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Original article

Evaluation of heavy metal toxicity in sediments of selected rivers from Southern Nigeria's Peri-Urban Region using pollution indices

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ABSTRACT

From June 2021 to March 2023, an assessment of sediment quality was carried out in five rivers across Edo State, Nigeria (Illushi, Okhuaihe, Onyami, Osse and Ossiomo). The focus of the study was to evaluate heavy metal contamination and its potential ecological risks. Sediment samples were collected from two strategic locations along each river. Standard analytical methods were employed, and six heavy metals were quantified using an Atomic Absorption Spectrophotometer (AAS). The analysis revealed that iron (Fe) had the highest concentration, followed by zinc (Zn), copper (Cu), manganese (Mn), chromium (Cr), and lead (Pb), in descending order. Pollution Load Index (PLI) values for the rivers ranged from 0.9897 (Okhuaihe) to 1.0289 (Ossiomo). While some values slightly surpassed the baseline threshold of 1.0, they generally indicate mild contamination. The Geoaccumulation Index (Igeo) values, spanning from -3.5996 to -3.2635, with an average of -3.4821, classified the sediments as practically uncontaminated (Igeo ≤ 0). Similarly, the Potential Ecological Risk Index values ranged between 24.0351 and 25.0756, suggesting a low ecological risk across all rivers surveyed. These results point to the role of natural processes, such as self-purification and river flow dynamics, in maintaining sediment quality. Heavy metal accumulation in sediments typically occurs through intricate physical and chemical adsorption processes. The extent of this accumulation is influenced by both the composition of the sediment matrix and the nature of the pollutants. Elevated concentrations of such metals often serve as reliable indicators of human-induced pollution rather than natural background levels. Despite the low levels of contamination observed, the presence of heavy metals - often attributed to anthropogenic activities rather than natural geological sources - underscores the need for continuous environmental monitoring. Sustained vigilance is crucial to safeguarding these aquatic ecosystems, given their sensitivity and the potential for future pollution.

Keywords: Sediments, Heavy Metals, Pollution Load Index (PLI), Geo-accumulation Index (Igeo) and Potential Ecological Risk Index (PERI).

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INTRODUCTION

In the recent past, there have been increasing interests regarding heavy metal contaminations in the environments, apparently due to their toxicity and perceived persistency within the aquatic systems [1]. There are basically three reservoirs of metals in the aquatic environment: water, sediment and biota [2]. The analysis of river sediment is a useful method of studying environmental pollution with heavy metals [3]. Heavy metals accumulate in the sediments through complex physical and chemical adsorption mechanisms depending on the nature of the sediment matrix and the properties of the adsorbed compounds. The occurrence of elevated concentrations of trace metals in sediments found at the bottom of the water column can be a good indicator of man induced pollution rather than natural enrichment of the sediment by geological weathering [4].

River sediments have been identified as important carriers and sinks for the heavy metals discharged into the aquatic systems [5]. Heavy metals in river sediments mainly stem from rock weathering, soil erosion, runoff from agriculture, sewage treatment, and atmospheric precipitation [6]. The heavy metals loaded into the river environment can be transferred to and concentrated in sediments together with organic matter, Fe/Mn oxides, and sulphides by adsorption and accumulation on suspended fine-grained particles, however they cannot be permanently fixed in sediments [7]. Under ecological disturbances such as a decline in redox potential or pH and the degradation of organic matter, the heavy metals in sediments can be released back into the overlying water by various processes of remobilization, which may lead to secondary pollution [8, 9].

Statistical method is used widely in studying the relationship between different heavy metal concentrations and samples. A variety of evaluation methods for heavy metals have been developed by international organizations and conventions, which have been applied to evaluate heavy metal pollution and the potential ecological risks in the sediments. These methods are associated with the enrichment factor, pollution degree, pollution load index, contamination factor, and geo-accumulation index, which were mainly used to evaluate the ecological risks according to the ratio of a single heavy metal concentration to the background value [10, 11].

However, these methods neither provide information on the toxicity of heavy metals nor indicate the comprehensive toxic effects in the overall heavy metal assemblage. The potential ecological risk index (PERI), developed by the famous Swedish scholar Håkanson, is a well-known method for the potential risk of heavy metal pollution in soils and sediments, which could fill this gap and consider both total contents of heavy metals and the toxic response factors for each heavy metal [12, 13].

