Heliyon 10 (2024) e28032

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Impacts of gas flaring on soil physicochemical and microbial properties: A case study on kailashtila gas field

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ARTICLE INFO

Keywords:
Gas flaring
Soil quality
Heavy metal contamination
Health risk assessment

ABSTRACT

Gas flaring, a common practice in many countries, has been associated with environmental and health concerns. A recent study in Bangladesh's largest gas field, Kailashtilla, assessed the influence of gas flaring on soil quality in the surrounding areas. Physical, chemical, and microbiological characteristics were assessed on soil samples collected from three union zones. Considerable influences have been found on soil quality, with several physical and chemical characteristics failing to meet the standards for healthy plant growth. Heavy metal contamination in the earth's soil was identified, specifically cadmium and lead, having a risk index indicating a moderate risk to the ecosystem in the future. Gas flaring also impacted the amount of bacteria in the soil, with the highest number being found farthest from the flaring zone. The soil was only marginally contaminated and potential health risks found. AAS and digestion methods were used to estimate the content of heavy metal contamination in the soil. To depict the geographically distributed abundance of heavy metals in the study area, the Kriging spatial interpolation procedure was utilized, and PCA and CA were used to assess the condition of soil. Findings indicate that particular gas flaring may have a deleterious influence on soil bacteria, which could have further consequences for the ecosystem. The study is likely to contribute to our understanding of the current state of soil's surrounding gas fields and serve as a platform for future research in this area emphasizing the necessity for sustainable energy methods and the importance of limiting environmental repercussions.

1. Introduction

The burning of natural gas used in oil extraction is referred to as gas flaring. The combustion of petroleum-based products, mostly oil, gas, and coal, has warmed the planet by producing carbon dioxide, the principal greenhouse gas [1]. Nitrogen, carbon, hydrocarbons, sulfur oxide, particulate matter, hydrogen sulfide (H_2S), ash, and photochemical oxidants are among the pollutants discharged into the environment because of gas flaring [2,3]. One of the most difficult issues currently facing the world is gas flaring [4]. Gas flaring is a method of getting rid of waste gases that naturally arise during the refining of crude oil through the top of a pipe or stack where the burner and igniters are positioned [5]. This flare is emitting roughly 2,52,500 tons of carbon and other pollutants each day around the world, which poses a threat to nearby communities [6]. According to the World Bank's (WB) 2022 Global Gas Flaring

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https://doi.org/10.1016/j.heliyon.2024.e28032
Received 20 August 2023; Received in revised form 17 February 2024; Accepted 11 March 2024
Available online 15 March 2024
2405-8440/

Tracker report, thousands of gas flares at oil producing facilities around the world burned almost 139 billion cubic meters of gas in 2022. 350 million tons of CO_2 equivalent emissions are produced annually by gas flaring throughout the world, along with 42 million tons of unburned methane. The short-term climate impact of methane exceeds that of CO_2 by almost 80 times. Flaring is ineffective and preventable, with the potential to replace more harmful fuels. Additionally, it releases black carbon, which hastens the melting of the Arctic ice and accounts for up to 40% of annual deposits [7]. Flaring gases can mix with soil in several ways such as direct deposition, soil aeration, soil leaching, and rainfall. Enuenwemba (2021) reported gas flaring impacts in Delta State, Nigeria: changed soil properties, elevated ECEC, varying heavy metals concentration, and acidic pH [8]. Bangladesh is now known as a vital player in the global energy market because of its large natural gas reserves. The eastern part of Bangladesh has so far been home to the discovery of 80% of Bangladesh's gas reserves. Bangladesh currently has 28 natural gas fields. However, not all of Bangladesh's gas fields exhibit a sign significant ring. The World Bank's (WB) 2022 Global Gas Flaring Tracker report says in 2021, Kailastila, a Petrobangla-operated flaring field, has the biggest gas burn rate at 18.28 million cubic meters (mcm) [9]. The government has established a favorable tax regime for oil and gas exploration activities and has provided subsidies for the development of the country's infrastructure, such as pipelines and storage facilities [10]. The government has reformed the legal and regulatory framework to provide greater stability and security for international investors. This has helped to attract international investment and has facilitated the development of Bangladesh's oil and gas industry [11]. The immediate consequences of gas flaring and venting are detrimental, particularly for ecological development and biodiversity [12]. Due to the acidity of the soil caused by several contaminants linked to gas flaring in the area, the soils of the gas flaring area are rapidly losing their productivity as well as their ability for long-term farming [13]. Odu et al. (2019) found that gas flaring in Niger Delta significantly altered soil microbial communities, impacting soil health and fertility [14]. Flare systems emit a variety of pollutants, both inorganic and organic, into the environment in addition to thermal pollution caused by gas dispersion [15]. Okoh and Osuji (2019) observed gas flaring led to higher heavy metals, lower microbial activity, and degraded soil properties, emphasizing environmental concerns [16]. It has been claimed that an increase in temperature induced by gas flares reduced agricultural output and altered the natural environment [17]. The changed microenvironment in terms of the flare site's air and temperature, relative humidity, soil moisture, and other soil chemical variables influenced not only maize germination but also extension and agricultural productivity [13]. According to Motte et al. (2021), Gas flaring has great impact on the public health that quantified using life cycle assessments and revealed significant disability-adjusted life years (DALYs) burdens. It also found that flaring contributes significantly to both air pollution and climate change-related DALYs [18]. Gas flaring effects both physico-chemical and microbial parameters of environment and so far no such research is found based on the study area. The urgent need to address the

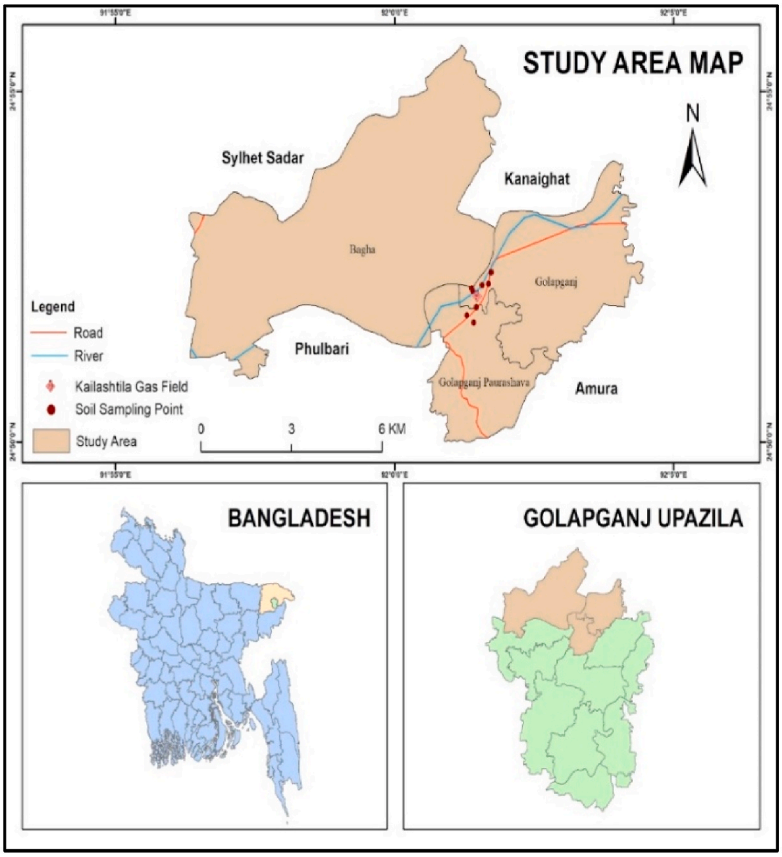

Fig. 1. The study area map.

major environmental and public health consequences of gas flaring in Bangladesh's largest flaring field is the reason that motivates the investigation's conduct. The following were the investigation's main goals: (i) Determining the physicochemical state of soil near the gas flaring area, (ii) Determining the microbiological makeup of soil near the gas flaring area, and (iii) Assessing the risk of heavy metals to human health.

