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Heavy Metal Pollution in Gas Flare-Impacted Soils: An Assessment Using Pollution Indices in Obunagha, Bayelsa State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Gas flaring is the controlled burning of natural gas which occurs as a result of the activities of oil exploration and exploitation using flare stacks. In Nigeria, gas flaring activities is high and it mainly takes place in the Niger Delta region. The aim of this study was to investigate the bioavailability and

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concentration of heavy metals pollution of gas flare-impacted soils using pollution indices such as contamination factor, geo-accumulation index and pollution load index. Soil samples were collected with soil auger at depths of 0-15 cm from distances of 200 m, 500 m, 1000 m, 2000 m, and 3000 m away from the flaring point. Flame atomic absorption spectrometry was used to assess the presence of the following heavy metals in the soils: cadmium, chromium, nickel, zinc, copper, and manganese. The findings revealed that Fe (90% bioavailability) had the highest bioavailability among the metals tested in the soils, while Cr (45%) had the lowest. The metals bioavailability decreased in the order of Fe>Mn>Cu>Cd>Ni>Zn>Cr. The geo-accumulation index revealed that the soils were practically uncontaminated by Zn and Cu at all distances, moderately polluted by Cd and Ni at 1000 m and 2000 m and strongly polluted with Cd at a distance of 200 m. The Contamination factor results were consistent with the geo-accumulation index results. The pollutant load index (PLI) was found to be high but decreasing (1.37-0.49) as the distance from the flare point increased, indicating that the research region was polluted. In conclusion, the study's overall findings suggested that the soils were contaminated with heavy metals (particularly Cd) as a result of nearby gas flaring. As a result, the area must be appropriately monitored and managed to prevent future soil contamination by heavy metals to a level that is hazardous to human health.

Keywords: Pollution indices; metal pollution; contamination; gas flaring.

1. INTRODUCTION

Soil is a very important natural resource to man as it is a source of his life on this planet. Without soil the earth would be as barren as the moon hence lifeless [1]. Despite its importance, soil is often contaminated and this is reflected in the high horizontal and vertical variability brought about by the anthropogenic influence on soil formation and development [2]. The soil is a natural resource of great importance due to its ability to act as reservoir and sink for different contaminants, heavy metals inclusive, which results from the deposition of pollutants from various human activities, including manufacturing, construction, gas flaring etc. [3] and these human activities have left their impacts on soils in the form of elevated and high level of toxicants. The level of heavy metals in soil can affect the quality of food, groundwater, microorganisms' activity, and plant growth [4].

Gas flaring is the controlled burning of natural gas that occurs as a result of oil exploration and extraction activities, utilizing flare stacks. It is a prevalent practice in the oil and gas industry, particularly in developing countries. It is often utilized to dispose of unwanted natural gas that is released during the extraction of oil due to the lack of infrastructure to capture and utilize the gas. In Nigeria, especially in the Niger Delta region, gas flaring has been a significant environmental and public health concern for decades.

The Obunagha Community in Bayelsa State is heavily affected by continuous gas flaring, a major source of thermal pollution that has impacted agriculture and other related activities in the area. This study focuses on Obunagha because it hosts the Gbarain-Ubie Integrated Oil and Gas Project commonly called LNG in Bayelsa State and is owned by Shell, Agip, Elf, and Eni Joint Ventures. For more than a decade, the facility has vented undesired gasses into the environment. Fig. 1 depicts the Obunagha Creek, LNG road, host community, and gas flaring point.

Gas flaring has had a substantial impact on soils in flare locations, including Obunagha. The majority of the soils in this area are infertile, which inhibits plant growth. The pressure from gas flares raises soil acidity, which reduces soil fertility by depleting important elements including nitrogen, phosphorus, and potassium [5].