This study aims to evaluate ecological and potential risks influencing heavy metals in sediments from the selected rivers in Edo State, thereby providing benchmark data for future sediment quality monitoring and management.

MATERIALS AND METHODS

Description of Study Area

Edo State is in the South-South region of Nigeria, between Latitudes 05^0 44'N and 07^0 34'N and Longitudes of 05^{0}04'E and 06^0 40'E. It covers an area of around 19,794 square kilometres and it occupies the rain forest zone [14]. The northern part of the state is underlain by Precambrian rock formations, while the southern part consists of Cretaceous and Tertiary sediments. Metal and industrial minerals are abundant in the north and are currently being exploited. The mineral composition significantly influences rock's petrographic characteristics. The state experiences two distinct seasons: a wet season from April to October, characterized by high rainfall, humidity, and low temperatures, and a dry season from November to March, marked by low humidity, high temperatures, and cooler nights. The Harmattan period, occurring between December and January, brings dusty winds. Typical temperatures range between 25°C during the wet season and 30°C in the dry season [15].

Sampling Stations: This study examines five rivers in Edo State - Onyami, Illushi, Osse, Ossiomo, and Okhuaihe; focusing on their ecological conditions across reference (upstream) and impacted (downstream) sites of each river.

Onyami River: located in Akoko-Edo Local Government Area (Latitude 7° 19'N, Longitude 6° 9'E), is dammed at Ojirami Oke with a 3.9-meter-high structure holding 900,000 gallons. It supplies water to Akoko communities at 245 m^3/hr. The upstream station, at 272.5m elevation and 57cm depth, remains undisturbed and clear, supporting vegetation like; *Rhizophora*, *Avicennia*, and *Eichhornia crassipes*. The downstream station, 1km away (Figure 1), is impacted by farming and domestic use, resulting in turbid water and vegetation including *Musa paradisiaca* and *Pistia stratiotes* [14].

Illushi River: part of the River Niger system, flows through Illushi in Esan South Local Government Area (Latitude 6° 40'N, Longitude 6° 37'E). The upstream station shows minimal impact, with only fishing noted. The downstream station, 0.5km away and at 55m elevation (Figure 1), is affected by farming, waste dumping, and open defecation, leading to seasonal turbidity [16].

Osse River: situated in Ovia North-East Local Government Area (Latitude 6° 9'N, Longitude 5° 18'E), originates from Akpata Hills and flows into the Benin River (Figure 1). The upstream site is relatively pristine, supplying drinking water and supporting species such as *Azolla spp.* and *Hevea brasiliensis*. The downstream site, 0.6km away, experiences runoff and human activity, with vegetation including *Bambusa spp.*, *Elaeis guineensis* and *Pistia stratiotes* [17].

Ossiomo River: situated in Ikpoba Okha Local Government Area (Latitude 6° 32'N, Longitude 5° 40'E) stretches 250km into Delta State (Figure 1). The upstream station at 12m elevation is mainly influenced by fishing. The downstream station, 0.7km away at 14m elevation, is affected by agriculture and waste disposal. Common vegetation includes *Lemna spp.*, *Nymphaea lotus* and *Potamogeton spp* [18].

Okhuaihe River: flows through Ikpe Community in Ikpoba-Okha Local Government Area (Latitude 6° 12'N, Longitude 5° 45'E), empties into Ossiomo

River (Figure 1). The reference site has minimal impact, supporting vegetation like *Mimosa pudica* and *Sida acuta*. The downstream site, 0.8km away, is subject to runoff and multiple anthropogenic activities, hosting plants such as *Raphia hookeri*, *Carica papaya* and *Colocasia esculenta* [19].

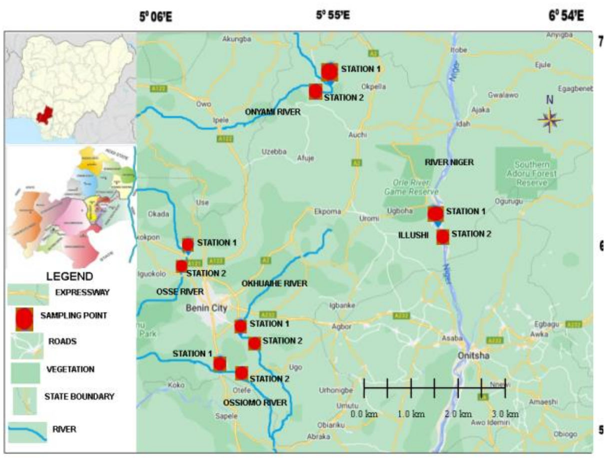

Figure 1: A Map showing the Five Rivers with their various Study Stations.