2. Materials and procedures

2.1. Area of study

Kailashtila gas field, placed in Golapganj Union, Golapgonj Upazila, Sylhet district, is one of the largest. Golapganj upazila is in Bangladesh's north-eastern region, between 24°41′ and 24°55′ north latitudes and 91°55′ and 92°06′ east longitudes. The overall area of Golapganj, including all physical elements and land usage, is approximately 278.34 square kilometers. However, due to their proximity to the flaring region, samples were taken from three Unions. Golapganj Union, Golapganj Pourasava Union, and Bagha Union were the three unions. Five samples were taken from Golapganj Union, three from Golapganj Pourasava Union, and one from very close to the Bagha Union boundary. Near this region of flare, soil samples have been gathered (see Fig. 1).

2.2. Collecting soil samples and testing in laboratories

Eight soil samples were collected from the Kailashtila gas field location on October 9th, 2022. The eight soil samples were gathered from different places around the flare-up region using normal soil sampling techniques, with care made to verify that the samples were representative of the soil conditions at each site. A Polyvinyl Chloride (PVC) corer was used to gather samples ranging in depth from 0 to 0.2 m. All positions were recorded using a portable Global Positioning System (GPS). Before collecting samples, plastic bags were washed with water from distillation. It was done in clean, dust-free environments. Soil Moisture Content (SMC) was measured using a Time-Domain Reflectometer 100 (TDR). The total Nitrogen content of the soil was determined with Meso Kelvin. A flame photometer was used to determine Sodium concentration. Using Ultra-Violet (UV) spectrophotometer chemical parameters like calcium, magnesium, potassium, phosphorus, and manganese concentration were assessed. Before distillation, the samples were placed in a changing heat burner with concentrated H_2SO_4 and an accelerator, and the distillate was measured by titration with a 0.01 mol per liter hydrogen chloride solution as a standard. The acidity (pH) of the soil's surface was tested using a 1:5 soil-to-water solution following a 2-h period of mixing thoroughly. AAS was used for measuring concentrations of iron, copper, and zinc. The mixtures were cleaned with Whatman no. 42 filtration before being moved to a cone-shaped flask for AAS measurement of nickel, cobalt, lead, chromium, and cadmium concentrations. Pour plating method was used for the bacterial count.

3. Data analysis

Data analysis is a crucial step in understanding and interpreting data, and it involves various methods to look at, manipulate, and display the data to gain insights and make informed decisions [19]. The outcomes of data mining are evaluated on a regular basis for the purpose of obtaining better knowledge of the data as well as deciding what next steps to take. Multivariate analysis is a data analysis method that is useful in examining complex datasets with several variables. Cao et al. (2018) proposed this strategy as a useful approach for investigating soil conditions around gas flaring. Geostatistical analysis is another of analyzing soil data that is used to understand spatial variability. When paired with multivariate analysis, this technique provides a thorough understanding of soil characteristics and aids in making informed judgments [20]. The assessment of metal-related health concerns in the soil is an important component of soil investigation because it helps determine the possible hazards that heavy metals bring to the health of people [21–23]. The USEPA technique (the United States Environmental Protection Agency) is commonly employed in this context since it provides a consistent and scientifically-based approach to determining the health concerns related to contaminants such as heavy metals in soil [24–29].

3.1. Statistical assessment

To assess the relationship between the presence of metallic substances in soils and their most likely origins, the correlation coefficient analysis of Pearson and the principal component analysis (PCA) were utilized [30]. It occurred while running the popular statistics program SPSS version 26.0 for Microsoft. The coefficient of correlation quantifies the amount of force that exists between the two metallic substances. PCA is a multidimensional method of analysis applied to minimize the number of initial parameters to identify a limited number of hidden elements (principal components, PCs) and investigate heavy metal relationships. The analysis of clusters (CA) is a set of statistical methods used for categorizing items based on the characteristics that appear to be most significant to them [31]. It groups objects to ensure every component in the cluster has the same determination criteria as the others.

3.2. Assessment of correlation

A correlation analysis was performed to assess how effectively the heavy metal sources were connected to one another and to discover the causes of heavy metal pollution in relation to one another. The significant relationship between distinct components indicates that metallic substances have a strong association or homology [32–34]. The correlation coefficient analysis of Pearson was utilized in this correlation analysis to demonstrate the links between the heavy metals it contained. A correlation coefficient around 1 or -1 denotes an intense association, whereas a coefficient near 0 denotes an insufficient connection [35]. Pearson correlation tests were employed in this work to examine the correlations within the heavy metals contained.

3.3. PCA (principal component analysis)

PCA attempts to generate extra independent variables from the initial principal component. The primary components can be represented by the equation

$$zij = ai1x1j + ai2x2j + ai3x3j + \dots \dots \dots \dots + aimxmj$$

where z denotes the component score, a is the component loading, x is the variable's observed value, i is the element number, j is the sample quantity, and m is the overall number of variables. The main elements are directly equivalent to the sum of starting components and eigenvectors [36,37]. The revolving strategy was employed in this investigation to determine the primary component that describes data fluctuation.

3.4. The cluster analysis (CA)

CA tries to cluster data sources while the actual components of the clusters are unknown [38]. A dendrogram is an example of a graph that demonstrates remarkable comparison among any number of samples and the whole collection of data [39]. The fundamental goal of a dendrogram is to demonstrate a hierarchical framework of groupings discovered via related studies [40].

3.5. Geostatistical analysis

Kriging is a geostatistical technique of interpolation that calculates the entire space's spatial variability. The semivariogram generated from sampling attributes is used to investigate the effects of sample data locations on the calculated value of attributes [41,42]. Because of its impartial qualities and benefits, kriging has frequently been used in geostatistical approaches [43]. As a result, Kriging has been used in the spatial analysis of heavy metallic compound pollution in soil [44].

3.6. Assessment of pollution

3.6.1. Index of geoaccumulation

For the purpose of assessing heavy metal pollution in the soil, the geo-accumulation index (Igeo) was utilized. This method was used to evaluate soil pollution [45,46]. The formula is defined as follows:

$$I_{geo} = \log 2\,[C_n / (1.5 \times B_n)]$$

Where, C_n represents the concentration of the metal measured in soil samples in the study area, and B_n represents the background value of the corresponding metal. The I_{geo} is classified into six grades [47]. These are given in Table 1.

3.6.2. Factors of contamination

A contamination factor (Cf) is a tool that can calculate the contamination of dangerous substances. The Cf can be calculated using the formula below.

$$Cf = C_{metal}/\ C_{background}$$

In where Cf denotes the contamination factor determined in terms of a particular metal content, C_{metal} is the element's concentration in each soil sample, and $C_{background}$ denotes the background value of that particular metal. $Cf < 1$ is regarded low; $1<Cf < 3$ is considered medium; $3<Cf < 6$ is considered significant, and $Cf > 6$ is considered excessive [48].

Table 1
Six degree of I_{geo}.

Geo-accumulation Index		
Class	Value	Classification
0	<0	Uncontaminated
1	0–1	Uncontaminated to Moderately Contaminated
2	1–2	Moderately Contaminated
3	2–3	Moderately to Strongly Contaminated
4	3–4	Strongly Contaminated
5	4–5	Strongly Contaminated to Extremely Contaminated
6	>5	Extremely Contaminated

3.6.3. Factors of enrichment

Metal Enrichment Factors (EF) are measures of the existence and severity of human-caused metal formation on the soil's surface [49]. The standardizing technique employs an established metal concentration. Fe and Al are among the most commonly utilized standard elements owing to their broad abundance and absence of interaction with other pollutants [50]. The enrichment factor was calculated using the equation below:

$$EF = (C_n/C_{ref})\ \text{sample} \ / \ (C_n/C_{ref})\ \text{baseline}$$

Here, C_n is the metal concentration and C_{ref} is the concentration of reference element (Fe). Sample and baseline indicate soil samples and background, respectively. To normalize a pair of data derived from the Metal-Iron ratio of the sample and the surrounding background, the element iron (Fe) was employed [51,52]. When $EF < 2$ that denotes no enrichment to minor enrichment; $2 \leq EF < 5$ denotes as enrichment that is mild; $5 \leq EF < 20$ refers to severe enrichment; $20 \leq EF < 40$ rates as very severe enrichment and $EF > 40$ suggests extreme severe enrichment in soil [50].

