavy metals including iron, copper, zinc, nickel, chromium, lead, cadmium, mercury, arsenic, calcium, potassium, titanium, zirconium, and rubidium. The environmental impact was assessed using the Contamination Index calculation and the Correlation Matrix. Results indicated that most physical parameters met standards, except for the electrical conductivity of water and soil. However, elevated levels of iron, chromium, lead, cadmium, mercury, arsenic, and ammonium ion were found in the BATOKE River water. The soil showed heavy contamination with various metals, and cassava and macabo tubers were also found to be contaminated. The contamination index calculations confirmed severe pollution in the BATOKE environment, with a risk of further escalation without remediation efforts.

1. Introduction

The rapidly increasing global population is leading to a heightened demand for energy ([1,2]). This demand is predominantly satisfied by crude oil, which undergoes refining processes to yield various products such as petrol, paraffin, and diesel. According to the European Commission (February 2013), oil refineries in isolation cater to 42 % of the EU's energy requirements and supply 95 % of the fuels essential for the transport sector. In the course of the refining process, by-products such as oil sludge and other industrial wastes [3] are generated, constituting the largest group of organic pollutants ([4,5]). Improper storage of these wastes can result in surface and sub-surface soil and water contamination. Of particular concern is hydrocarbon contamination, given its adverse effects on all forms of life [6]. Previous studies focusing on the physicochemical characterization of hydrocarbon-polluted soils have largely concentrated on determining the concentration levels of identified heavy metals. For example [7], evaluated the concentrations of

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total petroleum hydrocarbons, lead, chromium, and mercury in soil samples sourced from various locations in Wonocolo, Indonesia, where oil drilling and production activities are prominent. Similarly [8], conducted physical and chemical analyses to assess the properties of oil-contaminated soils within the same area.

Several researchers have investigated the repercussions of hydrocarbons on water and soil quality. For instance Ref. [9], analyzed soil samples from storage tanks and landfill ponds at the Al-Daura refinery site in Baghdad to determine soil pollution by petroleum products. They identified maintenance operations as a major contributor to heavy hydrocarbon sludge pollution. In 2014 [10], examined the effects of crude oil pollution on the heavy metal content in soil microorganisms and their impact on plant growth. Experiments on maize and cowpea plants in both polluted and unpolluted soils revealed high concentrations of heavy metals in plants in polluted areas, leading to inhibited growth. Studies in Cross River State, Nigeria ([11]) expanded these experiments to various plant varieties and recommended that farmers avoid cultivating polluted plots, instead suggesting the use of fertilizers, liming, and harrowing to enhance yields. Additionally, oil pollution has detrimental effects on soil biocenosis, leading to alterations in the chemical composition, structure, and properties of the soil ([12,13]). High concentrations of pollutants often result in the disappearance of certain species ([14]), and their potential to infiltrate and reach groundwater sources is contingent on their state, quantity, and composition ([15]).

The present study, distinguished as the first of its kind in Cameroon, endeavors to evaluate the environmental impacts of oil and solid waste sludge dumps on water, soil, tubers, and the population of the village of Batoke, South West Cameroon. This pioneering research focuses on assessing how these pollutants affect various environmental and health parameters in the region. The study is organized around the following key points:

- describe the site condition of the Batoke oil sludge dump;
- sample and characterize the oil sludge discharged at the landfill to obtain the various contaminants found in it;
- sampling and analyzing the waters of the Batoke River;
- sampling and analysing the soils of the site and the surroundings of the landfill (Batoke) for contamination;
- Sampling and testing food grown around the landfill
- Determination of correlations between the parameters studied and calculation of contamination indices.

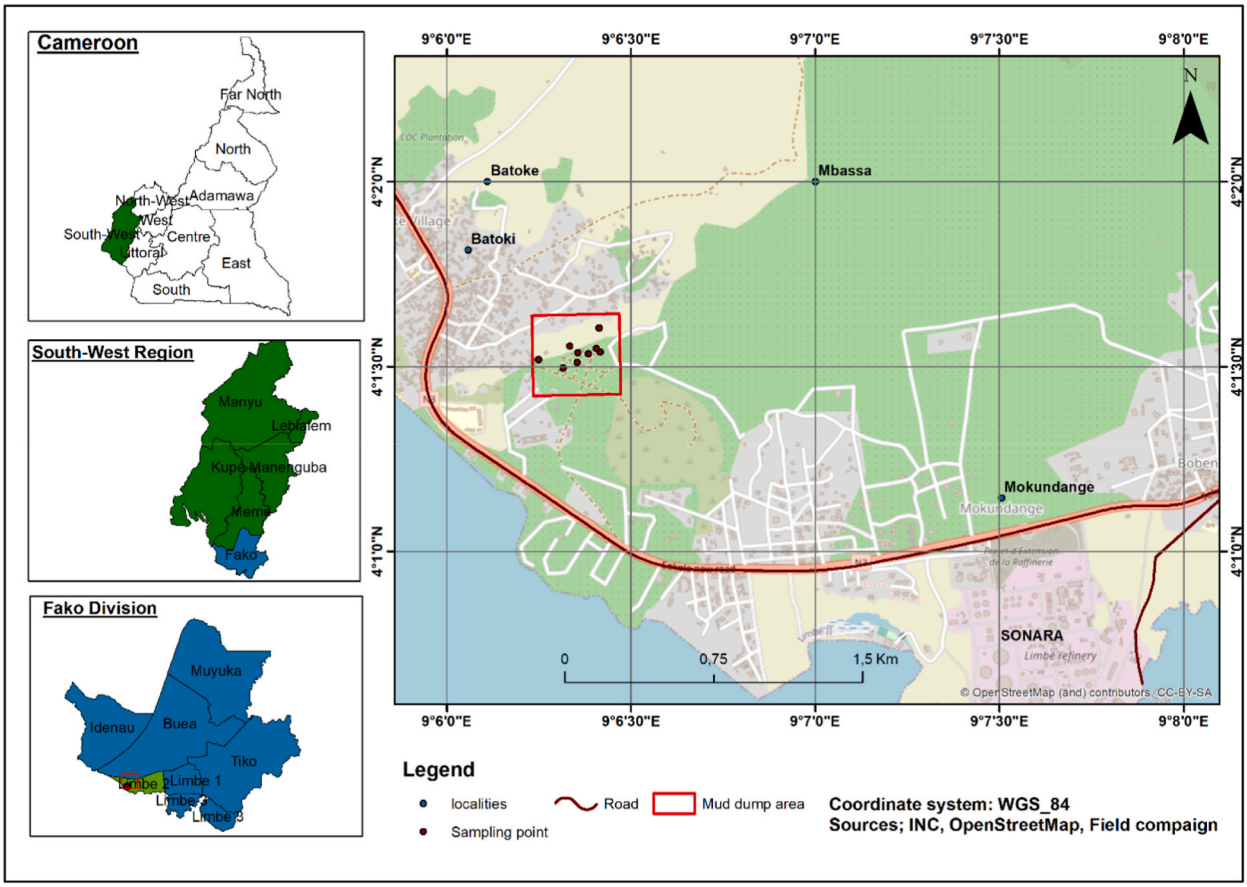

Fig. 1. Location map.

This comprehensive approach will provide a detailed understanding of the environmental and health consequences of oil and waste sludge pollution in Batoke, guiding future policies and remediation efforts in Cameroon.

2. Materials and methods

2.1. Presentation of the study area

The study area is located between 9°6″ and 9°7″ North latitude and 4°1″ and 4°2″ East longitude in Batoke, a small village in Limbe 3 subdivision at 3.5 km from the National Refining Compagny Limited (SONARA) (Fig. 1). Batoke is located in the coastal plain of the South-West region of Cameroon, which extends along the entire western Cameroonian shore of the Atlantic.

The Batoke sludge dump located in a fragile ecosystem area, at 1 km from the sea. To the north-west, the Batoke River is found at the bottom of a ravine which flows into the sea. Agro-pastoral activities are carried out here (plantations, livestock) and there is also an increase urbanisation. The first houses are located 50 m to the south. This landfill has existed for at least three decades; it is an area that allows SONARA to store its hazardous waste, like liquid waste, which is hydrocarbon sludge awaiting further treatment, and solid waste, which is made up of raw hydrocarbons, soiled earth, soiled rags, civil engineering waste, metal waste, plastic waste, wood waste, and insulation waste (glass fibres).

The landfill consists of an open pit about 97 m long, 37 m wide and 5 m deep with a capacity of about 1745 m^3 (and a solid waste storage area in two bins and on the ground) (Fig. 3).

The field equipment kit used for the sampling consisted of a GARMIN GPS to record the coordinates of the sampling points, a manual auger for soil sampling, 1-L breakable jars and plastic bottles for water samples, a cooler for storing the samples and a digital camera for taking photos.

2.2. Sludge sampling

Two sludge samples were taken in 900 mL breakable jars (Fig. 2) at different points. B_1 corresponds to the sludge taken from the SONARA crude oil storage tank A13 and B_2 corresponds to the sludge taken from the Batoke sludge dump.

2.3. Soil sampling

Four soil samples (Fig. 3) were taken using a hand auger. Samples S1, S2 and S3 were taken at the entrance to the Batoke landfill sludge pit, at the landfill's biosolids treatment area and the solid waste area, respectively, and St was the control sample taken far from the landfill site. These samples were stored in plastic jars and transported to the laboratory in a cooler.