Sample Collection

Sediment sampling was conducted quarterly over a 24-month period, encompassing both wet and dry seasons. A total of eight sampling events were carried out - four during the wet season (June 2021 to October 2022) and four in the dry season (November 2021 to April 2023). Each study location included two designated points: a reference site and an impacted site. Sampling was performed between 7:30 hrs and 9:00 hrs to maintain consistency.

Sediment samples were collected from the riverbed using an Ekman grab sampler, then transferred into labeled polythene bags. These samples were transported to the Benin-Owena River Basin Development Authority/University of Benin Joint Analytical Research Laboratory in Benin City, Edo State. Upon arrival, samples were registered in the laboratory inventory, dried on racks, and prepared for heavy metal analysis using a Unican 929 Atomic Absorption Spectrophotometer [20].

Data Analysis: Evaluation of Data - Risk Assessment

To evaluate contamination and pollution risk, several indices were employed:

Enrichment Factor (EF): Used to identify anthropogenic contributions to heavy metal concentrations, with iron (Fe) as the reference element [21]. EF is calculated as: EF = (X/Fe) sample / (X/Fe) background, using a background Fe value of 921.238 mg/kg. EF values <1 suggest depletion or natural origin, while values >1 indicate anthropogenic sources. Enrichment is categorized from minimal (EF < 2) to extreme (EF > 40) [22, 23].

Contamination Factor (CF) and Pollution Load Index (PLI): Cf assesses individual metal contamination using the formula: $Cf_{metal} = C_{metal} / C_{background}$. Contamination is ranked from low (CF < 1) to very high (CF > 6) [21, 24]. PLI provides an overall pollution level, calculated as the geometric mean of all Cf values. PLI > 1 denotes pollution presence; PLI < 1 indicates absence [25].

Geo-accumulation Index (Igeo): Evaluates metal accumulation relative to background values using:
$Igeo = \log_2 (Cn / 1.5Bn)$, where Cn is the metal concentration and Bn is the geochemical background [23, 26]. The factor 1.5 accounts for natural variability. Igeo ranges from unpolluted (≤0) to extremely polluted (>5), categorized across seven classes [27].

Potential Ecological Risk Index (PERI): It was used to associate ecological and environmental effects with their toxicology and the toxic-response factor T_{ri} of Cu, Zn, Mn, Fe and Pb [25]. An ecological risk factor (*Er*) quantitatively expressed as the potential ecological risk of a given contaminant are given by [28] in equation below.

$$E_r^i = T_r^i \cdot C_f^i$$

Where *Tr* is the toxic-response factor for a given substance and *Cf* is the contamination factor. The following terminologies are used to describe the ecological risk factor: $Eri < 40$, low potential ecological risk; $40 \leq Eri < 80$, moderate potential ecological risk; $80 \leq Eri < 160$, considerable potential ecological risk; $160 \leq Eri < 320$, high potential ecological risk; and $Eri \geq 320$, very high ecological risk [29].

The potential ecological risk index (PERI) was in the same manner as degree of contamination defined as the sum of the risk factors.

$$PERI = \sum_{i=1}^{n} E_r^i$$

Where *Eri* is the single index of ecological risk factor, and n is the count of the heavy metal. The following terminologies are used for the potential ecological risk index as given by [30]; RI < 150, low ecological risk; 150 ≤ RI < 300, moderate ecological risk; and *RI > 600*, very high ecological risk (Table 1).

Table 1: Adjusted grading standard of Potential Ecological Risk of Heavy Metals in Sediment.

E^i_R	Pollution degree	Ri	Risk level	Risk degree
EiR< 30	Slight	Ri < 40	A	Slight
30 ≤ EiR< 60	Medium	40 ≤ Ri < 80	B	Medium
60 ≤ EiR< 120	Strong	80 ≤ Ri < 160	C	Strong
120 ≤ EiR< 240	Very Strong	160 ≤ RI 320	D	Very strong
EiR ≥ 240	Extremely strong	RI ≥ 320	-	-

E^i_R is the potential ecological risk index of a single element; RI is a comprehensive potential ecological risk index.