Assessing the extent of heavy metal contamination in soils near gas flaring sites is crucial for understanding the environmental impact and developing mitigation strategies. Environmental quality indices are a powerful tool for development, evaluation and conveying raw environment data's which is helpful to decision makers, managers, technicians and the public [6,7]. Pollution index is a method of comparing the concentration of soil heavy metals with an international standard to determine the degree of pollution of a given location and the effect of the concentration on soil plant and environment [8]. Pollution indices application is considered the most comprehensive method for soil pollution evaluation. The most widely used pollution indices are the Degree of contamination (C_d), Contamination Factor (CF), Enrichment Factor

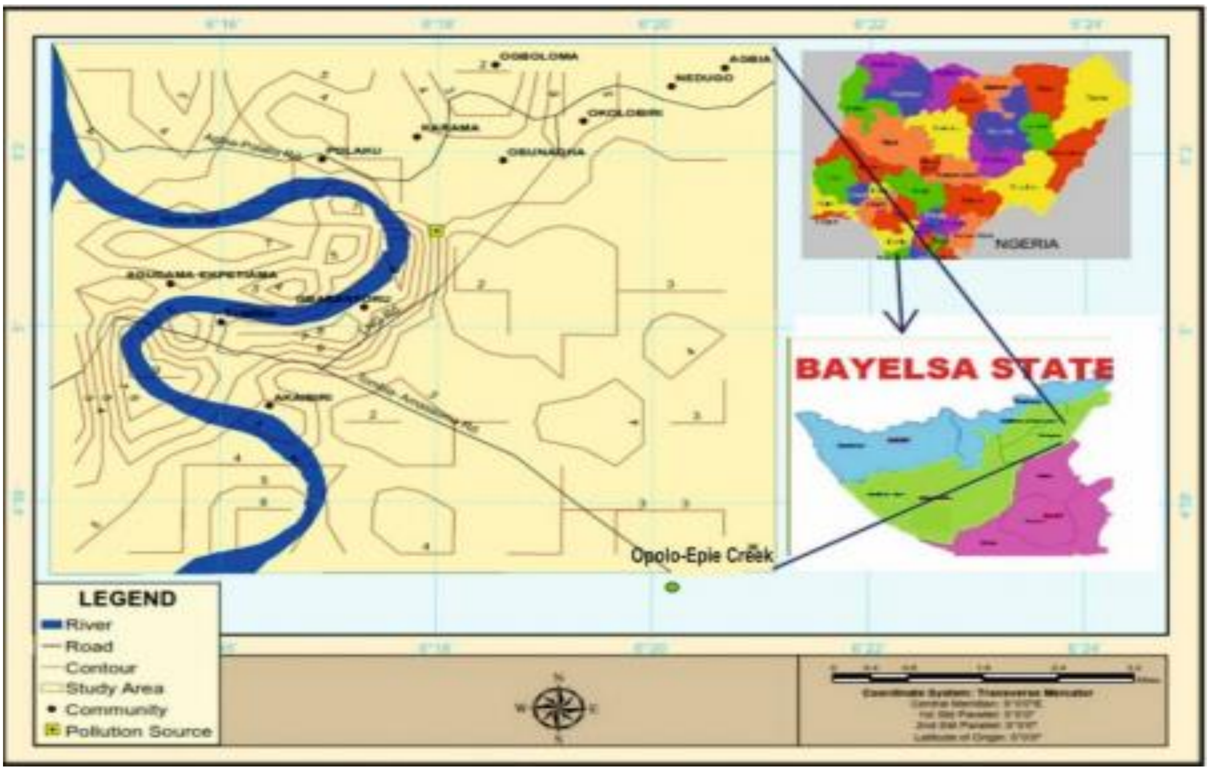

Fig. 1. Map of the Study Area

(EF), Pollution Load Index (PLI), Index of Geo-accumulation (Igeo) and Potential Ecological Risk Index (PERI) [9]. Pollution indices assist in the evaluation of environmental risk and soil degradation, the prediction of future ecosystem sustainability as well as provide the opportunity to increase environmental awareness in society [9]. This study uses pollution indices such as the Pollution Load Index (PLI), Geo-Accumulation Index (Igeo), and Contamination Factor (CF) to assess contamination levels in soils from the Obunagha Community. Furthermore, understanding the bioavailability of these heavy metals is critical for determining their potential danger to human health and the environment.

The aim of this study was to assess the bioavailability and the concentration of heavy metal pollution in soils using pollution indices such as geo-accumulation index, Contamination factor (CF) and Pollution load index (PLI).