2.4. Water sampling

Four water samples were taken. Samples E1, E2 and E3 correspond respectively to the sample taken upstream of the Batoke River, at the point of impact of the river with the landfill, and downstream of the river. A1 corresponds to a control sample taken in the same river but far away from the landfill. The water samples were taken in 1 L glass bottles (Fig. 4) by the guide for taking water from rivers for physicochemical analysis (Loire Bretagne water agency):

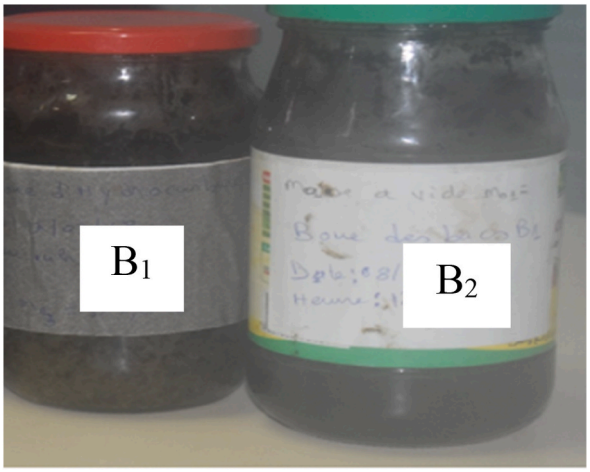

Fig. 2. Sludge samples.

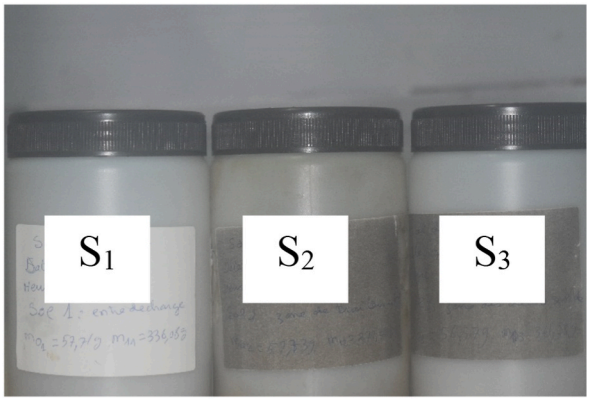

Fig. 3. Soil samples.

Fig. 4. Water samples.

2.5. Tuber sampling

Two food samples were taken from different parts of the site. (Fig. 5).
Below is the sample map (Fig. 6):

2.6. Methods of analysis in the laboratory

2.6.1. Physico-chemical parameters of water and soil in SONARA's oil sludge landfill BATOKE

The pH was determined using a glass electrode pH meter; the electrical conductivity was determined using a CDM 210 conductivity meter. Chemical Oxygen Demand (COD); Biochemical Oxygen Demand for 5 days (BOD5).

2.7. Determination of suspended solids (MES)

the amount of suspended matter retained on the filter paper is calculated by equation (1):

$$\boldsymbol{MES} = \frac{\boldsymbol{m_1 - m_0}}{\boldsymbol{Prise\ Essai}}\ \boldsymbol{X}\ \mathbf{100} \tag{1}$$

Fig. 5. Cassava tuber (left) and macabo tuber (right).

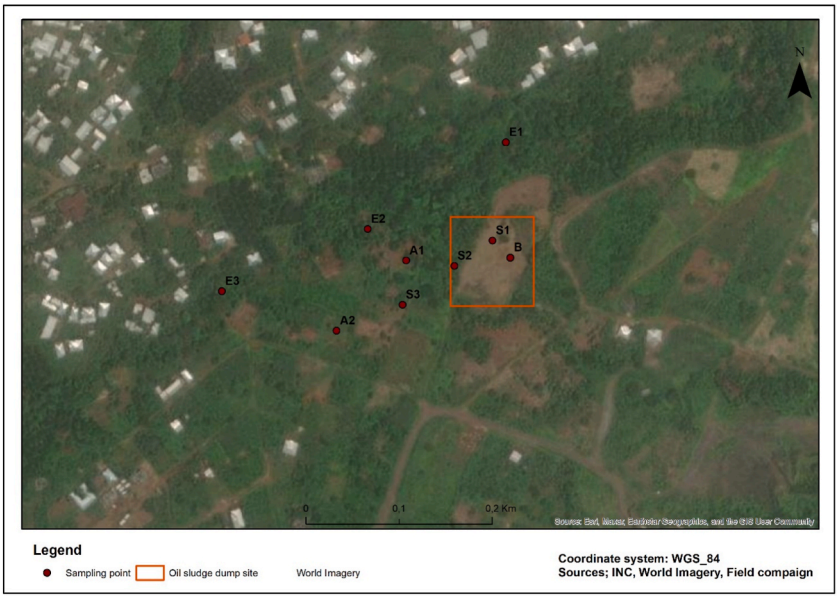

Fig. 6. Sample map.

Where $\begin{cases} m_0 = \text{mass of the vacuum membrane} \\ m_1 = \text{mass of the membrane containing the suspended matter} \end{cases}$.

2.8. Determination of total hydrocarbons

The determination of the number of total hydrocarbons in the water samples was done with the Eracheck eco SNR 563/17 analyser. Its measurement principle uses infrared (hydrocarbon absorption wavelength range).

2.9. Determination of trace metal elements (TMEs) in water, soil, oil sludge and tubers

Analyses to identify heavy metals in water samples were carried out by atomic absorption spectrometry (AAS). Hydrochloric and nitric acid were needed to colour the sample by supplementing the metal and analysing it at a well-defined wavelength. This analysis was carried out at the chemistry laboratory of the University of Yaoundé I.

The heavy metals that were determined are iron, copper, zinc, mercury, cadmium, arsenic, chromium and lead.

The analyses of heavy metals in hydrocarbon sludge, soils, cassava and macabo were carried out at CAPAM using the X-ray fluorescence spectrometry method.

2.10. Determination of major anions and cations

The analyses of major anions and cations in the waters were carried out at the laboratory of hydrobiology and environment of the University of Yaoundé I. The anions and cations that were determined are: potassium (K^+), calcium $\left(Ca^{2+}\right)$, magnesium $\left(Mg^{2+}\right)$ and sodium (Na^+), ammonium $\left(NH_4^+\right)$, $\left(SO_4^{2-}\right)$, (Cl^-), nitrate, $\left(NO_3^-\right)$, phosphate $\left(PO_4^{3-}\right)$.

2.11. Individual survey of the population

The survey was conducted on a household basis using a questionnaire with questions on the economy, agriculture, the atmosphere around the landfill, Batoke water, fauna, flora and human health.

2.12. Data processing

The data processing consists of determining the contamination index (IC) and the correlation matrix between these contaminants. Equation (2) below shows the formula for calculating the IC.

$$\mathbf{IC} = \frac{\boldsymbol{measured\ concentration}}{\boldsymbol{reference\ concentration}} \tag{2}$$

The average contamination index (Icm) will then allow the sampling points to be compared and characterised about the overall pollution, to establish a ranking according to the extent of the contamination in the whole study area. The average contamination index (Icm) is calculated using equation (3)

$$\mathbf{Icm} = \frac{\mathbf{\Sigma Ic}}{\mathbf{n}} \tag{3}$$

n: is the number of indices for each sampled point.

2.12.1. Correlation matrix

The correlation matrix was used to determine the correlation between the different parameters.

3. Results and interpretations

3.1. The state of the Batoke landfill site

The Batoke landfill site were identified by a large sludge pit and a polluted solid waste storage area (PSW). Spills at the entrance of the pit during the unloading of tankers, overflows from the pit and infiltration of sludge effluent are observed, which can affect the water of the Batoke river, the soil and the groundwater table of the site. As the pit is not protected by a geo-membrane (impermeable tarpaulin), there is no effluent retention barrier.

At the PSW storage site, this waste is dumped on the ground without a protective cover. Around the landfill are fruit trees such as avocado, coconut, mango and wild greenery with a variety of fauna, the population of Batoke farms (maize, cassava, macabo) around the landfill and behind the landfill is the Batoke river. Figs. 7 and 8 shows the state of the landfill site.

3.2. The geographical coordinates of the sampling points

Table 1 shows the coordinates of the different sample points.

3.3. Physical characterization of oil sludge

The physical characterization of the hydrocarbon sludge consisted of determining the pH, total hydrocarbons. The results of these analyses are presented in Table 2.

The pH of samples B1 and B2 are basic 7.8 and 8.9 respectively. The total hydrocarbons determined in 25 g of the B1 and B2 sludge samples are 493.7 mg/L and 458.2 mg/L respectively. The results of the hydrocarbon sludge analyses for heavy metals are presented in Table 3.

Table 3 shows that the hydrocarbon sludge samples of samples B1 and B2 characterised are loaded with iron, copper, zinc, nickel, arsenic, chromium, lead, calcium, rubidium, titanium and zirconium with very high concentrations. Mercury and cadmium concentrations are zero.

3.4. Physico-chemical parameters of water

3.4.1. Total hydrocarbons

According to Table 4, the total hydrocarbon levels in the 04 samples E1, E2, E3 and Et are zero.