3.7. Health risk assessment

The USEPA's algorithm for estimating individual intake of heavy metals and health issues accounts for both carcinogenic and non-carcinogenic risks. The chronic daily intake (CDI; mg/kg/day) of heavy metals in soil was determined using formulas for ingestion (CDI_{Ing}), dermal contact (CDI_{Derm}) and inhalation (CDI_{Inh}) for children and adults [24–27],

$$CDI_{Ing} = \frac{C_{soil}.\ R_{ing}.\ EF.\ ED}{BW\ .\ AT}\ .\ 10^{-6} \quad CDI_{Derm} = \frac{C_{soil}.\ SA\ .\ AF\ .\ ABS\ .\ EF\ .\ ED}{BW\ .\ AT}\ .\ 10^{-6} \quad CDI_{Inh} = \frac{C_{soil}\ .\ EF\ .\ ET.\ ED}{BW\ .\ AT\ .\ PEF}\ .\ 10^{-6}$$

Where.

C_{soil} = concentration in soil (mg/kg)
R_{ing} = Rate of ingestion (Adult- 100 mg/day; child- 200 mg/day)
EF = Exposure Frequency (350 d/a)
ED = Exposure Duration (Adult-24years; Child-6years)
ET = Exposure time (24 h/d)
BW = Body weight (adult-70kg; child-15kg)
AT = Average Time (365 × ED)
SA = Exposed Skin Area (5700 cm^2)
AF = Adherence Factor (0.07 mg cm^{-2})
ABS = Dermal Absorption Fraction (As-0.03; Other metals-0.001)
PEF = Particle emission factor (1.36 × 109 $m^3 kg^{-1}$)

The hazard index (HI) is a typical method in estimating the cumulative non-carcinogenic danger posed by several heavy metal infections in humans. The hazard index (HI) is calculated by adding the hazard quotients (HQs) for each heavy metal. The HQ is a non-carcinogenic danger indicator calculated by dividing the heavy metal's chronic daily intake (CDI) by its chronic reference dose (RfD).

$$HQ = CDI\ /\ RfD$$

$$HI = \sum HQ$$

The RfD is a measure of a heavy metal's daily exposure that is estimated to generate no negative health impacts over a person's entire life of the contact. The RfD is expressed in mg/kg/day and is specific for each heavy metal. The RfDs for various heavy metals listed in the equation are Cu - 0.0371, Co - 0.02, Fe - 0.7, Pb - 0.0035, Zn - 0.3, Cr - 0.003, Cd - 0.001, Ni - 0.0008, and As - 0.0003.

It is important to understand that a number of heavy metals, such as As, Cd, Cr, and Pb, are categorized as carcinogenic, whilst others, such as Fe, Zn, Cu, Ni, and Co, are not. This information should be considered when assessing the health concerns presented by heavy metal exposure.

The hazard index (HI) is a method for assessing the possible non-carcinogenic health concerns provided by numerous heavy metal exposures. If the HI is less than one, negative health impacts are unlikely. If the HI is more than one, however, there is a probability of non-carcinogenic health impacts, and the likelihood of effects grows with higher HI values.

Heavy metal intake's carcinogenic risk (CR) is calculated by multiplying the chronic daily intake (CDI) by the carcinogenicity slope factor (SF). The SF values for Cd, Cr, Pb, and As are 6.3, 0.5, 0.0085, and 1.5 mg/kg/day, respectively. The cumulative lifetime probability of cancer (LCR) is calculated by adding the CR for each individual heavy metal.

$$CR = CDI \times SF$$

$$LCR = \sum CR$$

If the CR is less than 10^{-6}, the possibility of developing cancer from contact with soil becomes minimal. If the CR falls in the range of 10^{-6} to 10^{-4}, it seems to offer an acceptable danger to humans. However, if the CR is greater than 10^{-4}, It is thought to pose a significant danger of cancer development in people. The acceptable limit for CR is 10^{-4}, and the tolerable range for LCR is from 10^{-6} to 10^{-4} [24,25,25–28].

Table 2
SMC, pH, EC, Total Nitrogen, concentration of heavy metals (mg/kg) and background value (mg/kg).

Parameters	MC	pH	EC	Na	Mg	Ca	K	P	N	Ni	Co	Cd	Cu	Zn	Cr	Pb	As	Mn
mean	14.53375	5.1125	0.03	0.6775	23.81	2.6225	1.0625	0.9725	0.08925	0.22325	0.2095	0.078625	1.46	0.14625	0.047875	9.5975	0.006875	0.056791
max	16.79	6.8	0.08	0.81	28.18	4.96	1.5	1.85	0.154	0.322	0.54	0.094	3.11	0.26	0.084	14.12	0.025	0.078187
min	12.16	3.7	0	0.57	19.44	1.12	0.4	0.39	0.054	0.149	0.031	0.061	0.63	0.01	0	7.02	0	0.04649
SD	1.689556	0.976053	0.027255	0.087953	2.64797	1.471217	0.329231	0.489774	0.034829	0.057539	0.157151	0.011526	0.779817	0.109406	0.03127	2.261881	0.008425	0.00998
CV	11.62505	19.09149	90.85135	12.98198	11.12125	56.09978	30.98642	50.36237	39.02429	25.77354	75.01218	14.65894	53.41211	74.80743	65.31681	23.5674	122.5468	17.57271
Background										33.7	17.1	0.13	25.7	82.4	86.6	29.3	13.3	591

Table 3
Heavy metal Pearson correlation coefficients.

	PH	MC	EC	Cu	Zn	Mn	Cr	Ni	Co	Cd	Pb	As	Na	Mg	K	P	N	Ca	Fe	Bacteriacount
PH	1																			
MC	0.690	1																		
EC	−0.628	−0.174	1																	
Cu	−0.471	−0.705	0.216	1																
Zn	−0.018	−0.663	−0.139	0.455	1															
Mn	−0.018	−0.663	−0.139	0.455	1.00[a]	1														
Cr	−0.853[a]	−0.719[b]	0.555	0.516	0.239	0.239	1													
Ni	−0.304	−0.360	0.279	0.685	0.400	0.400	0.290	1												
Co	−0.041	0.001	−0.298	−0.108	−0.404	−0.404	−0.103	−0.380	1											
Cd	−0.633	−0.564	0.332	0.395	0.383	0.383	0.532	0.496	−0.606	1										
Pb	−0.045	0.563	0.429	−0.390	−0.730[b]	−0.730[b]	−0.063	−0.012	0.287	−0.394	1									
As	−0.820[b]	−0.287	0.715[b]	0.178	−0.177	−0.177	0.671	0.451	−0.162	0.604	0.435	1								
Na	−0.574	−0.887[a]	−0.030	0.572	0.652	0.652	0.542	0.308	−0.210	0.770[b]	−0.756[b]	0.219	1							
Mg	−0.508	−0.901[a]	0.000	0.700	0.726[b]	0.726[b]	0.660	0.522	0.039	0.412	−0.456	0.233	0.745	1						
K	0.019	−0.148	0.016	0.029	0.543	0.543	−0.032	0.417	−0.835[a]	0.730[b]	−0.440	0.158	0.450	0.119	1					
P	−0.306	−0.449	0.021	0.822[b]	0.090	0.090	0.314	0.247	0.095	0.153	−0.408	−0.095	0.398	0.345	−0.259	1				
N	−0.558	−0.855[a]	0.099	0.721	0.730[b]	0.730[b]	0.650	0.600	−0.403	0.803[b]	−0.637	0.337	0.910[a]	0.835[a]	0.523	0.413	1			
Ca	−0.034	−0.388	0.195	0.195	0.689	0.689	0.214	0.037	−0.738[b]	0.490	−0.674	−0.135	0.496	0.208	0.634	0.067	0.502	1		
Fe	−0.726[b]	−0.262	0.852[a]	0.051	−0.183	−0.183	0.769[b]	−0.002	−0.087	0.274	0.415	0.744[b]	0.042	0.122	−0.166	−0.071	0.114	0.103	1	
Bacteria Count	0.978[a]	0.558	−0.625	−0.434	0.168	0.168	−0.775[b]	−0.291	−0.115	−0.567	−0.173	−0.841[a]	−0.454	−0.378	0.109	−0.335	−0.437	0.124	−0.699	1

[a] Correlation significant at 0.01 level (2-tailed).
[b] Correlation significant at 0.05 level (2-tailed).