2. MATERIALS AND METHODS

2.1 Study Area

Obunagha community in Gbarain Clan, is located in Yenagoa LGA, Bayelsa State, Nigeria (Fig. 1), that lies latitudes 4°59'N - 5°28'N and longitudes 6°15'E - 6°21'E. The community is bordered on the north by Okolobiri, on the south by Tunuama, on the east by the Opokuma clan, and on the west by the Onopa village in Atisa Kingdom.

2.2 Collection of Sample

Test samples of soil were collected from the Gbarain-Ubie Integrated Oil and Gas Flow Station in Obunagha Community. With the aid of soil auger, soil samples were collected at depths of 0 to 15 cm. The collected samples were carefully labeled and stored in polyethylene bags for onward transfer to the laboratory. The sampling points are radial distances away from the flaring point: 200 m, 500 m, 1000 m, 2000 m, and 3000 m. The samples were collected in triplicates and were sent to the lab for analysis.

2.3 Sample Preparation

The soil samples were air dried for 8 days using plastic trays which were labeled according to those on the polythene bags. The air-dried soil samples were crushed in a ceramic mortar and then sieved in a 2 mm plastic sieve. The finely sieved portions of the soil samples were kept in well labeled polythene bags which were used for the preliminary studies (pH measurements, Electrical Conductivity, and Cation Exchange

Capacity), speciation, and total metal determination.

2.4 Heavy Metals Analysis

Two (2g) of finely sieved samples were digested using 10.0 mL mixture of HNO_3 (65%)/H_2O_2 (30%) (v/v) (1:1 ratio). The mixture was maintained at temperature of 80ºC for 2−3 hours on the hot plate. After cooling the resulting clear solution for about 10 minutes, 20 mL of distilled water was added. Each replicate sample was filtered into 50 mL volumetric flasks using a funnel and WhatmanNo.41 filter paper. The resulting solution was diluted to 50 mL with distilled water and subsequently analyzed using Atomic Absorption Spectrophotometer.

2.5 Methods of Assessment of Contamination in Soils

Pollution assessment models are indicators used to assess the presence and intensity of anthropogenic contaminant deposition on soils. In this study, the following pollution assessment models were employed: Geo-accumulation index (lgeo), Contamination Index (CI) and Pollution Load Index (PLI) with respect to heavy metals concentration present in soil.

The Geo–Accumulation Index (Igeo): The Geo–Accumulation Index was proposed by Müller, [10] to assess the pollution levels of each heavy metal in surface sediments, taking their background values (35, 0.25, 25, 10, and 130 mg/kg for Cu, Cd, Pb, Ni and Zn); mathematically,

$$Igeo = log_2 \frac{Cn}{K \times Bn} \qquad (1)$$

where Igeo is the index of geo-accumulation for each heavy metal; Cn is the concentration of heavy metals determined in the sediment sample; Bn refers to the chemical background value of the heavy metals, K = 1.5 represents a constant, which compensates for weathering and lithogenic effects.

Contamination Factor (CF): The contamination factor describes the pollution level of sediment with a given heavy metal and is calculated as the ratio between the concentration of each measured heavy metal (C_n) and its background value (C_{bn}). The CF was calculated according to the method used by Nyarko *et al.*, [11]. The equation used is given by;

$$CF = \frac{C_s}{C_{bn}} \qquad (2)$$

C_s = measured metal concentration in Sample.

C_{bn} Background = baseline or background concentration in unpolluted soil.

Where the contamination factor CF < 1 refers to low contamination; 1 ≤ CF < 3 means moderate contamination; 3 ≤ CF ≤ 6 indicates considerable contamination and CF > 6 indicates very high contamination.

Pollution Load Index (PLI): The PLI is a tool used to assess the global level of sediment contamination, taking the concentrations of several heavy metals into account. This is calculated using the following equation:

$$PLI = (CF_{Me1} \times CF_{Me2} \times ... \times CF_{Men})^{1/n} \qquad (3)$$

Where PLI is the pollution load index, $CF_{Me1,2,3,\ldots n}$ represents the contamination factor or each metal $M_{e1,\ 2,\ 3}$, … n and n is the number of metals.

The value of PLI < 1 indicates the absence of heavy metal contamination, whereas PLI >1 shows the presence of heavy metal pollution.