Table 4 shows that the four (04) water samples E1, E2, E3 and Et respectively upstream of the landfill, at the level of the landfill, downstream of the landfill and the control sample taken from the BATOKE river have a neutral pH in agreement with the WHO

Fig. 7. Sludge pit almost full and overgrown with weeds all around.

Fig. 8. Solid waste landfill area with waste dumped on the ground.

Table 1
Geographic coordinates of the various sampling points.

Sampling point	Longitude	**Latitude**
B	9.106929563	4.025635111
E_1	9.106885196	4.026743521
E_2	9.105554192	4.025908953
E_3	9.104147126	4.025310293
S_1	9.106758434	4.025798705
S_2	9.106388889	4.025555556
S_3	9.105888526	4.025179891
A_1	9.105924178	4.0256066590
A_2	9.105253921	4.0249309430

Table 2
Results of the physical parameters of the sludge.

Parameters	**B1**	**B2**	**Unit**
pH	7.8	8.9	
Total hydrocarbon	493.7	458.2	mg/L

Table 3
Results for heavy metals in sludge.

Parameters	B_1	B_2	EU Directive	Unit
Iron	9.31	9.77	0.005	%
Copper	0.052	0.137	0.003	%
Zinc	0.609	0.615	0.009	%
Nickel	0.029	0.031	0.005	%
Mercury	0	0	–	%
Cadmium	0	0	–	%
Arsenic	0.004	0.0185	–	%
Chromium	0.0119	0.0128	0.007	%
Lead	0.019	0.0211	0.0035	%
Calcium	0.70	4.212	–	%
Rubidium	0.0006	0.0014	–	%
Titanium	1.213	1.668	–	%
Zirconium	0.021	0.0254	–	%
Potassium	0	0	–	%

standard for surface water, namely $6.5 < pH < 8.5$. It can be seen that the electrical conductivity values are higher than the WHO standard (14 μs/cm). Fig. 9a-e shows that the COD values of samples E1, E2, E3 and Et are lower than the WHO standard (120 mg/L). The BOD_5 and TSS values of samples E1, E2, E3 and Et are lower than the WHO standard, which sets respective values of 50 mg/L and 30 mg/L.

Table 4
Results of physical water parameters.

Parameters	E_1	E_2	E_3	E_t	Norms OMS	unit
pH	7.58	7.71	7.72	6.5	6.5–8.5	
Conductivity	105.6	104.6	103.4	16.8	14	µs/cm
TSS	8.680	13.040	12/320	8	50	mg/L
COD	0.8	1.0	0.5	0.7	120	mg/L
BOD5	8	13	25	12	30	mg/L
Total hydrocarbon	0	0	0	0	10	mg/L

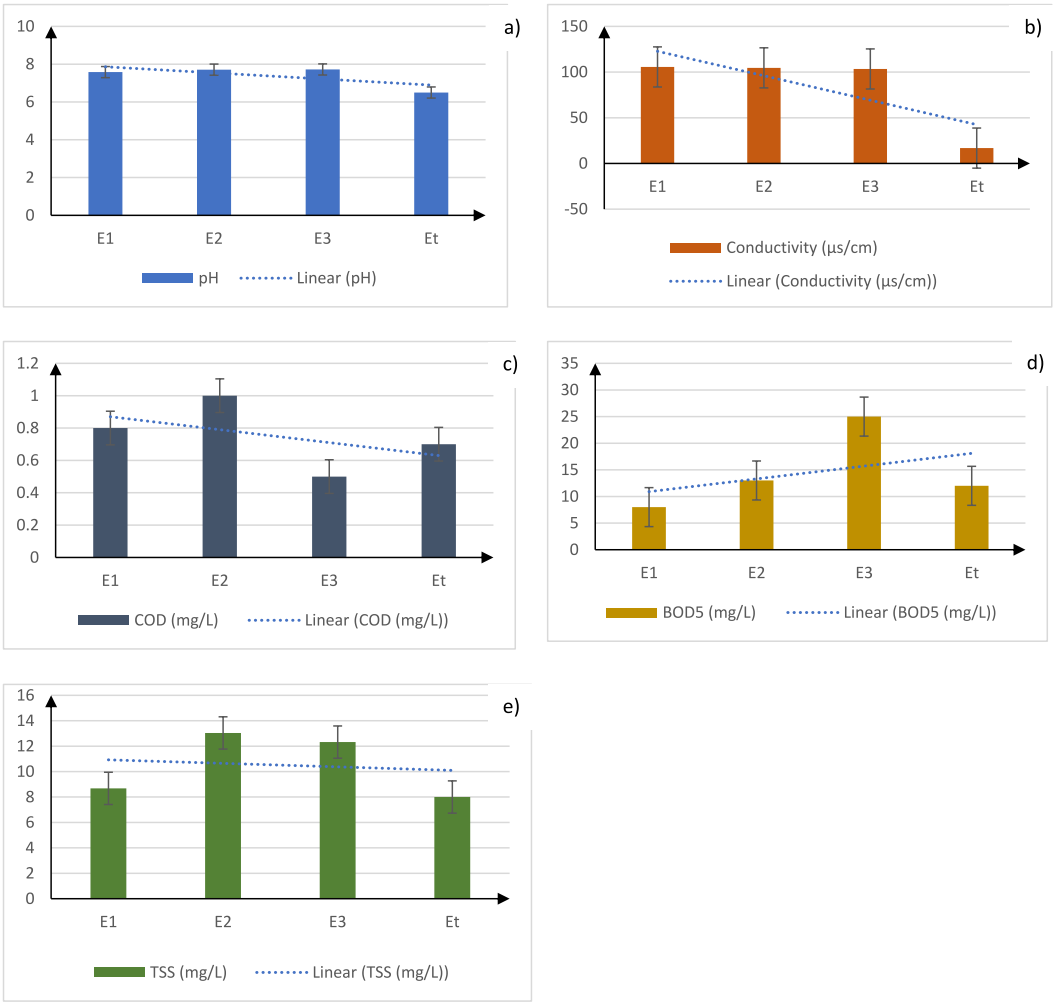

Fig. 9. Graphs of physical parameters of water samples: a)pH; b)EC; c)COD; d) BOD5; e)TSS.

3.5. Results of analyses of heavy metals, cations and major anions in water

The results of the analyses of heavy metals and major cations and anions are given in Table 5.

Fig. 10(a–h) shows the variation in heavy metal concentrations in the water samples collected. The iron concentrations of samples E1 and Et are below the WHO standard (0.3 mg/L). However, the concentrations of samples E2 and E3 are higher. Copper concentrations in samples E1, E2, E3 and Et are below the WHO standard (2 mg/L). Zinc concentrations in samples E1, E2, E3 and Et are below the WHO standard (3 mg/L) but the zinc concentration at the landfill is higher. Nickel concentrations in samples E1, E2, E3 and Et are zero. The mercury concentration values of samples E1, E2, and E3 are higher than the WHO standard (0.006 mg/L) and that of Et is zero. The cadmium concentration of samples E1 and Et are lower than the WHO standard (0.03 mg/L). On the other hand, the cadmium concentrations of samples E2 and E3 respectively at the level of the landfill and downstream of the landfill are above the WHO standard (0.03 mg/L). The arsenic concentration values in samples E1, E2 and E3 are higher than the WHO standard (0.01 mg/L), and that of

Table 5
Results of analyses of heavy metals, cations and major anions in water.

Parameters	Samples					
	E1	E2	E3	Et	norms	Unit
Iron	0.043	1.73	0.58	0.06	0.3	mg/L
Copper	0	0.012	0.01	1	2.0	mg/L
Zinc	0.06	0.44	0.33	0.015	3.0	mg/L
Nickel	0	0	0	0	0.02	mg/L
Mercury	0.012	0.22	0.15	0	0.006	mg/L
Cadmium	0	0.37	0.02	0	0.003	mg/L
Arsenic	3.7	18.7	31.6	0	0.01	mg/L
Chrome	13.7	18.76	21.63	0.15	0.3	mg/L
Lead	0.72	6.81	5.36	0.002	0.01	mg/L
Major cations						
Na^{+}	18.9	27.3	39.4	5.32	200	mg/L
NH^{4+}	0.01	0.86	0.15	0.45	0.50	mg/L
K^{+}	1.23	3.78	2.34	2.67	12	mg/L
Mg^{2+}	35.2	42.7	30.78	12	50	mg/L
Ca^{2+}	17.8	35.5	23.4	1.53	100	mg/L
Minor anions						
SO_4^{2-}	2.5	14	16.7	3	250	mg/L
Cl^{-}	0.03	1.72	0.65	0.07	250	mg/L
NO_3^{-}	0.12	1.78	4.5	0.05	50	mg/L
PO_4^{3-}	0.06	1.98	0.48	0.35	–	

sample Et is zero. The lead concentrations of samples E1, E2 and E3 are above the WHO standard (0.01 mg/L). Sample Et has a lead concentration below the standard.

3.6. Physical parameters of soils

The results of the physico-chemical soil parameters are presented in Table 6.

The pH of the St sample respects the standard (6.5–8.5) with a value of 6.8. On the other hand, the pH of samples S1. S2 and S3 are below the standard with values varying between 5.58 and 6.49. The electrical conductivity of the St sample respects the standard while the conductivity values of the S1. S2 and S3 are above the standard (14 μs/cm). The total hydrocarbon levels in samples S1. S2 and S3 are below the standard (10 mg/l) and for the St sample the total hydrocarbons are zero as shown in Fig. 11(a–c).