4. Results and discussion

4.1. Descriptive statistics

Table 2 displays basic statistical information on geochemical features and contaminants in the soil surrounding the gas flaring area. The mean concentrations of Ni, Co, Cd, Cu, Zn, Cr, Pb, As, and Mn are all significantly lower when compared to the background value, whereas the overall mean concentration of Pb is much greater. In general, the coefficient of variation (CV) value can be divided into 3 categories: less than 10% CV suggests mild variability, 10% < CV < 100% indicates considerable variability and greater than 100% CV denotes moderate to high variability [32,53]. The CV of heavy metals in nearby areas of the Kailashtila gas field showed moderate variability in the sequence of Co > Zn > Cr > Cu > Ni > Pb > Mn > Cd, due to variable climatic conditions and soil quality. But as exhibited in significant variability as CV > 100%.

4.2. Correlation analysis

The interaction between numerous physical, chemical, and microbiological elements in soil, such as soil moisture content, pH, electrical conductivity, nutrients, and heavy metals, was explored in this study. The concentrations of heavy metal components in the examined area are strongly linked to soil base materials and are immediately altered by anthropogenic activities [54,55]. The data were analyzed using Pearson correlation coefficients. Table 3 revealed that Zn and Mn had a perfect positive connection, implying that Zn levels increased as Mn levels increased. A substantial negative connection existed between pH and Cr, As, and Fe, indicating an excessive association. However, pH correlated positively with bacteria, indicating a proportional link. Moisture content correlated negatively with Cr, Na, Mg, and N, indicating an unbalanced connection. Electrical conductivity had a positive correlation with As and Fe, indicating a proportionate relationship. Cu and P had a positive correlation, while Zn and Pb had a strong negative correlation, suggesting disproportionate relationships between these elements. Mg, Zn, and N had positive correlations with Mn, indicating proportionate relationships. Ni did not show any significant correlation with other variables. Co had a significantly negative correlation with P and Ca, indicating an imbalanced relationship. Cd had positive correlations with N, K, and Na, indicating a proportionate relationship. Pb had a strong negative correlation with Zn, Mn, and Na, indicating an imbalanced relationship. As had positive correlations with Fe and EC, while bacteria and pH had a strong negative correlation with As, indicating an imbalanced relationship. Na had a high negative association with MC and Pb and a large positive correlation with Cd and N, indicating asymmetric relationships. Mg correlated positively with Zn, Mn, Cd, Na, and N, demonstrating proportionate relationships between these elements. The existence of all positive relationships implies their homogeneity. It denotes persons who have a pleasant relationship and have some similar qualities. They could have come from the same place.

4.3. Principal component analysis of heavy metals

In order to determine the reason for the decline in soil quality, PCA was employed to explore the relationship between variables and components (see Fig. 2 Scree plot of PCA). The components were identified based on eigenvalues that exceeded one. This analysis revealed the existence of four primary components that met the eigenvalue criterion. Table 4 describes the main components of soil near gas flaring areas with eigenvalues greater than one. More than 0.75, 0.50–0.75, and 0.30–0.50 relative weighting values were used to classify factor loadings as strong, moderate, and weak respectively [56]. Fig. 2 depicts the eigenvalue scree plot, which demonstrates a significant fall after obtaining eigenvalue 1. Table 4 demonstrates that PC1 comprises 36.523% of the overall variance in the soil near gas-flaring areas. Cd and Cr have significant positive loadings in PC1, Ni, and Cu have moderate positive loadings, so PC1 was strongly associated with Ni, Cd, Cu, and Cr. PC2 is tightly associated with Pb and Fe, which have significant positive loadings, whereas As has moderate positive loadings and Zn has moderate negative loadings, and PC2 contributed 25.856% of the overall

Table 4
PCA of heavy metals.

	Component matrix			
Metal	PC1	PC2	PC3	PC4
Component Matrix				
Ni	**0.742**	−0.134	−0.484	0.134
Co	−0.512	0.282	−0.151	**0.710**
Cd	**0.851**	−0.084	0.072	−0.339
Cu	**0.668**	−0.29	0.075	0.584
Zn	0.523	**−0.706**	−0.015	0.052
Cr	**0.751**	0.355	0.419	0.283
Pb	−0.246	**0.846**	−0.348	−0.025
As	0.681	**0.692**	−0.142	−0.1
Mn	−0.33	−0.026	**0.846**	0.021
Fe	0.447	**0.760**	0.343	−0.019
Eigenvalue	3.652	2.586	1.481	1.072
Cumulative variance (%)	36.523	62.378	76.561	87.278
Total variance (%)	36.523	25.856	14.183	10.717

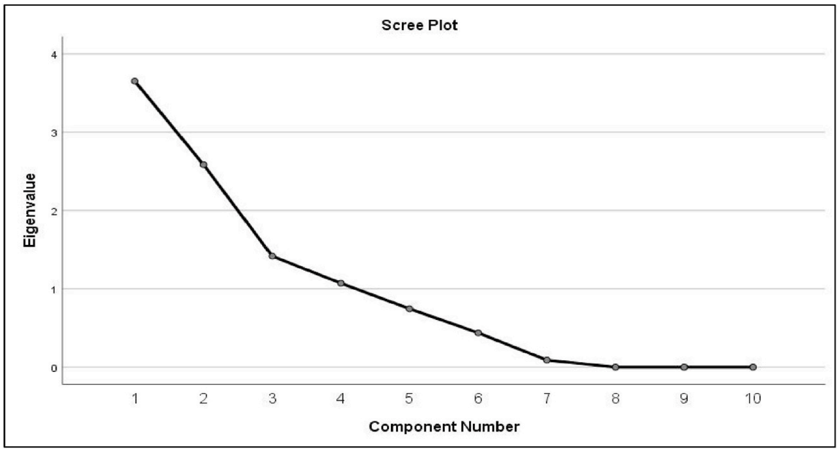

Fig. 2. Scree plot of PCA

variation. Because the soil in the research area is upper layer soil, heavy metal contamination from human-caused sources is more likely than from lithogenic sources. Anthropogenic sources are more likely to change the top layer of soil than the underlying or lower layers, which contain more metal-rich parent material [57]. PC1 and PC2 have a higher total variance than PC3 and PC4. Thus, the artificial influence of heavy metals on the earth's surface, which corresponds to PC1 and PC2, is depicted. Again, the greater the EF for a particular metal, the more likely it has an anthropogenic origin [57]. The EF in the studied region is extremely high for Pb, Cd, and Cu, which belong to PC1 and PC2, indicating the impact of anthropogenic sources such as gas flaring, transportation, agriculture, car emissions, and other activities, among others. Pb is emitted by car exhaust and should not be discharged. Because of the vast population dispersion, this remote region has no main roadways, only secondary roads for frequent travelers. Other heavy metals, with the exception of Zn, may be affected by anthropogenic sources since they are positively related to Pb, Cd, and Cu in PC1 and PC2. Zn is an essential part of soils and has previously been connected to soil base substances in multiple factor analysis [58]. In acidic soils, the mean concentration of Zn is not harmful. High levels of Zn in soil may result from improper disposal of zinc-containing waste, or inorganic fertilizers [31].