3. RESULTS AND DISCUSSION

Table 1 states the distribution of the heavy metals in different fractions in soil samples. Studies by Johansson, [12] shows that %bioavailability correlates with toxicity of the metal to plant or animals. The total and bioavailable concentration of heavy metals is presented in Table 2. From the table, %bioavailability is highest for Cu, Mn, Fe, Ni, Cd in soil sampled at 3000 m away from the flaring point and lowest for Cr, Zn, Mn in soils samples at 200 m away from flaring point**.** The highest bioavailability among the metals in the soils investigated was Fe (90%), while the lowest was Cr (45%). The metals bioavailability decreased in the order of Fe>Mn>Cu>Cd>Ni>Zn>Cr.

Pollution indices are controlling implement for environmental quality evaluation. Generally, the pollution indices for heavy metals in soils and sediments are categorized as single and integrated pollution index [13,14]. The current study, two single indices; index of geo-accumulation (Igeo), contamination factor (CF), as well as, one integrated indices; pollution load index (PLI), were used.

Table 1. Distribution of Cr, Cd, Ni, Zn, Cu, Mn and Fe in different fractions in soil samples

Metal	Distance (m)	Concentration (mg/L) in fractions					
		I	II	III	IV	V	VI
Cr	200	9.94 ± 0.02	8.41 ±0.01	6.74±0.04	6.20±0.04	5.21±0.06	3.92±0.02
	500	6.81 ± 0.01	6.17 ±0.02	4.03±0.01	3.48±0.02	3.04±0.02	1.75±0.02
	1000	4.17 ± 0.01	3.87 ±0.02	2.18±0.01	1.83±0.04	1.07±0.07	1.00±0.01
	2000	3.66 ± 0.01	2.45 ±0.03	1.64±0.01	1.18±0.03	0.74±0.03	0.60 ±0.01
	3000	1.74 ± 0.04	1.22 ±0.05	1.17±0.02	1.82±0.01	0.53±0.03	0.22 ±0.01
Cd	200	1.01±0.10	0.79± 0.01	0.53±0.01	0.34±0.12	0.30±0.11	0.19±0.11
	500	0.67±0.01	0.42± 0.10	0.39±0.10	0.16±0.01	0.26±0.01	0.13±0.01
	1000	0.59±0.04	0.38± 0.11	0.21±0.11	0.10±0.01	0.10±0.02	0.10±0.04
	2000	0.50±0.10	0.21± 0.01	0.15±0.01	0.09±0.03	0.08±0.01	0.06±0.02
	3000	0.32±0.10	0.17± 0.12	0.10±0.02	0.05±0.01	0.04±0.01	0.03±0.01
Ni	200	13.17±2.11	10.52±1.23	7.59 ± 2.12	5.89 ±2.01	3.72±1.99	1.94 ±0.55
	500	11.05±0.21	9.38 ±2.54	5.87 ± 0.55	4.16 ±1.87	3.21±1.47	1.30 ±0.11
	1000	8.24±2.54	8.86 ±1.05	5.14 ± 2.45	3.60 ±0.21	1.62±0.02	0.86 ±0.01
	2000	7.62±0.27	8.13±0.11	3.84 ± 0.22	3.05 ±0.01	1.15±0.21	0.57 ± .22
	3000	7.22±0.88	6.30±0.88	3.16 ± 0.03	2.29 ±0.55	1.0 0.12	0.31 ±0.01
Zn	200	3.17 ± 0.60	2.61 ± 0.11	2.02 ± 0.12	1.59 ±0.11	1.04 ±0.11	0.74 ±0.11
	500	2.37 ± 0.51	2.20 ± 0.12	1.65 ± 0.11	1.00.01	0.85 ±0.22	0.37 ±0.02
	1000	2.03 ± 0.21	1.55 ± 0.01	1.14 ± 0.14	0.75 ±0.01	0.31 ±0.01	0.10 ±0.04
	2000	1.47 ± 0.11	1.14 ± 0.52	0.84 ± 0.11	0.35 ±0.03	0.15 ±0.44	0.05 ±0.02
	3000	1.16 ± 0.01	0.68 ± 0.03	0.53 ± 0.02	0.17 ±0.01	1.0 ±0.21	0.02 ±0.02
Cu	200	8.45 ± 1.22	6.51 ± 0.22	3.37 ± 0.01	3.83 ±0.44	2.65 ±0.21	1.59 ±0.01
	500	7.21 ± 2.11	6.01 ± 1.47	5.14 ± 1.25	3.01 ±0.11	2.02 ±0.11	1.04 ±0.14
	1000	6.40 ± 0.01	4.90 ± 0.57	4.64 ± 0.24	1.21 ±0.01	1.36 ±0.14	0.52 ±0.11
	2000	5.85 ± 0.22	4.90 ± 0.21	2.75 ± 0.11	1.00.10	0.76 ±0.21	0.28 ±0.01
	3000	5.01 ± 0.40	4.10 ± 1.02	2.15 ± 0.32	0.82 ±0.04	0.42 ±0.01	0.06 ±0.01
Mn	200	2.46 ± 0.11	2.04 ± 0.11	1.67 ± 0.01	1.17 ±0.04	0.91 ±0.03	0.37 ±0.01
	500	2.00 ± 0.01	1.64 ± 0.12	1.08 ± 0.21	0.81 ±0.01	0.62 ±0.04	0.16 ±0.02
	1000	1.85 ± 0.04	1.19 ± 0.10	0.43 ± 0.02	0.51 ±0.21	0.27 ±0.02	0.07 ±0.01
	2000	1.37 ± 0.01	0.74 ± 0.01	0.20 ± 0.02	0.20 ±0.12	0.11 ±0.01	0.03 ±0.01
	3000	1.05 ± 0.01	0.42 ± 0.10	0.09 ± 0.01	0.08 ±0.01	0.05 ±0.04	0.02 ±0.01
	200	4.15 ± 1.02	2.40 ± 0.02	1.37 ± 0.09	0.97 ±0.02	0.57 ±0.01	0.20 ±0.01