3.7. Soil chemical parameters

The results of the heavy metal analyses in the soil are presented in Table 7.

Fig. 12(a–k) shows that the iron concentrations in samples S1, S2 and S3 are well above the Bowen standard (0.005 %) but the St sample is below it with a value of 0.002 %. The copper concentrations in the samples are well above the Bowen standard (0.003 %) but the St sample is equivalent to the standard with a value of 0.003 %. Zinc concentrations in samples S1, S2 and S3 are above the Bowen standard (0.009 %), however sample St is below the standard with a value of 0.0006 %. Nickel concentrations in samples S1 and S3 are above the standard (0.006 %) but St and S2 are below with values of 0.0006 % and 0.002 % respectively. Chromium concentrations in samples S1 and S3 are above the Bowen standard (0.007 %) whereas samples St and S2 are below the standard with values of 0.0002 % and 0.002 % respectively. The lead concentrations in samples S1, S2 and S3 are above the Bowen standard (0.0035 %), while sample St is below the standard with a value of 0.00003 %. The concentrations of mercury, cadmium and arsenic in the soil samples are zero.

In Table 7 we note the presence of calcium; rubidium; titanium; zirconium; and potassium in the tubers. However, the regulation on these metals in the soil was not found.

3.8. Results of the analysis of heavy metals in food

The results of the heavy metal analyses in the cassava and macabo tuber samples are presented in Table 8.

The concentration of iron in cassava is zero, while in macabo it is higher than the limit value (0.0015 %–0.002 %). The concentration of copper in cassava is lower than the limit value (0.01 %), while in macabo it is higher. The concentration of zinc in cassava is lower than the norm (0.01 %), while in macabo the concentration is higher.

3.9. Data processing

3.9.1. Contamination index

Table 9 shows the contamination indices of all samples for all heavy metals determined.

The contamination index calculation results (refer to Table 9) indicate that all water sampling points show contamination indices

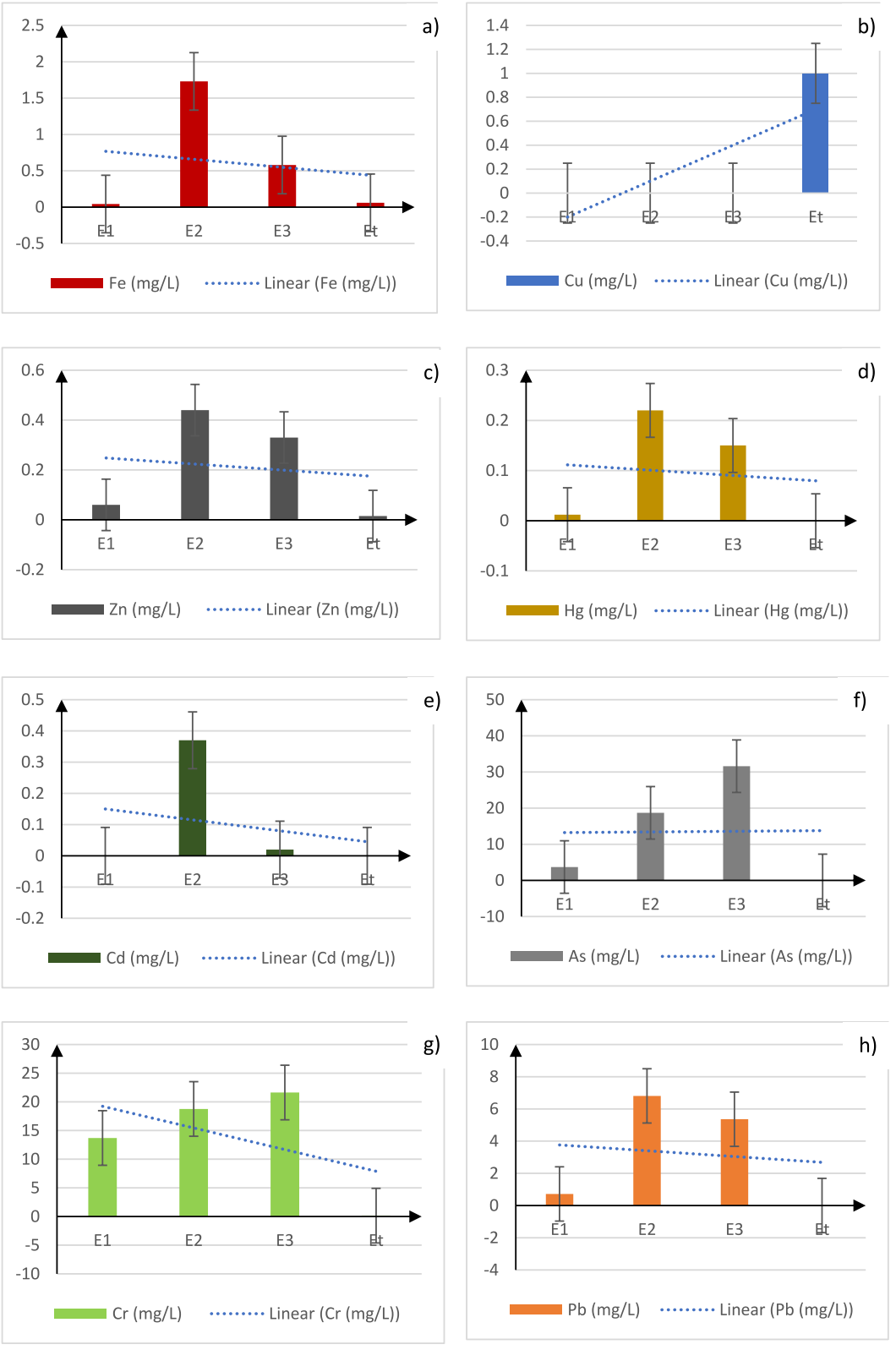

Fig. 10. graphs of heavy metal concentration variations in water samples: a)Fe; b)Cu; c)Zn; d) Hg; e)Cd; f)As; g)Cr; h)Pb.

Table 6
Results of physical soil parameters.

Parameters	Samples					
	S_1	S_2	S_3	S_t	norms	unit
pH	6.49	6.10	5.58	6.8	6.5–8.5	–
Conductivity	30.1	40.3	24.8	13	14	µs/cm
Total hydrocarbon	4.2	3.2	0	0.6	10	mg/L

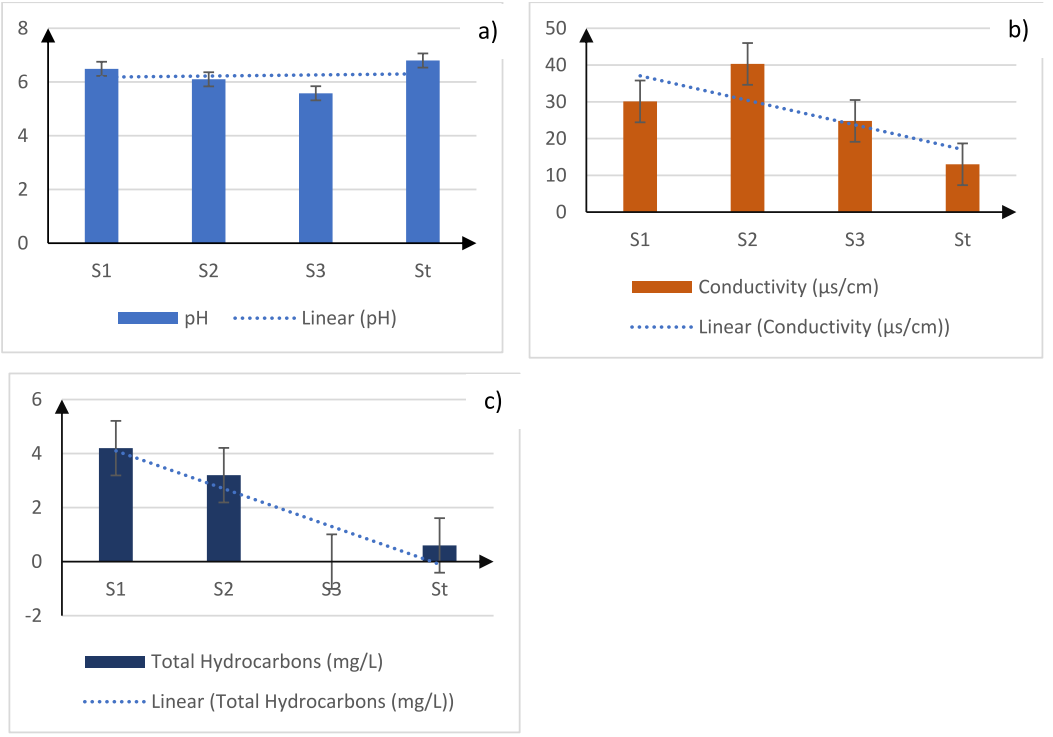

Fig. 11. graphs of physical parameters of soil samples: a)pH; b)EC; c)TH.

Table 7
Results of heavy metal analyses in soils.