In PC3, Mn has strong positive loadings among all the heavy metals, so PC3 was closely related to Mn and PC3 contributed 14.183%

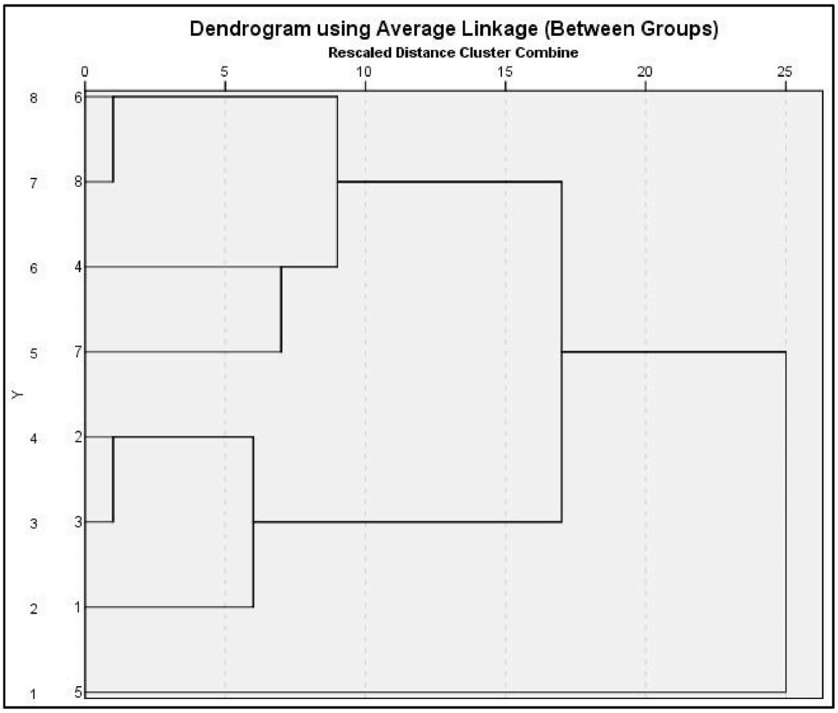

Fig. 3. Cluster analysis.

of the total variance. In PC4, only Co has moderate positive loadings among all the heavy metals, so PC4 was closely related to Co, and PC4 contributed 10.717% of the total variance. There are several elements that contribute to its concentration in a single component (no influence on the other components). Because these heavy metals are found in the soil's underlying component, a lithogenic source for both of these elements can be proposed [57]. PC1 and PC2 both described 62% of the variation, indicating the presence of the anthropogenic component dominated the location of the bulk of the items studied in the present investigation.

4.4. Heavy metal cluster analysis

Cluster analysis was used to determine the link between the sampling locations. This method works ideal for depicting varied interactions [59]. Fig. 3 displays a cluster analysis dendrogram according to soil quality around gas flaring. Clustering is a technique for identifying categories or collections of comparable samples. According to this dendrogram, stations S2, S3, S6, and S8 are the most comparable items since the height of the link connecting them is the shortest. The samples S1, S2, and S3 are identical. Stations S4 and S7 displayed equivalent qualities because they are in identical clusters. Stations S4, S6, and S8 shared similar features because they are in the same cluster. The dendrogram shows a significant variation between these samples.

4.5. Physicochemical analysis

Fig. 4 depicts the values of soil physicochemical characteristics at various sampling points close to the gas flaring location. Soil moisture content ranges from 12.16 to 16.79% around gas-flaring locations. The moisture content declines with increasing distance from the gas flaring source, with the nearest station (s1) having the lowest value and the farthest station (s7) having the highest. The acidity (pH) ranges from 4.3 to 6.8, with the lowest observed at s1, which is closest to the source of the gas flaring. Except for station s5, the pH readings normally increase as one moves away from the gas flaring source. This pH range is lower than the 4.12–6.51 range discovered by Umeda et al. [60] in soils affected by gas flares. However, the pH range recorded for the investigated soils is within the 6.0–9.0 range that has been established as acceptable by the WHO [61]. The electrical conductivity of the soil is generally low, with a mean value of 0.03 ms/cm, indicating that the soils are unsuitable for plant growth due to a lack of efficient nutrients. The ideal electrical conductivity value for plant growth is typically between 0.8 and 1.8, with a maximum of 2.5. However, the average EC value in the soils affected by gas flares is below the WHO-acceptable level of 100.0 S/cm [61]. The salt concentration in the soil ranges from 0.62 to 0.81 mg/kg, with a mean value of 0.61 mg/kg, which falls short of the stated criterion for healthy and productive soil. The magnesium concentration is highest at station s1 (28.18 mg/kg) and lowest at station s7 (19.44 mg/kg). The optimal magnesium range for plant growth is 40–50 ppm (80–100 mg/kg). Calcium concentrations range from 1.12 to 4.96 mg/kg, with the maximum concentration found at station s2, which is located 200 m distant from the flare zone. Calcium content is 2.62 mg/kg on average. Station s2 has the maximum potassium concentration of 1.5 mg/kg, while station s4 has the smallest value of 0.4 mg/kg. These results are much lower than the healthy potassium levels in soil, which range between 40 and 80 mg/kg. The phosphorus content ranges from 0.6 to 1.85 mg/kg, with the highest value at station s1 and the lowest value at station s6, which is 600 m distant from the flare zone and has a concentration of 0.6 mg/kg. The total nitrogen concentrations range from 0.054% to 0.154%, with station s1 having the highest concentration at 0.154%. Overall, all the sampling points have relatively low total nitrogen concentrations.

Nickel (Ni), cobalt (Co), cadmium (Cd), copper (Cu), zinc (Zn), chromium (Cr), lead (Pb), arsenic (As), and manganese (Mn) concentrations were evaluated in soil samples. These elements were found to have average concentrations of 0.22325 (Ni), 0.2095 (Co), 0.078625 (Cd), 1.46 (Cu), 0.14625 (Zn), 0.047875 (Cr), 9.5975 (Pb), 0.006875 (As), and 0.056791167 (Mn) in the samples. The USEPA has determined allowable limits for these components in soil, which are depicted in Fig. 5. These limits describe the maximum

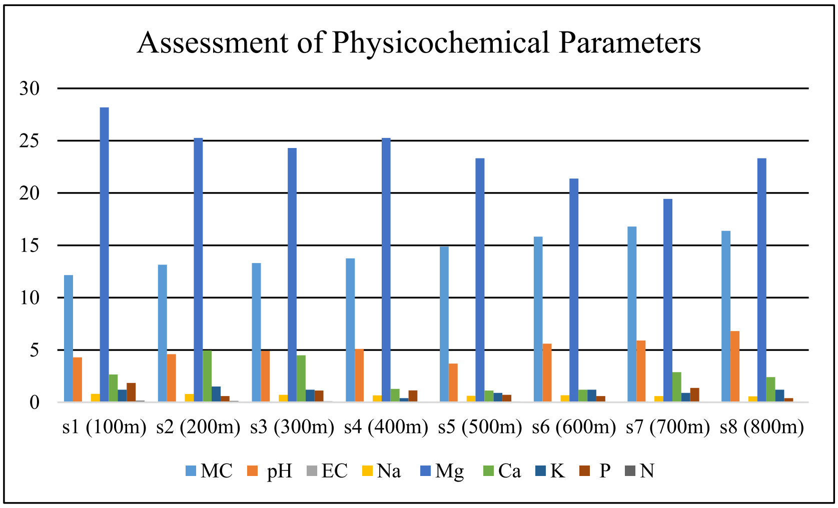

Fig. 4. Values of soil Physicochemical Parameters.