Metal	**Distance (m)**	**Concentration (mg/L) in fractions**					
		I	**II**	**III**	**IV**	**V**	**VI**
	500	3.26 ± 0.21	2.02 ± 0.21	0.76 ± 0.05	0.73 ±0.07	0.36 ±0.02	0.05 ±0.02
Fe	1000	2.86 ± 0.11	1.48 ± 0.08	0.53 ± 0.12	0.42 ±0.02	0.18 ±0.02	1.01 0.01
	2000	2.19 ± 0.11	1.02 ± 0.02	0.13 ± 0.01	0.31 ±0.15	0.05 ±0.01	1.01 0.01
	3000	1.57 ± 0.01	0.43 ± 0.14	0.10 ± 0.01	0.09 ±0.03	0.03 ±0.01	n.d

Values are presented as mean ± standard deviation (n=3), n.d: not detected Fraction I: water soluble metals, Fraction II: Exchangeable metals, Fraction III: Metals bound to carbonates, Fraction IV: Metals bound to Fe-Mn oxide, Fraction V: bound to organic carbon metals, Fraction VI: residual metals.

Table 2. Percentage (%) Bioavailability of heavy metals in soil samples

Distance (m)	**% Bioavailability**						
	Cr	**Cd**	**Ni**	**Zn**	**Cu**	**Mn**	**Fe**
200	45	57	55	52	57	52	68
500	51	54	58	54	54	58	74
1000	57	66	60	61	59	70	79
2000	59	65	65	65	69	80	87
3000	52	69	67	52	73	86	90

Table 3. Geo–accumulation Index of individual elements in soils samples

Distance (m)	**Igeo values**			
	Cd	**Ni**	**Zn**	**Cu**
200	3.07	1.51	-4.1	-0.99
500	2.44	1.22	-4.5	-1.1
1000	1.98	0.92	-5.1	-1.46
2000	1.54	0.7	-5.6	-1.76
3000	0.92	0.44	-5.8	-2.06

Table 4. Contamination factor of heavy metals in the soils

Distance (m)	Contamination factor			
	Cd	Ni	Zn	Cu
200	12.64	4.28	0.09	0.75
500	8.12	3.5	0.06	0.7
1000	5.92	2.83	0.05	0.54
2000	4.36	2.44	0.03	0.44
3000	2.84	2.03	0.03	0.36