Parameters	S1	S2	S3	St	EU directive	unit
Iron	12.973	32.927	10.852	0.002	0.005	%
Copper	0.0196	0.0231	0.0185	0.003	0.003	%
Zinc	0.0104	0.0130	0.1574	0.0006	0.009	%
Nickel	0.006	0.0020	0.0221	0.0005	0.005	%
Mercury	0	0	0	0	–	%
Cadmium	0	0	0	0	–	%
Arsenic	0	0	0	0	–	%
Chromium	0.008	0.002	0.017	0.0002	0.007	%
Lead	0.0048	0.0192	0.010	0.00003	0.0035	%
Calcium	4.3847	2.0522	4.7146	0	–	%
Rubidium	0.0004	0.0014	0.0032	0	–	%
Titanium	3.1474	5.7815	2.4745	0	–	%
Zirconium	0.0397	0.0583	0.0567	0	–	%
Potassium	3.3720	0	0	0	–	%

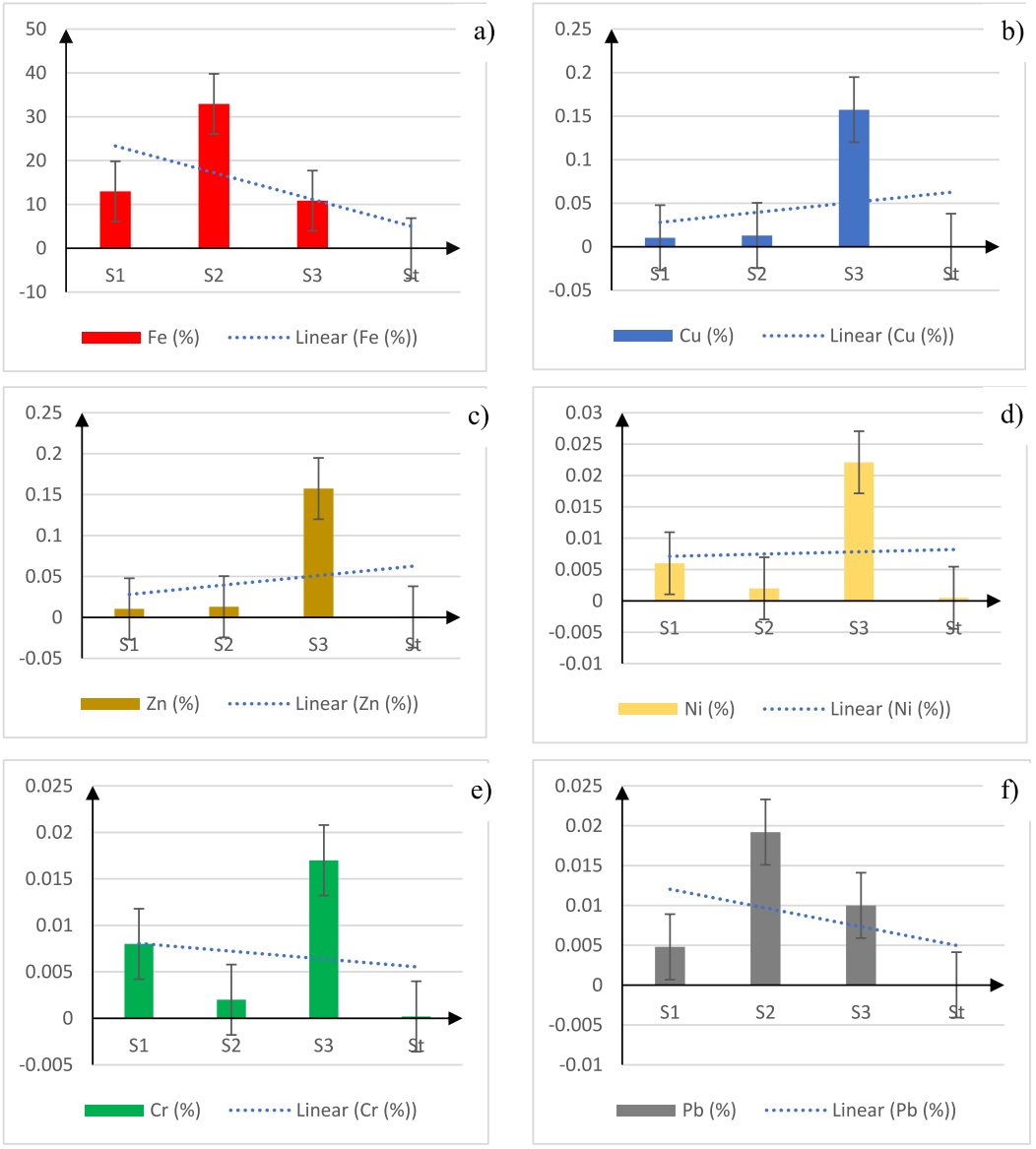

Fig. 12. graphs of heavy metal concentration variations in water samples: a)Fe; b)Cu; c)Zn; d) Ni; e)Cr; f)Pb; g)Ca; h)Rb; i)Ti; j)Zr; k) K

exceeding 1 for iron, zinc, chromium, lead, and cadmium, except for the point sampled downstream of the landfill. This particular point exhibits a contamination index lower than 1 for iron and 1 for lead. Conversely, all water sampling points show contamination indices lower than 1 for copper.

4. Correlation matrix

4.1. Discussion

4.1.1. Inventory of the BATOKE landfill site

Based on the condition of the landfill mentioned previously, there is a potential for pollution of the soil, the BATOKE River, and the plantations situated 50 m from the landfill. This pollution may occur through the infiltration and leaching of biohazardous waste, or the leaching of Persistent, Bioaccumulative, and Toxic Substances (PBTs) deposited on the ground.

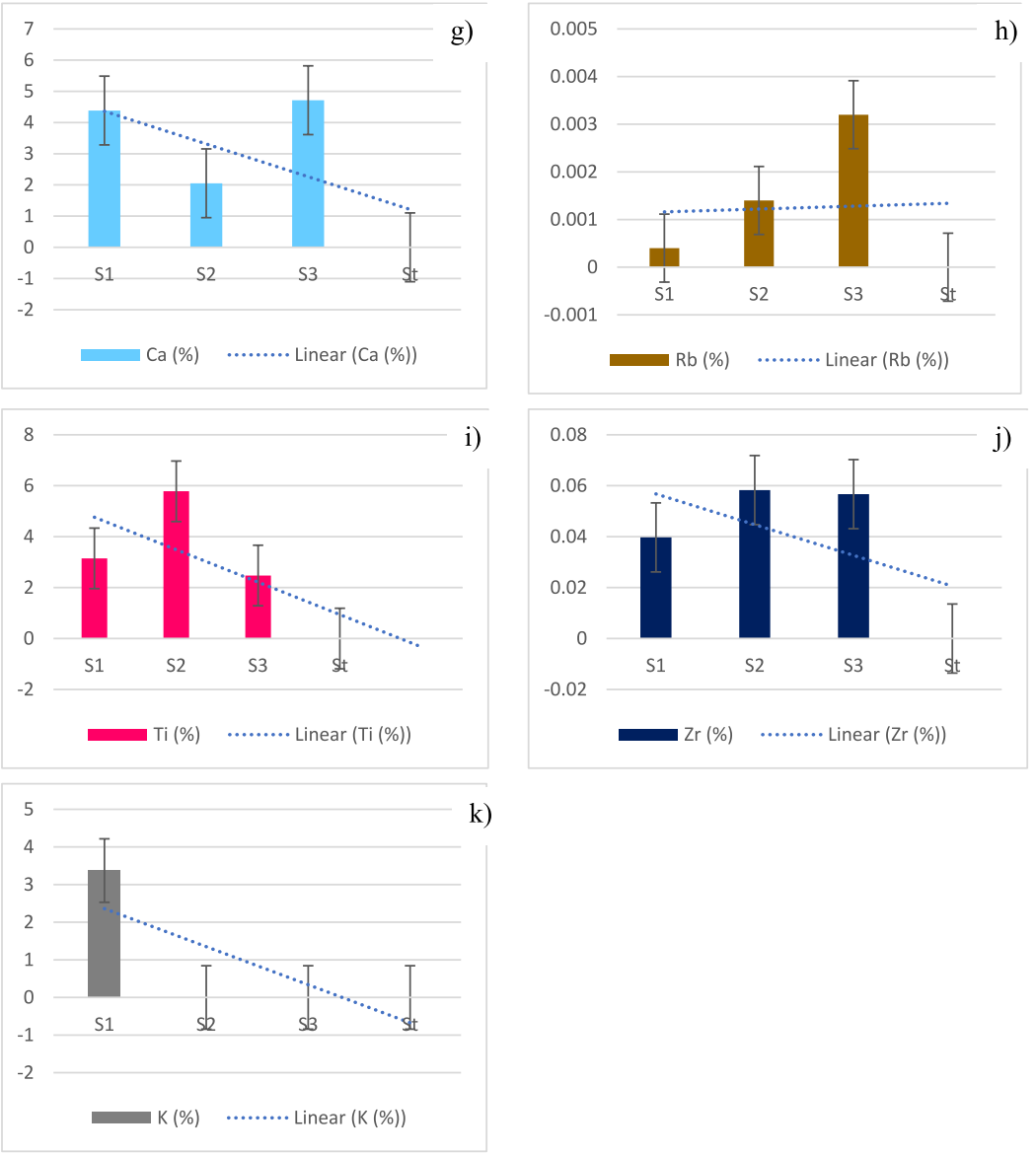

Fig. 12. (*continued*).