RESULTS

Pollution Load Index (PLI)

The values obtained in relation to Pollution Load Index (PLI) at the various rivers: Onyami, Illushi, Osse, Ossiomo and Okhuaihe were 1.0006, 0.9909, 1.0064, 1.0289 and 0.9897 respectively as shown in (Table 3), while Table 2 showed the summary of concentrations of heavy metals in sediment samples from the five rivers. Table 3 showed the summary of Contamination factors that were accumulated to the PLI value at the various stations, while Figures 2 and 3 indicated the graphical representations for the Contamination Factors and PLI respectively. Generally, Okhuaihe River bore the lowest value and Ossiomo River had the highest value of PLI respectively. From the values, Illushi and Okhuaihe Rivers had no metal pollution PLI < 1, while Onyami, Osse and Ossiomo Rivers had metal pollution PLI ≥ 1.

Geo-accumulation Index (*Igeo*)

Table 4 showed the summary of the Geoaccumulation Index values for the various heavy metals in the Selected Rivers. The *Igeo* values for Okhuaihe River was the lowest, while Ossiomo River was the highest when compared with the rest rivers. Figure 4 showed the summary of Igeo of heavy metal contamination in various Sediment Samples from the five rivers. The Igeo values were ranged from -3.5996 to -3.2635 with an average of -3.4821. All the metals (Cr, Cu, Fe, Pb, Mn and Zn) Igeo values were practically uncontaminated (Igeo ≤ 0). On the basis of the mean values of Igeo, the degree of heavy metal pollution in the sediments yielded the following ranking: Mn > Cu > Cr > Fe > Zn > Pb.

Potential Ecological Risk Index (PERI)

Table 5 showed the summary of the Potential Ecological Risk values for the various heavy metals. The Risk Index (RI) values of the Sediment Samples from the various rivers; Onyami, Illushi, Osse, Ossiomo and Okhuaihe were 24.33, 24.04, 24.55, 24.91 and 25.08 respectively. Figure 5 showed the representation of the Potential Ecological Risk values across the sampled rivers of the study. For the individual heavy metals, their ecological risk factor values ranged as followed; Fe (0.97 – 1.04), Cu (4.74 – 6.35), Pb (4.04 – 4.96), Mn (9.99 – 12.11), Cr (1.99 – 2.10) and Zn (0.94 – 1.02). The PERI values were ranged from 24.04 in Illushi River to 25.08 in Okhuaihe River with an average of 20.48

Table 2: The Concentrations of Heavy Metals in Sediment Parameters from the Selected Water Bodies

Stations	Parameters					
	Cr	Cu	Fe	Pb	Mn	Zn
Onyami Reference	7.23	46.79	362.44	2.12	11.99	87.11
Onyami Impacted	7.21	47.64	351.86	2.08	12.43	87.19
Illushi Reference	7.46	47.53	328.22	2.19	14.08	81.04
Illushi Impacted	7.83	45.07	319.79	2.02	14.94	80.85
Osse Reference	7.65	58.51	341.93	2.64	15.44	86.82
Osse Impacted	7.82	55.76	343.73	2.62	16.62	86.25
Ossiomo Reference	8.49	53.82	347.16	2.37	13.74	86.99
Ossiomo Impacted	8.77	68.38	341.56	2.13	13.73	88.98
Okhuaihe Reference	16.09	42.36	373.14	3.56	9.51	85.02
Okhuaihe Impacted	16.01	41.95	387.32	2.88	11.52	79.70
Mean	9.46	50.781	349.715	2.461	13.4	84.995
Standard Deviation (SD)	3.51	8.30	20.15604	0.481651	2.086571	3.247526

Table 3: The Contamination Factor and Pollution Load Index of Heavy Metals in Sediments from the Selected Water Bodies