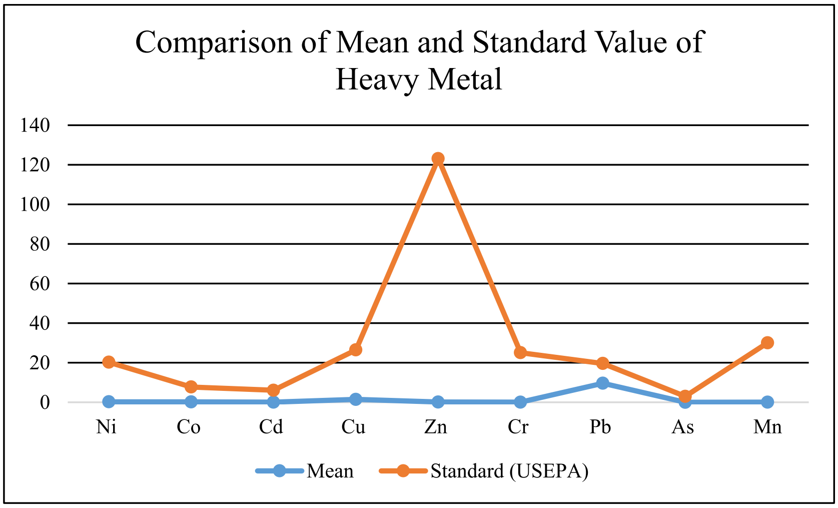

Fig. 5. Mean and standard values of soil heavy metals.

allowable concentration of each element in soil, which if exceeded, may be hazardous to the health of humans or the environment. Ni, Co, Cd, Cu, Zn, Cr, Pb, As, and Mn have limits of 20, 7.5, 6, 25, 123, 25, 10, 3, and 30, respectively. The results demonstrate that the average Ni, Co, Cd, Cu, Zn, Cr, Pb, As, and Mn contents in the samples are lower than the respective USEPA limits.

4.6. Assessment of bacteria

Soil bacteria are crucial in a range of ecological processes, including organic matter breakdown, nitrogen fixation, and nutrient cycling. Bacterial densities are higher in soils with a favorable moisture and temperature regime. Previous studies have reported that soil characteristics and microorganisms were negatively impacted by gas flared products [62]. Additionally, it has been noted that gas flaring has a variety of effects on microbial communities and significantly decreased agriculturally significant soil microorganisms [63]. One such situation is acid rain, which develops when nitrogen oxides from flares and rainwater combine to change the pH of the soil into the acidic range [64] and limit the number of soil microorganisms that are essential for agriculture. Fig. 6 shows that the number of bacteria increased with increasing distance from the flaring area, with the exception of sample site s5. The sampling site s5 has the lowest quantity of bacteria. S1 is the closest to the flare area, and its total bacteria is also lower than others. Sampling location s8 is the furthest away from the flaring zone and has the largest bacterial concentration in soil. As a result, gas flaring may damage a large number of bacteria.

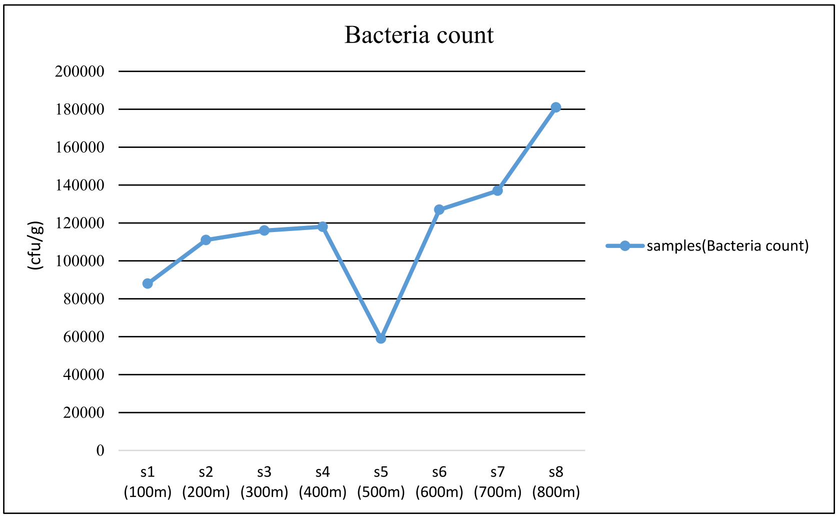

Fig. 6. Showing total bacteria at different sampling stations.

4.7. Assessment of soil heavy metals contamination

The Index of Geo-accumulation (Igeo) can be used to assess the contamination level of different soil components. In Fig. 7, station s2 had the highest Igeo value for Cd of −1.05, while station s6 had the lowest Igeo value for Mn of −14.23. The greatest mean Igeo value was −1.23 for Cd, while the lowest was −13.95 for Mn. Because all heavy metal Igeo values were less than 0, the data imply that the soil near the gas flaring is not contaminated. Zn contamination was notably high in sediment samples collected from location s5, whereas Pb contamination was particularly high in samples collected from location s1. Fig. 8 demonstrates that the contamination factor (Cf) for all metals tested in each sampling point were less than one, indicating that the soil was relatively clean. A Cf value less than one indicates that the element exists in the soil at an amount lower than the maximum permitted level, and so the soil is considered low-contaminated. As, Cr, Zn, and Mn had the lowest metal enrichment levels in the soil, with enrichment factor (EF) values less than one in all soil sites, suggesting their low presence in the soil, according to Table 5. Ni and Co enrichment levels are slightly greater, with modest enrichment reported in two locations for Co. The research region has significant levels of Cd, Pb, and Cu, especially in the s1 Cu sample point, with moderate to severe enrichment in the remaining Cu sampling points. Cd has extremely high EF values in all sampling points, with the highest value reported in s2, indicating that the soil is severely enriched. Cd > Pb > Cu > Co > Ni > Zn > As > Cr > Mn, with Mn displaying the lowest enrichment near the gas flaring area, with a mean EF value of 0.08. Overall, the results indicate that Cd and Pb have extremely high levels of enrichment in the soil, while the other metals have comparatively modest levels of enrichment.

4.8. Risk assessment for health

4.8.1. Assessment of carcinogenic risk

Carcinogenic risk is defined as the probability of developing cancer as a consequence of interaction with substances that cause cancer [65]. The risk for carcinogens ranges from 10^{-6} (which equates to a 1 in 1,000,000 chance of developing cancer) to 10^{-4} (a 1 in 10,000 chance) [65,66]. Toxicants with individual values below 10^{-6}, such as heavy metals, suggest minimal cancer risk. Four heavy metals - arsenic, chromium, lead, and cadmium - were evaluated for carcinogenic risk. Daily intake rates for cadmium in the ingestion pathway were found to be greater than 10^{-6}, indicating acceptable risk for adult humans. However, for the other three heavy metals, daily intakes in the ingestion pathway were below 10^{-6}, indicating negligible risk. Ingestion of all heavy metals in children resulted in daily intakes greater than 10^{-6}, indicating acceptable risk. No health risks for cancer were associated with inhalation and dermal pathways for both children and adults, as daily intake rates for metals were lower than 10^{-6}. The table emphasizes the need for caution in exposure to heavy metals such as As, Cr, Pb, and Cd. Cadmium and children have higher LCR values, indicating that these populations are at a higher risk for cancer as a consequence of heavy metal intake. The LCR results also suggest that the most common route of exposure for these heavy metals is ingestion. As a result, it is vital to implement proper heavy metal exposure prevention strategies to reduce the risk of cancer and other negative health effects associated with these chemicals.

4.8.2. Assessment of non-carcinogenic risk

The Hazard Index (HI) of several heavy metals in both young and old populations is depicted through 3 exposure pathways: ingestion, inhalation, and interaction with the skin. Most notably, As, Cr, Pb, Cd, Cu, Zn, Ni, Co, and Fe were taken into account while estimating non-carcinogenic risk. A non-carcinogenic risk value greater than one (>1) indicates a potentially detrimental non-carcinogenic risk, whilst values less than one (<1) indicate the lack of any potentially harmful health effects [65,66]. For non-carcinogenic risk in ingestion, inhalation, and dermal pathway, daily intakes of metals were found less than 1 which indicates it has negligible health risk for humans. The results also suggest that for all heavy metals, the ingestion pathway poses a greater potential risk than the inhalation or dermal contact pathways. Ingestion of heavy metals can occur through contaminated food, water, or soil, and can lead to toxic effects on various organs and systems in the body.