4.2. Characterization of oil sludge

4.2.1. pH

In Tables 2 and it is indicated that the pH of samples B1 and B2 is basic, with values of 7.8 and 8.9. According to sources [16,17], this value ranges from 5.5 to 8. However, based on [18], the pH of sludge containing zinc, copper, nickel, lead, chromium, and iron should fall between 6.5 and 7.5. The increase in pH may be attributed to the presence of heavy metals such as zirconium, calcium, rubidium, titanium, and arsenic in these oil sludges.

4.2.2. Total hydrocarbon

As per Table 2, the total hydrocarbons found in 25 g samples of B1 and B2 are 493.7 mg/L and 458.2 mg/L, respectively. These levels indicate the presence of total hydrocarbons in these hydrocarbon slurries. Additionally [18], mentions that the total petroleum hydrocarbon content in oil sludge can vary from 5 to 86.2 % by mass, with the more common range being 15–50 %. This prevalence of total hydrocarbons may be attributed to the quality of the crude oil used or the refining methods employed at SONARA.

4.2.3. Heavy metals in sludge

Table 3 indicates that the characterised oil sludge contains high concentrations of iron, copper, zinc, nickel, arsenic, chromium,

Table 8
Results of heavy metals in food.

Result				
heavy metals	cassava	macabo	Limit value	Unit
Iron	0	0.0168	0.0015–0.002	%
Copper	0	0.0117	0.01	%
Zinc	0.0011	0.0109	0.01	%
Nickel	0	0	–	%
Mercury	0	0	–	%
Cadmium	0	0	–	%
Arsenic	0	0	–	%
Chrome	0	0	–	%
Lead	0	0	–	%
Calcium	0.3462	0.09		%
Rubidium	0.0045	0.007		%
Titanium	0.0467	0.09		%
Zirconium	0.0131	0		%
Potassium	1.422	1.206		%

Table 9
Indices of contamination of the different samples.

Sampling point	Parameters							
	Iron	Copper	Zinc	Chrome	Nickel	Lead	Calcium	The average index of contamination
Water								
Indicator	1	1	1	1	–	1	1	
Upstream of the landfill	0.72	0	4	91.33	–	1	11.63	21.74
At landfill level	28.83	0.012	29.33	125.06	–	9.46	23.20	41.43
Downstream of the landfill	9.67	0.01	22	144.2	–	7.44	15.29	33.10
Soils								
Indicator	1	1	1	1	1	1	–	
Landfill entrance	6486.5	6.53	17.33	40	12	160	–	1120.4
BH treatment area	16463.5	7.7	21.66	10	4	640	–	2857.81
DSP area	5426	6.16	262.33	85	44.2	333.33	–	1019.5

lead, calcium, rubidium, titanium, and zirconium. According to Ref. [18], refinery oil sludge contains heavy metals such as zinc, copper, nickel, lead, chromium, and iron. However, their chemical composition can vary widely depending on the source of crude oil, processing method, equipment, and reagents used in the refining process.

4.3. Physico-chemical parameters of water and soil

4.3.1. pH

The data presented in Table 6 indicates that the pH levels of soils S1, S2, and S3 are predominantly acidic, aligning with the findings of [11] which ranged from 5.64 to 5.87. In contrast [8,12], reported pH levels ranging from 6.88 to 8.46 and 6.43 to 7.90, indicating an acidic to basic and acidic to neutral range, respectively. The acidity of the landfill soils may be attributed to the presence of heavy metals such as iron, copper, zinc, nickel, chromium, and lead. In Table 4, the pH values of the water samples range between 6.5 and 7.72, which falls within the range indicated by the WHO. On average, these values are higher than those reported by Ref. [19] (6.26–6.97).

4.3.2. Electrical conductivity

The electrical conductivity of the St sample (control soil) complies with the standard, while the conductivity values of the S1, S2 and S3 soil samples are all higher than the standard and the values obtained by Ref. [8] (EC = [2; 10,5] µs/cm). This indicates a significant presence of heavy metals in the sampled soils.

4.3.3. Total hydrocarbon

The levels of total hydrocarbons in samples E1, E2, E3, Et, S3 and St are zero. This could be explained by the fact that there was a dilution of the total hydrocarbons because the sampling was done during the rainy season. The river flow was high. For samples S1 and S2, the total hydrocarbons are in trace amounts, varying between 600 and 4200 µg/L but lower than the norm against the value of 211 025 73 µg/L obtained by Ref. [20]. The presence of these traces could be explained by the infiltration of these total hydrocarbons into the soil.

4.3.4. Iron

The samples E1, Et, and St show no signs of iron contamination, possibly due to their distance from the landfill. Elevated iron levels

in water samples E2 and E3, as well as soil samples S1, S2, and S3, as shown in the table, may be attributed to various sources such as leaching from hydrocarbon sludge, paint cans in the PSWs, seepage of oil sludge into the soils, or dissolution of iron oxide from the pozzolan quarry adjacent to the landfill. Notably, the highest iron concentration in sample E2 (1.73 mg/L) is lower than the average value (4.29 mg/L) reported by Ref. [19].

4.3.5. Copper

The water samples E1, E2, E3 and Et unpolluted by copper could be explained by the lack of dissolution of the metal copper in these waters. Copper concentrations in soil samples S1, S2 and S3 are very high; these concentrations could be explained by the infiltration of copper by leaching from sludge and PSW. The St sample is equal to the standard. The presence of copper in this control soil could be a natural phenomenon originating from the volcanic soil.

4.3.6. Zinc

Fig. 10c shows that the zinc concentrations in the water samples are below the standard. This could be explained by the fact that there was no dissolution of zinc. The average of these values is higher than that obtained by Ref. [21] which is 0.1 mg/L. On the other hand, Fig. 7c shows that the soil samples S1, S2 and S3 are all polluted by zinc. This pollution could come from the leaching and infiltration of oil sludge and PSW. The sample St is lower than the standard, but its presence in this soil could be a natural phenomenon coming from the volcanic soil.

4.3.7. Lead

Samples E1, E2, E3, S1, S2 and S3 have lead concentrations above the standard as shown in Figs. 10 and 12 with a minimum value for the water samples of 0.002 mg/L corresponding to the control sample below the WHO target value (0.01 mg/L) and that (0.01 mg/L) obtained by Refs. [19,21], 0.039 mg/L. This pollution could be from dissolution of lead from oil sludge by leaching of oil sludge, leaching of PSW or leaching of volcanic soils. For the Et and St samples their lead concentrations are lower than the standard, but their presence in this soil could be a natural phenomenon originating from the volcanic soil. Studies have shown that long-term lead exposure causes memory impairment.

4.3.8. Nickel

Table 5 shows that the nickel concentrations of the 03 samples E1, E2, E3 and Et are zero. On the other hand, soil samples S1 and S3 have very high nickel contamination. This pollution could be explained by: for sample S1, the infiltration of hydrocarbon sludge discharged at the pit entrance and for sample S3 by the leaching of PSW. For samples, S2 and St. the concentrations are lower than the standard. This could be explained for S2 by the fact that during the treatment of the sludge on the S2 soil, a good part of the nickel was eliminated, and for the St. soil it could be a natural phenomenon coming from the volcanic soil.

4.3.9. Mercury; cadmium

The concentrations of mercury and cadmium in samples S1, S2, S3, Et, and St are all zero as presented in Tables 5 and 7 This could be explained by the fact that the oil sludge and PSWs do not contain mercury and cadmium. On the other hand, water samples E1, E2 and E3 have mercury and cadmium concentrations above the standard as shown in Fig. 10d and e. The presence of mercury could be a result of the water cycle. Mercury in the atmosphere comes into contact with water vapour at high temperatures, after condensation, the mercury falls back into the water as mercury oxide as shown in equation (4). The origin of cadmium in water could be atmospheric fallout.

$$H_g + H_2O \rightarrow H_gO + 2H \quad (4)$$

The mercury (Hg) in the atmosphere is likely to return to the ground in the form of HgO through dry and wet deposition processes.

Wet deposition occurs when mercury compounds are washed out of the atmosphere by rain or snow. During precipitation events, raindrops or snowflakes capture airborne mercury particles and carry them to the ground.

And dry deposition refers to the direct transfer of mercury from the atmosphere to land surfaces without involving precipitation. Gaseous elemental mercury (GEM) and other forms can be deposited through dry processes. Measurement uncertainties arise due to incomplete capture of targeted forms and interference from unwanted forms. The total global Hg deposition includes both wet and dry deposition [22]. Forests play a critical role in Hg cycling, acting as both sinks and sources. Vegetation uptake contributes to the removal of atmospheric Hg but continued deforestation and climate change threaten this role [23].

4.3.10. Arsenic

Water samples E1, E2 and E3 have arsenic concentrations above the standard as shown in Fig. 10. This pollution could be due to the leaching of arsenic from the oil sludge. On the other hand, the arsenic concentrations in the soil samples Et, S1, S2, S3 and St are zero as shown in Tables 5 and 7 The absence of arsenic in these samples could be explained by the fact that there was a natural elimination of arsenic by certain soil microorganisms or by the presence of clay in these soils.