Stations	Contamination Factor						PLI
	Cr	Cu	Fe	Pb	Mn	Zn	
Onyami	0.99723	1.01817	0.97081	0.981132	1.036670	1.000918	1.0006
Illushi	1.04960	0.94825	0.97432	0.92237	1.06108	0.99766	0.9909
Osse	1.02222	0.95300	1.00526	0.99242	1.07643	0.99343	1.0064
Ossiomo	1.03298	1.27053	0.983870	0.898734	0.99927	1.02288	1.0289
Okhuaihe	0.99503	0.99032	1.038002	0.808989	1.21136	0.93743	0.9897

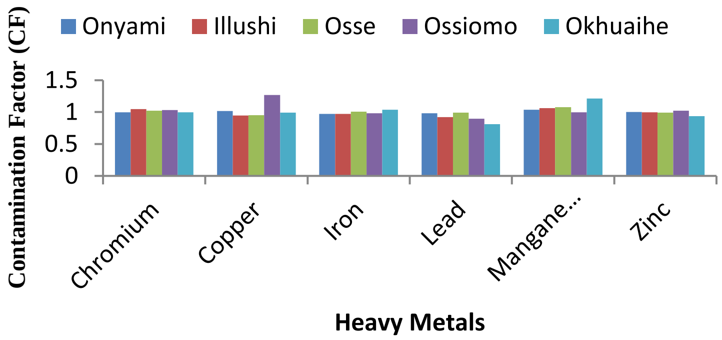

Figure 2: Contamination Factor across the Sample Stations of the Selected Rivers

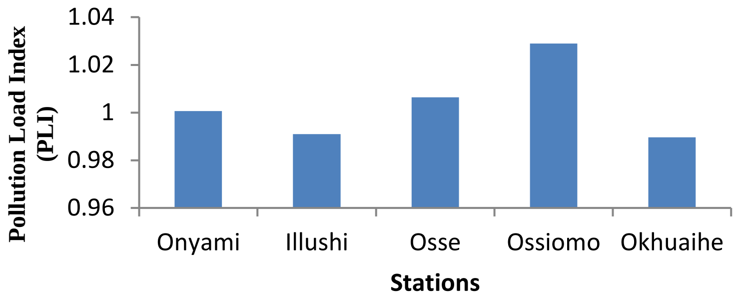

Figure 3: Pollution Load Index across the Sample Stations of the Selected Rivers

Table 4: The Geoaccumulation Index Values and Pollution Levels of Heavy Metals in Sediments from the Selected Rivers

Stations	Heavy Metals						Igeo Value	Igeo Class	Pollution Level
	Cr	Cu	Fe	Pb	Mn	Zn			
Onyami	0.6648	0.6788	0.6472	0.6541	0.6912	0.6673	-3.5047	0	Uncontaminated
Illushi	0.6997	0.6322	0.6495	0.6149	0.70734	0.6651	-3.5886	0	Uncontaminated
Osse	0.6815	0.6353	0.6702	0.6616	0.7176	0.6623	-3.4542	0	Uncontaminated
Ossiomo	0.6887	0.8470	0.6559	0.5992	0.6662	0.6819	-3.2635	0	Uncontaminated
Okhuaihe	0.6634	0.6602	0.6920	0.5393	0.8076	0.6250	-3.5996	0	Uncontaminated

Table 5: The Summary of Potential Ecological Risk Index of Heavy Metals in Sediments from the Selected Rivers

Stations	Ecological Risk Factor (Er)						PERI
	Cr	Cu	Fe	Pb	Mn	Zn	
Onyami	1.9945	5.0909	0.9708	4.9057	10.3667	1.00092	24.3294
Illushi	2.0992	4.7413	0.9743	4.6119	10.6108	0.9977	24.0351
Osse	2.0444	4.765	1.0053	4.9621	10.7643	0.9934	24.5345
Ossiomo	2.0655	6.3527	0.9839	4.4937	9.9927	1.0229	24.9117
Okhuaihe	1.9901	4.9516	1.038	4.0449	12.1136	0.9374	25.0756