Table 5. Pollution load index (PLI) of heavy metals in soils

Distance (m)	PLI
200	1.37
500	1.07
1000	0.8
2000	0.62
3000	0.49

Table 6. Index of geo-accumulation classes

Igeo	Class	Pollution Intensity
Igeo ≤ 0	0	unpolluted
0 < Igeo < 1	1	Unpolluted to moderately polluted
1 < Igeo < 2	2	Moderately polluted
2 < Igeo < 3	3	Moderately to strongly polluted
3 < Igeo < 4	4	Strongly polluted
4 < Igeo <5	5	Strongly to very strongly polluted

Table 7. Risk grades of contamination factor of heavy metal pollution

CF Value	Contamination
CF < 1	Low
1 ≤ CF < 3	Moderate
3 ≤ CF < 6	Considerable
CF > 6	Very high

The geo-accumulation index (Igeo) is a quantitative check used to describe concentration inclination of metals in soils, plants, sediments and rocks [15]. According to Varol, [16], index of geo-accumulation classes (Igeo, class, pollution intensity) are presented in Table 6. Table 3 presents the geo-accumulation index for the quantification of heavy metal accumulation in the study area. Soils sampled at (3000 m away from flaring point) and soils sampled at (1000 m, 2000 m, away from flaring point) are respectively rated as unpolluted to moderately polluted with Cd and Ni, because their Igeos are 0 < Igeo < 1, soils sampled at (200 m, 500 m, away from the flaring point) were moderately polluted with Ni (1 < Igeo < 2), whereas at 1000 m, 2000 m the Igeo for Cd fell within the moderately polluted range. The Igeo result also showed that the soil at 200 m is strongly polluted with Cd (3). For Zn and Cu in all distances they have negative Igeo values (Table 3) which indicates no contamination or enrichment above background value with the reference to Bn.

The contamination factor is used to determine the contamination status of the soil around the gas flared sites in the present study. Risk grades of contamination factor of heavy metal pollution as stated by Weissmannová & Pavlovský, [17] are presented in Table 7. The results of the contamination factor for the soils are shown in Table 4. Considering the contamination factor classification, the analyzed soil sampled at 200 m, 500 m, 1000 m, 2000 m, and 3000 m away from flaring point for Cu and Zn are classified as low contaminated (CF < 1 Table 7), soil sampled at 1000 m, 2000 m, and 3000 m away from flaring point for Ni and 3000 m away for Cd were moderately contaminated (1 ≤ CF < 3), soil sampled at 1000 m, 2000 m away from flaring point for Cd and 200 m, 500 m away from flaring point for Ni were considerately contaminated (3 ≤ CF < 6), while soil sampled at 200 m, 500 m away from flaring point for Cd has very high contamination (CF > 6). The high degree of contamination of Cd at these distances could be attributed to their closeness to the point source. The analyzed soil was highly contaminated with Cadmium which is in line as reported by [3] and this can be linked to gas flaring in the study area.

Pollution load index (PLI) is an empirical index which provides a simple, comparative means for assessing the level of heavy metals pollution. To effectively know the measure of degree of overall contamination, the pollution load index (PLI) was calculated using equation (3) for the sampled areas and presented in Table 5. Based on the results presented in Table 5 it was observed that soil sampled at 200 m and 500 m away from the flaring point show the presence of heavy metal pollution as PLI >1 whereas soil sampled at 1000 m, 2000 m, and 3000 m away from flaring point indicates the absence of heavy metal contamination (PLI <1) (Table 5). The PLI (0.49-1.37) vary with distance from flaring points which confirm that the study area is facing probable environmental pollution with heavy metals especially soils closest to the gas plant which could be as a result of increased gas flaring activities.

4. CONCLUSION

The present study was carried out to assess the concentration of level of various heavy metals in the soils of Obunagha Community in Bayelsa State, Nigeria. Pollution indices analysis was implemented to assess the contamination of heavy metals in the soils. From the study, it can be concluded that the different pollution index models used in assessing the level of contamination reveals that the soils were contaminated, polluted by heavy metals at varying concentrations which may be due to gas flaring activities in the study area. Therefore, the area needs to be adequately monitored and regulated to avoid further soil contamination by heavy metals to a degree that will be dangerous to human health.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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