4.3.10.1. Chrome. Water samples E1, E2 and E3 and soil samples S1 and S3 have concentrations above the standards as shown in Figs. 10 and 12. This increase in concentration could be due to the leaching of oil sludge and PSDs or the infiltration of liquid effluents from the BH into the soil. On the other hand, the chromium concentration of the samples Et, S2 and St are negligible (below the

standard); this could be explained for S2 by the fact that during the treatment of the sludge on this soil, a good part of the chromium was eliminated.

4.4. Results of the analysis of heavy metals in food

4.4.1. Iron

Iron is an essential element for humans and other organisms. The concentration of iron in cassava is zero, while it is above the limit value in macabo. This high concentration could be due to the absorption of iron from the soil by the plant roots or by watering the plant with copper-contaminated water. Excess iron causes digestive disorders in humans (O. P. S. 1987).

4.4.2. Copper

Copper is an essential trace element for life [24]. The copper concentration in cassava is above the limit value. This high concentration could be due to the absorption of copper from the soil by the roots of the plants or by watering the plants with copper-contaminated water. Copper in high doses and in its oxide forms is a poison for humans [25].

4.4.3. Zinc

Zinc in small amounts is necessary for plants and humans. The concentration of zinc in cassava is lower than the norm, while in macabo it is high. Zinc in high doses causes nausea, gastrointestinal disorders, respiratory disorder and skin effect [26].

4.4.4. Other metals

The presence of rubidium, titanium, zirconium in tubers is noted, but the regulations do not refer to the limit of concentrations of these metals in food. The presence of these metals in food could be due to their absorption in contaminated soil by the roots of these plants. Studies have shown that the consumption of these metals could cause cancer [27].

Heavy metals pose significant health risks due to their toxicity. They can accumulate in the body, leading to various acute and chronic effects, including gastrointestinal issues, kidney dysfunction, neurological disorders, and cancer. Exposure routes include ingestion, inhalation, and dermal contact, often linked to industrial activities and contaminated food or water sources. Symptoms vary by metal and exposure duration, with children being particularly vulnerable. Treatment typically involves chelation therapy to remove metals from the body [28–30].

Young people (infants, toddlers, children) may be more sensitive than adults to dietary exposure containing concentrations of heavy metals in excess of standards. Although they are more fragile than adults, the standards set the same values for both categories, with a few exceptions. According to the Food and Drug Administration maximum daily limit for lead in children's food and reduced it by half. For adults, the limit is 12.5 μg/day to protect against fetal exposure and reduce infant exposure during nursing.

Table 10
Matrix of correlations between physico-chemical parameters of water.

Variables	pH	conductivity	Fe	Cu	Zn	Hg	Cd	As	Cr	Pb	Ca^{2+}	Na^{+}	K^{+}	NH^{4+}	Mg^{2+}	SO_4^{2-}	Cl^{-}	NO_3^{-}	PO_4^{3-}
conductivity	0.993	1																	
Fe	0.518	0.453	1																
Cu	-0.994	-1.000	-0.450	1															
Zn	0.703	0.623	0.911	-0.626	1														
Hg	0.664	0.583	0.933	-0.585	0.998	1													
Cd	0.401	0.357	0.964	-0.351	0.772	0.805	1												
As	0.688	0.603	0.530	-0.613	0.831	0.800	0.288	1											
Cr	0.967	0.932	0.570	-0.936	0.807	0.768	0.401	0.850	1										
Pb	0.708	0.626	0.893	-0.629	0.999	0.995	0.745	0.854	0.818	1									
Ca2+	0.884	0.849	0.855	-0.847	0.905	0.894	0.776	0.672	0.882	0.896	1								
Na+	0.855	0.797	0.481	-0.805	0.791	0.750	0.259	0.957	0.955	0.812	0.754	1							
K+	-0.026	-0.113	0.829	0.114	0.665	0.711	0.818	0.304	0.097	0.648	0.427	0.113	1						
NH4+	-0.089	-0.148	0.801	0.154	0.535	0.590	0.867	0.062	-0.033	0.508	0.387	-0.089	0.957	1					
Mg2+	0.925	0.929	0.682	-0.925	0.709	0.691	0.651	0.478	0.842	0.697	0.941	0.648	0.157	0.186	1				
SO2-4	0.628	0.532	0.707	-0.540	0.926	0.910	0.494	0.967	0.798	0.940	0.735	0.886	0.535	0.315	0.498	1			
Cl-	0.526	0.458	0.999	-0.455	0.927	0.948	0.950	0.567	0.589	0.911	0.858	0.513	0.830	0.788	0.674	0.740	1		
NO3-	0.569	0.482	0.365	-0.493	0.708	0.674	0.105	0.978	0.754	0.737	0.505	0.913	0.211	-0.060	0.303	0.916	0.408	1	
PO3-4	0.343	0.282	0.978	-0.277	0.812	0.846	0.985	0.365	0.386	0.788	0.742	0.290	0.896	0.905	0.565	0.577	0.970	0.201	1

4.5. Data proccessing

4.5.1. Contamination index

According to Table 9, all water sampling points in the BATOKE River downstream of the landfill at the landfill and upstream of the landfill have a very high pollution load of iron, zinc, chromium, lead and cadmium. This would reflect the impact of the landfill on the chemical composition of the BATOKE River water.

The comparison of the classification of the sampling points according to their average water contamination indices gives the following decreasing order of contamination: At the landfill > Downstream of the landfill > Upstream of the landfill.

Soil sampling points at the landfill entrance, at the BH treatment area and at the PSD disposal area have a very high pollution load of iron, zinc, copper, nickel, chromium and lead. This would reflect the impact of this landfill on the soil. The comparison of the classification of the sampling points according to their average soil contamination indices gives the following decreasing order of contamination: BiH treatment area > landfill entrance > PSD disposal area.

4.5.2. Correlation matrix

Examination of the correlation matrix (Tables 10 and 11) between variables reveals that the linear correlations are either positive or negative (meaning that these variables vary on average in both directions):

✓ Some have a perfect correlation (coloured in purple "1") namely:
- **conductivity/Cu** (Table 10): this could be explained by the abundance of copper in the water; the higher the concentration of heavy metals in the medium, the higher the conductivity
- **Pb/Rb et Rb/Zr** (Table 11): this correlation between the elements could be explained by their common source which is oil sludge;

✓ Others have a very strong correlation (coloured in red "0.9") namely:
- **pH/Conductivity** (Table 10): this correlation could be explained by the fact that when the pH increases the conductivity decreases;
- **conductivity/Cr** (Table 10): this correlation could be explained by the fact that the higher the conductivity of a medium, the greater the presence of heavy metals;
- NO_3^-/SO_4^{2-} (Table 10); this correlation could be due to natural denitrification of nitrate in the presence of iron increases the sulphate;
- K^+/NH^{4+} this correlation could be justified by the fact that these two elements could come from fertilizers;

✓ Other elements have average correlations (coloured in blue "0.7 to 0.8") namely:
- **pH/Ca^{2+}** (Table 10): dissolution of calcite could lead to an increase in pH;
- **Cu/Ni, Ar et Ni/Cr** (Table 11); these correlations between metals could be explained by their common sources;

✓ Other elements have low correlations (coloured in green « 0.5 »);
- **pH/Cu, Ni, As** (Table 10); **pH/Ni, As, Cr** (Table 11): This could be explained by the fact that the mobility of these metals could be favoured by the variation of the pH;
- pH/NO_3^- (Table 10): this relationship could be explained by the fact that the presence of nitrate ions could increase the pH;

Table 11
Matrix of correlations between physico-chemical parameters of sludge, soil and tubers.

Variables	pH	conductivity	Hydrocarbures T	Fe	Cu	Ni	As	Cr	Pb	Ca	Rb	Ti	Zr	K
pH	1													
conductivity	-0.137	1												
Hydrocarbon T	0.577	-0.543	1											
Fe	0.351	-0.246	0.090	1										
Cu	0.621	-0.441	0.831	0.234	1									
Ni	0.600	-0.181	0.842	0.191	0.791	1								
As	0.569	-0.256	0.676	-0.042	0.884	0.561	1							
Cr	0.576	0.207	0.565	0.192	0.585	0.899	0.435	1						
Pb	0.158	0.408	-0.195	-0.277	-0.173	-0.298	0.259	-0.073	1					
Ca	0.407	0.172	0.273	0.464	0.599	0.681	0.384	0.785	-0.311	1				
Rb	0.152	0.410	-0.200	-0.282	-0.179	-0.303	0.255	-0.077	1.000	-0.315	1			
Ti	0.312	-0.148	0.004	0.991	0.193	0.170	-0.077	0.218	-0.275	0.527	-0.279	1		
Zr	0.160	0.416	-0.200	-0.266	-0.175	-0.296	0.256	-0.066	1.000	-0.302	1.000	-0.263	1	
K	-0.326	0.390	-0.366	-0.491	-0.374	-0.527	0.073	-0.351	0.869	-0.513	0.872	-0.482	0.867	1

Values in bold and in colour are significantly different from 0 at the alpha=0.05 significance level

- **conductivité/Zn, Hg, As, Pb** (Table 10): this correlation could be explained by the fact that the higher the conductivity of a medium, the greater the presence of heavy metals.
- **Cu/Zn, Hg, As** (tableau **10**): **Cu/Cr** (Table 11) these correlations between metals could be explained by their common sources;

✓ Tables 10 and 11 show that all parameters that have the matrices coloured in black have no correlation.