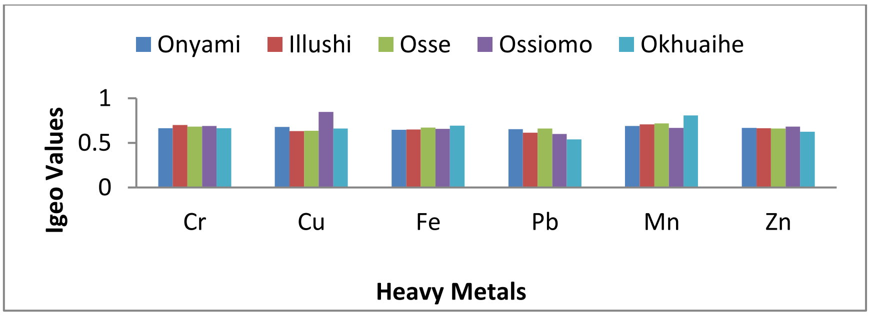

Figure 4: Igeo values across the Sample Stations of the Selected Rivers

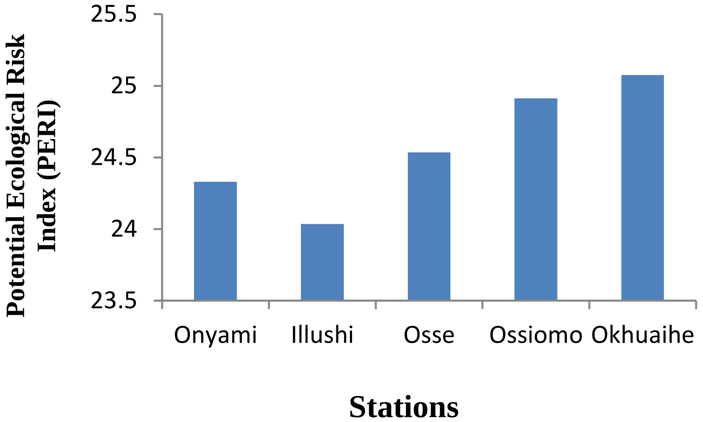

Figure 5: Potential Ecological Risk values across the Stations of the Selected Rivers

DISCUSSION

The Pollution Load Index explained the pollution severity and its variation as a function of concentration factor. The Contamination factor indicated that there was low contamination of heavy metals in all stations. Pollution Load Index less than zero (0), indicated that there is no metal pollution, while PLI equal or greater than 1, indicated that the sediments were polluted by heavy metals [23], The PLI values of the study area ranged from (0.9897 at Okhuaihe River to 1.0289 at Ossiomo River), which further indicated that the sediment samples from studied stations varied from were "not polluted by heavy metal" to "metal pollution". This can be attributed to the level of anthropogenic activities as a major contributor in the stations [31, 32]. The Geoaccumulation index was distinguished into seven classes (0 to 6) by [23]. Adopting this measure, the Geoaccumulation index values ranged from -3.5996 to -3.2635 with an average of -3.4821. All the metals (Cr, Cu, Fe, Pb, Mn and Zn) Igeo values were practically uncontaminated (Igeo ≤ 0). The low contamination conditions in the stations could possibly be a self-purification mechanism of the river and direction of water flow.

There are five pollution degree and four risk levels recognized with respect to a comprehensive potential ecological risk index according to [29]. The ecological risk index values varied in relation to heavy metal. For the individual heavy metals, their ecological risk factor values ranged as follow Fe (0.9708 – 1.0380), Cu (4.7413 – 6.3527), Pb (4.0449 – 4.9621), Mn (9.9927 – 12.1136), Cr (1.9901 – 2.0992) and Zn (0.9374 – 1.0229). The PERI values were ranged from 24.0351 in Illushi River to 25.0756 in Okhuaihe River with an average of 20.4811. This showed that the potential ecological risk was low ($Eri < 40$) and the Risk Index was also low (RI < 150) [25, 29].

CONCLUSION

Information provided on sediment quality in the selected rivers, indicates that the rivers were good for aquatic life as a result of low-level pollution. Due to the fragile nature of the health of aquatic bodies, a continuous monitoring of these rivers is encouraged, as there is little or no data available on some of the environmental indices of the rivers. It provides a robust scientific foundation for sustainable management, conservation, and policy development. The assessment reveals heavy metals concentration had little or no effect on the aquatic health of the rivers.

Authors Contribution

O-E, C.U., A, F.O., A, A.V., C, V.I. and O, U.C. all contributed to the writing, data analysis, editing, reviewing and grammar check of this manuscript.

Consent for publication

We the authors grant the consent to publish this work.

Competing interests

The authors do not have any financial competing interest

Disclosure of Funding

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