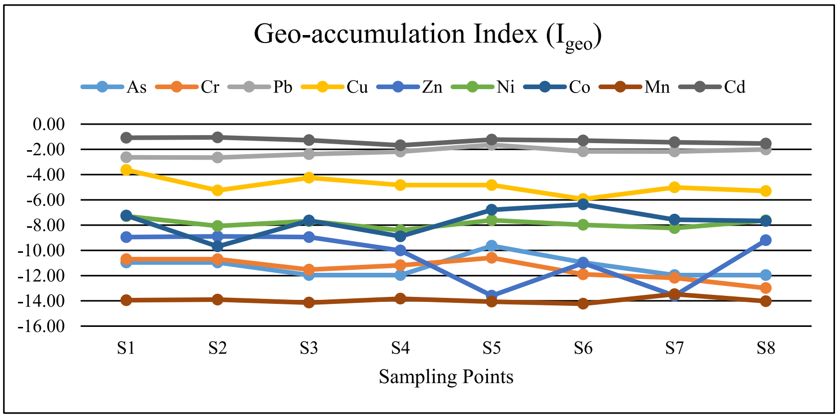

Fig. 7. Igeo value for each heavy metal in soil sample.

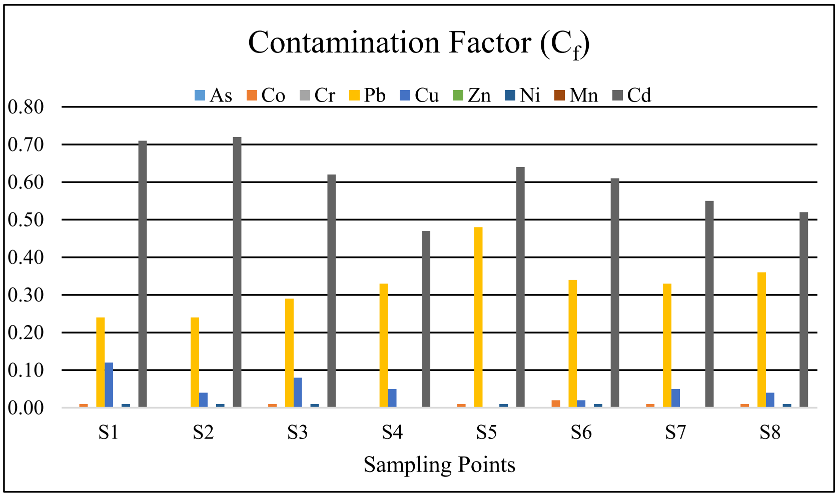

Fig. 8. C_f value for each heavy metal in soil sample.

Table 5
Enrichment Factor of heavy metals.

Enrichment Factor (EF)								
Heavy metals	S1	S2	S3	S4	S5	S6	S7	S8
As	0.23	0.16	0.09	0.09	0.32	0.29	0.10	0.13
Cr	0.27	0.19	0.12	0.16	0.16	0.15	0.09	0.06
Pb	72.78	51.82	70.07	83.29	81.97	131.44	89.49	123.81
Cu	36.24	8.50	19.15	13.27	9.00	9.50	12.51	12.94
Zn	0.91	0.68	0.74	0.37	0.02	0.28	0.03	0.86
Ni	2.86	1.21	1.78	1.11	1.31	2.32	1.33	2.57
Co	2.98	0.39	1.83	0.79	2.31	7.16	2.11	2.50
Mn	0.03	0.02	0.02	0.03	0.15	0.03	0.35	0.03
Cd	211.96	216.56	186.61	140.54	191.22	182.01	165.88	154.36

4.9. Heavy metals Spatial Distribution

Understanding the geographical spread of heavy metal levels is crucial for understanding the harmful effects of manufacturing processes like gas flaring. Figs. 9–18 depict the physical distribution of heavy metal concentrations within an area subjected to gas flaring. The first map, Fig. 9, depicts the concentrations of As. The map shows that the As concentration is generally low and equally distributed throughout the research region, however, there is a sector in the southwest part of the gas field area with a comparatively high As concentration. This shows that gas flaring activities in that location may have contaminated the soil with As.

Fig. 10 demonstrates the distribution of Cd concentrations. The map suggests that the Cd concentration is moderate throughout the study area, but it is relatively high around the gas field. Because Cd is a heavy element that can be harmful to humans as well as the environment, it is possible that the ecological effect of gas flaring operations is being investigated. The spread of Co concentrations is depicted in Fig. 11. According to the map, Co concentrations are nearly consistently distributed at moderate levels throughout the research area, with no noticeable changes in the distribution pattern. This suggests that gas flaring activities may have little effect on Co distribution in the soil.

Figs. 12–18, like the before maps in the series, show the geographical spread of heavy metal in the research region. Graph the geographic distribution of heavy metal concentrations in the research area. Heavy metal levels such as Cr, Cu, Fe, Mn, Ni, Pb, and Zn are usually consistent across the research area, but their levels vary in the gas field area, according to these maps. Some heavy metals have quite high amounts, whereas others have relatively low levels.

5. Limitations

This study had a number of limitations, including the lack of recently developed sample equipment, limited lab space, inadequate research skills, a brief one-month sampling period, time and resource limits from prior research, and self-funding difficulties for a more extensive inquiry.

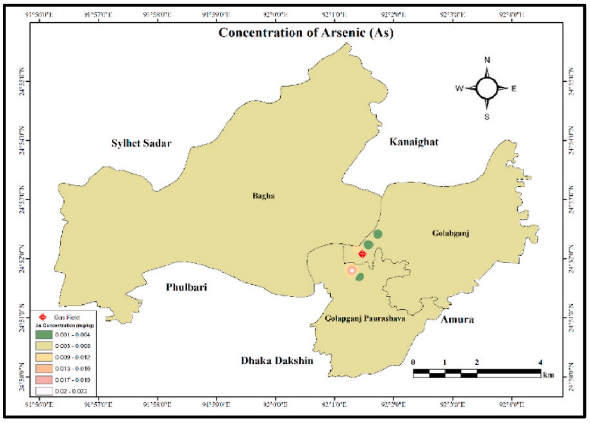

Fig. 9. Spatial distribution of As concentration.

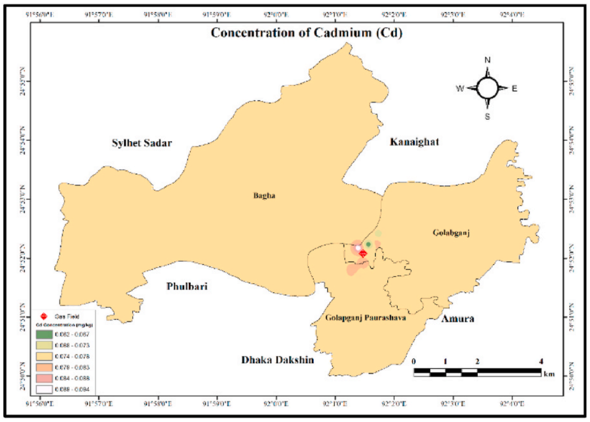

Fig. 10. Spatial distribution of Cd concentration.

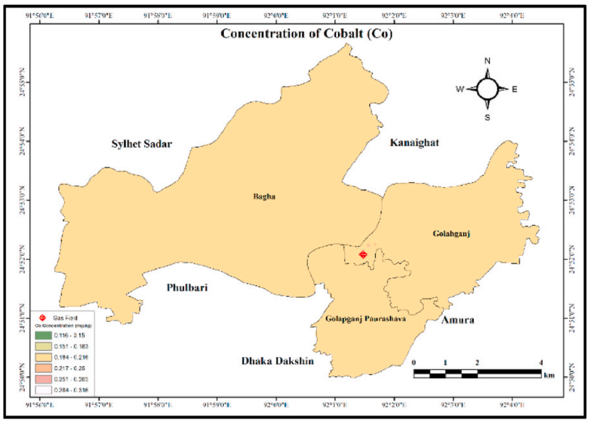

Fig. 11. Spatial distribution of Co concentration.