5. Conclusion

This investigation aimed to evaluate the ecological repercussions of the BATOKE oil sludge landfill on water, soil, and food, to conform to the landfill management regulations, or ultimately, shutter and rehabilitate the site. This endeavour encompassed on-site inspections to gauge the situation; sampling and characterization of the sludge enabled the identification of various pollutants comprising the sludge and their harmful nature; analysis of the physical properties of the water and soil indicated compliance with established standards. Nevertheless, chemical parameter assessments unveiled elevated concentrations of iron, copper, zinc, nickel, chromium, lead, cadmium, arsenic, and mercury in the water and soil, surpassing stipulated standards. Furthermore, chemical evaluations ascertained the presence of iron, copper, and zinc levels exceeding the standards in food items, with additional hazardous metals such as zirconium, titanium, and rubidium detected in these foodstuffs. In light of the analysis outcomes, it is evident that the landfill exerts adverse effects on its immediate surroundings and potentially on the resident population through the consumption of water and food.

CRediT authorship contribution statement

Mefomdjo Fotie Blanche: Writing – original draft, Investigation, Formal analysis. **Elhadji Daou Ibrahim:** Writing – original draft, Visualization, Resources. **Boukari Harouna:** Writing – original draft, Visualization, Resources. **Kapta Momegni Christian:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Funding acquisition, Formal analysis, Data curation. **Raihanatou Amadou:** Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation. **Tchuikoua Louis Bernard:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mambou Ngueyep Luc Leroy:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors certify that there's no financial/personal interest or belief that could affect their objectivity and there is NO **Conflict of Interest.**

References

[1] Claude Jean, et al., L'incidence des facteurs démographiques sur la consommation d'énergie. Application au cas français. Population, JSTOR, May-Jun., 1981, pp. 505–518, https://doi.org/10.2307/1532618. French Edition), vol.36, N°3.
[2] Mbaye Bass and Bertrand Tchanche, Analyse de la gouvernance Africaine du secteur de l'énergie, Revu des énergies Renouvelable 23 (2020) 86–108, 2020.
[3] Adebayo J. Olufemi, Chioma Affam Augustine, Petroleum sludge treatment and disposal: a review, Environ. Eng. Res. 24 (2) (2018) 191–201, https://doi.org/10.4491/eer.2018.134, 2019.
[4] M. Hawrot-paw, A. Nowak, Attempt at mathematical modelling of the process of microbiological biodegradation of diesel oil, Environ. Prot. Eng. 38 (2012) 23–29.
[5] International Energy Agency (IEA), Oil Market Report, International Energy Agency, Paris, France, 2019.
[6] S. Manish, al, Source and control of hydrocarbon pollution. Hydrocarbon Pollution and its Effect on the Environment, 2019. IntechOpen.
[7] L.S. Gina, Y. Trihadiningruma, C.S. Farradina, A.F. Hadiningb, IdentificationofTotalPetroleumHydrocarbonandHeavyMetalsLevels in crude oil contaminated soil at Wonocolo public mining, EnvironmentAsia 11 (2) (2018) 109–117, https://doi.org/10.14456/ea.2018.26. ISSN 1906-1714; ONLINE ISSN: 2586-8861.
[8] S. Zahermand, M. Vafaeian, M.H. Bazyar, Analysis of the chemival properties of soil contaminated with oil (petroleum) hydrocarbons, Earth Sci. Res. J. 24 (2) (2020) 163–168, https://doi.org/10.15446/esrj.v24n2.76217.
[9] M. Mahmood, al, Environmental site assessment of AlDaura refinery – evaluation of oil pollution with petroleum products, Eng.&Tech.Journal 28 (2010) N°20, 2010.
[10] Olulakin Adesina Gabriel, Kasali Amofe Adelasoye, Effect of crude oil pollution on heavy metal contents, microbial population in soil, and maize and cowpea growth, Agric. Sci. 5 (No.1) (2014) 43–50, https://doi.org/10.4236/as.2014.51004, 2014.
[11] U.I. Uquetan, J.E. Osang, O. EgorA, A. EssokaP, S.I. Alozie, A.M. Bawan, A case study of the effects of oil pollution on soil properties and growth of tree crops in cross river state, Nigeria, International Research Journal of Pure and Applied Physics 5 (No.2) (2017) 19–28. June 2017.
[12] O. Asem Samira, R.F. Miak, A. Alenezi, W. Roy, S.A. Shahidi, M. Al-Awadi, Effects of crude oil on some soil types of Kuwait, Kuwait J. Sci. 43 (4) (2016) 150–161.
[13] Olga Victorovna Gladkova and al, Effects of pétroleum on soil. https://encyclopedia.pub/entry/24868, 2021.
[14] E.S. Edori, O.S. Edori, D. Bekee, Total petroleum hydrocarbons contamination of the surface water and sediments of orashi river, engenni, ahoada west, rivers state, Nigeria, Asian Review of Environmental and Earth Sciences 8 (1) (2021) 68–76, https://doi.org/10.20448/journal.506.2021.81.68.76, 2021 ISSN(E) 2313-8173/ISSN(P) 2518-0134.
[15] Mendxue Hu, Environmental behavior of petroleum in soil and its harmfulness Analysis. IOP conf. Ser, Earth Environ. Sci. 450 (2020) 012100.
[16] S. Jerez, M. Ventura, R. Molina, M.I. Pariente, F. Martínez, J.A. Melero, Comprehensive characterization of an oily sludge from a petrol refinery: a step forward for its valorization within the circular economy strategy, J. Environ. Manag. 285 (2021) 112124.
[17] A. Aguelmous, L. El Fels, S. Souabi, M. Zamama, M. Hafidi, The fate of total petroleum hydrocarbons during oily sludge composting: a critical review, Rev. Environ. Sci. Biotechnol. 18 (2019) 473–493.

[18] Wagassi G. Guandji, , et al.B. Tiger, Recent Development in the Treatment of Oily Sludge Frorm Petvroleum Industry, vol. 261, 2013, pp. 470–490.
[19] S.A. Uzoekwe, F.A. Oghosanine, The effect of refinery and petrochemical effluent on water quality of Ubeji creek warri, Southern Nigeria, Ethiopian Journal of Environmental Studies and Management 4 (No.2 2011) (2011).
[20] L.S. Gina, Y. Trihadiningruma, Ni matuzahroh, Petroleum hydrocarbon pollution in soil and surface water by public oil fields in Wonocolo sub-district, Indonesia, Journal of Ecology Engineering 19 (2) (2018) 184–193, https://doi.org/10.12911/22998993/82800. March 2018.
[21] Samuel O. Akporido, Percy C. Onianwa, Heavy metals and total petroleum hydrocarbon concentrations in surface water of esi river, western Niger delta, Res. J. Environ. Sci. 9 (2015) 88–100.
[22] L. Zhang, P. Zhou, S. Cao, Y. Zhao, Atmospheric mercury deposition over the land surfaces and the associated uncertainties in observations and simulations: a critical review, Atmos. Chem. Phys. 19 (2019) 15587–15608, https://doi.org/10.5194/acp-19-15587-2019, 2019.
[23] Aryeh Feinberg, Thandolwethu Dlamini, Martin Jiskra, Viral Shah, Noelle E. Selin, Evaluating atmospheric mercury (Hg) uptake by vegetation in a chemistry-transport model, Paper) Environ. Sci.: Process. Impacts 24 (2022) 1303–1318, https://doi.org/10.1039/D2EM00032F, 2022.
[24] J.E. Fergusson, The Heavy Elements:chemistry, Environmental Impact and Health Effets, vol. 1, Pergamon Press, Oxford, 1990, p. 614.
[25] Geoffrey Plumlee, Morman Suzette, Ziegler Thomas, The toxicological geochemistry of earth materials: an overview of processes and the interdisciplinary methods used to understand them, Rev. Mineral. Geochem. 64 (2006) 5–57.
[26] M. Maywald, L. Rink, Zinc in human health and infectious diseases, Biomolecules 12 (2022) 1748, https://doi.org/10.3390/biom12121748.
[27] L. Parida, T.N. Patel, Systemic impact of heavy metals and their role in cancer development: a review, Environ. Monit. Assess. 195 (6) (2023 May 30) 766, https://doi.org/10.1007/s10661-023-11399-z. PMID: 37249740.
[28] M. Balali-Mood, K. Naseri, Z. Tahergorabi, M.R. Khazdair, M. Sadeghi, Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic, Front. Pharmacol. (2021), https://doi.org/10.3389/fphar.2021.643972. PMID: 33927623; PMCID: PMC8078867.
[29] Elena Loredana Ungureanu, Gabriel Mustatea, Toxicity of heavy metals. Environmental Impact and Remediation of Heavy Metals, IntechOpen, Rijeka, 2022, https://doi.org/10.5772/intechopen.102441.
[30] Saikat Mitra, Arka Jyoti Chakraborty, Abu Montakim Tareq, Talha Bin Emran, Firzan Nainu, Ameer Khusro, Abubakr M. Idris, Mayeen Uddin Khandaker, Osman Hamid, Fahad A. Alhumaydhi, Jesus Simal-Gandara, al, Corrigendum to “Impact of heavy metals on the environment and human health: novel therapeutic insights to counter the toxicity”, J. King Saud Univ. Sci. 35 (7) (2023) 102823. October 2023.