6. Conclusion

Soil's physical and chemical properties have changed, causing a large decrease in soil moisture, which puts agricultural productivity and soil erosion at danger. As a consequence of changing pH values, increased salinity, and decreased nutrient availability, soil's chemical characteristics are also impacted. Additionally, gas flaring can affect soil bacterial communities, especially when it occurs far

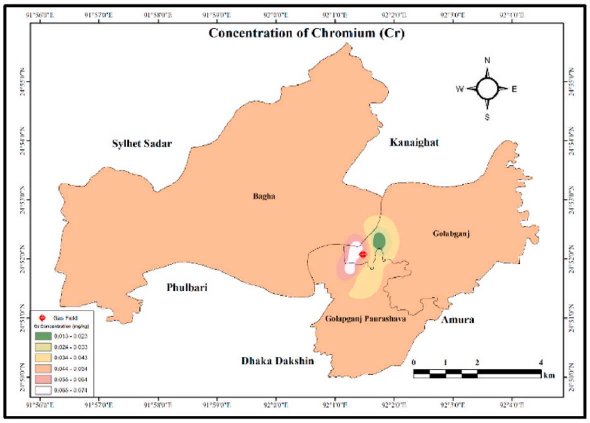

Fig. 12. Spatial distribution of Cr concentration.

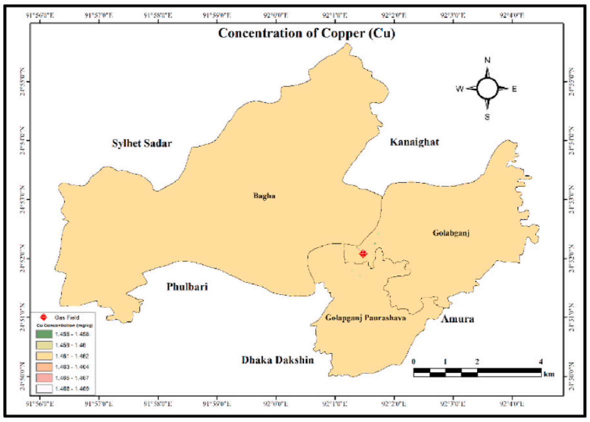

Fig. 13. Spatial distribution of Cu concentration.

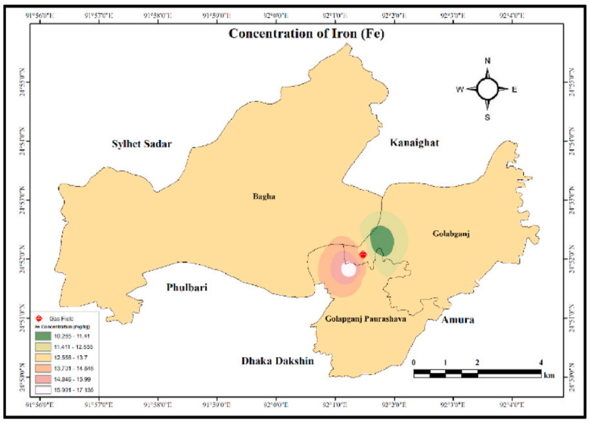

Fig. 14. Spatial distribution of Fe concentration.

from the source of the flaring. The contamination of heavy metals was discovered to be minimal, with lead and copper being the most common. Analysis of correlations showed complex relations among the physical, chemical, and microbiological components affected by heavy metal concentrations. PCA also emphasized the impact of anthropogenic causes on heavy metal contamination. According to the contamination factor study, heavy metals in soil offer no significant risk to the environment or the species that dwell there. Heavy metal pollution was found to provide a greater carcinogenic risk to youngsters in the study. However, as a result of gas flaring

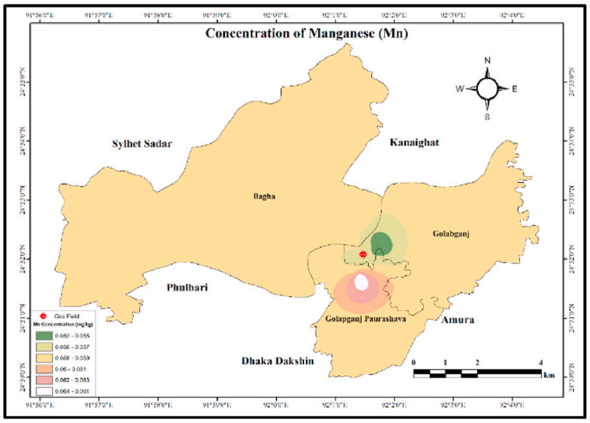

Fig. 15. Spatial distribution of Mn concentration.

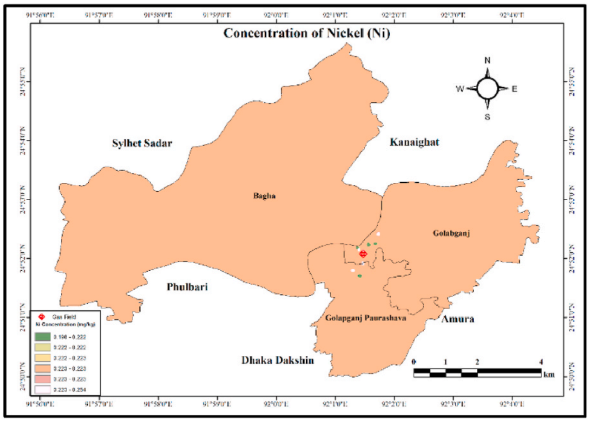

Fig. 16. Spatial distribution of Ni concentration.

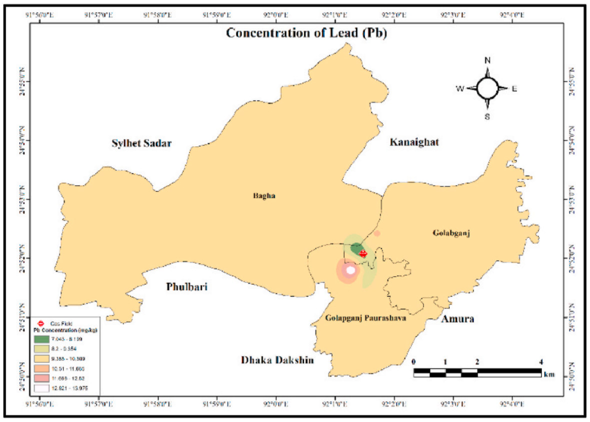

Fig. 17. Spatial distribution of Pb concentration.

activities, the soil in the study region did exhibit some degree of heavy metal pollution, although the contamination levels were typically tolerable and pose no risk to the environment or human health. Overall, the study recommends that steps be done to limit heavy metal contamination and the environmental impact of gas flaring in the studied area.

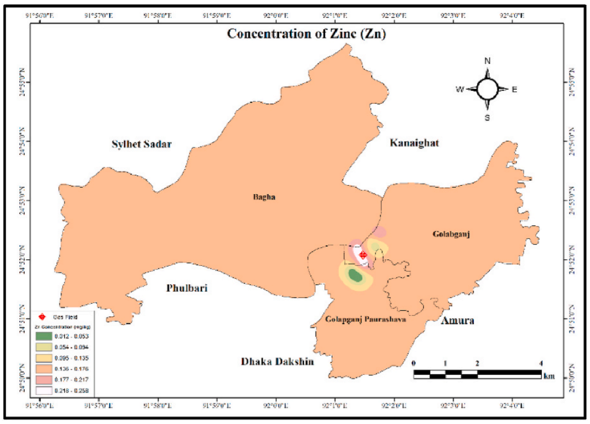

Fig. 18. Spatial distribution of Zn concentration.

Data availability

Data are included with the article as data tables named as "Tables" for further use in future research.

CRediT authorship contribution statement

Kanij Fatema Aktar: Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Conceptualization. **Rony Basak:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Sabrin Ara:** Validation, Resources. **Asif Mahmud:** Validation, Resources.

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.

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