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Research Article

Activity Concentration of ^{226}Ra and ^{232}Th in Sediments and Seawater of Cirebon (Northern West Java)

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Abstract

^{226}Ra and ^{232}Th are natural radionuclides with long half-lives, and they have a dangerous radiation exposure effect on marine biota and even humankind. This study investigates the activity concentration and horizontal distribution of natural radionuclides ^{226}Ra and ^{232}Th in sediments and seawater from the coastal waters of Cirebon, Indonesia, directly adjacent to the Cirebon Coal-Fired Power Station (CFPS). The activity concentrations of ^{226}Ra and ^{232}Th radioactivity were measured using gamma-ray spectrometry. Radioactivity analysis of ^{226}Ra and ^{232}Th was conducted on sediment and seawater columns. Furthermore, Ocean Data View (ODV) version 5.8.2 software was used to analyse the horizontal distribution pattern. The results showed that the highest concentrations of ^{226}Ra and ^{232}Th radioactivity were found in the sediment rather than the water column, even though they varied by location. The concentration activity of ^{226}Ra and ^{232}Th radioactivity was found to be a linear function of distance from the potential pollution source. Higher activity was detected at stations closer to the pollution source (CFPS). There was no significant effect of the depth of radionuclide distribution. Further monitoring activities at Cirebon's CFPS should be conducted to predict and manage the impact on biota and human life.

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1. Introduction

Cirebon waters have diverse and dynamic activities (Haryati *et al.*, 2023). Activities such as agriculture, industry, mining, and fisheries are known to be the leading sectors in the area (Jaelani, 2016). Using coal as a fuel for CFPS in industrial activity can cause NORM (Naturally Occurring Radioactive Material) (Malaka, 2019; Anggarini *et al.*, 2018). PT Cirebon Power Services (CPS), the coal-fired power plant established in 1980, was located in Cirebon (Yudisworo and Heri, 2019). Cirebon has 2 CFPSs capable of producing 660 mW and 1000 mW of electrical energy (Widiawaty *et al.*, 2020). The existence of the Cirebon CFPS with coal fuel contributes to changes in environmental qualities that are a concern on a national scale (Dede *et al.*, 2020). Coal combustion, as the driving force of CFPS turbines, contributes majorly to Naturally Occurring Radioactive Materials (NORM) (Prihatiningsih and Hudiyono, 2013). Coal used as CFPS fuel produces releases in the form of fly ash and bottom (Ozden *et al.*, 2018) and contains natural radionuclides ^{226}Ra and ^{232}Th in solid and gaseous form that can accumulate in the environment and living organisms (Cevik *et al.*, 2007).

Radium (Ra) and thorium (Th) are of concern in terms of their content in NORM because they have very long half-lives, are distributed throughout the environment (waters, sediments, air, soil, and foodstuffs) (Chau *et al.*, 2011; Milenkovic *et al.*, 2019). The effects of their radiation exposure are dangerous to human health (Taher *et al.*, 2018), and even the reproductive system, mortality, and morbidity of marine organisms (Garnier-Laplace *et al.*, 2008; Suliman and Alsafi, 2021). It is well known that radionuclides entering the marine environment contribute to increasing the radiation dose received by marine organisms and then transferred to humans through the food chain (Kiris and Baltas, 2019).

Cirebon is the necessary center for producing marine capture fishery products to ensure the availability of fishery food stocks in West Java province and DKI Jakarta (Supriyadi *et al.*, 2019). The potential of fish resources in Cirebon is more abundant, amounting to 27,553.01 tons in 2018 and 34,135 tons in 2020 (Central Bureau of Statistics-Cirebon Regency, 2021). However, along with the potential and high yield of fisheries production, several activities can cause an increase in radionuclide concentrations in Cirebon Waters. Natural radionuclides released into the marine environment will generally be dispersed through water and sediments (Aryanti *et al.*, 2021).

Studies on the presence of natural radionuclides in sediments globally have been conducted by most countries, such as the Potenga Sea (Yasmin *et al.*, 2018), the Nansha Sea (Liu *et al.*, 2021), the Barents (Yakovlev and Puchkov, 2020), the Gulf of Aliağa İzmir (Özden and Pehlivanoglu, 2021), and the Baltic Sea (Salahel and Vesterbacka, 2012). Meanwhile, only a small number of researchers at the global level have researched natural radionuclides in marine waters, such as Akram *et al.* (2005) in the Arabian Sea, Zare *et al.* (2015), and Darabi-Golestan *et al.* (2017) in the Oman Sea. In Indonesia, research on natural radionuclides in sediments has been conducted on the coast of Bangka Island (Prihatiningsih *et al.*, 2012), Tanjung Jati Jepara (Alviandini *et al.*, 2019), South Sulawesi (Prihatiningsih and Makmur, 2021), Central Sulawesi (Siregar *et al.*, 2021), and South Kalimantan (Prihatiningsih *et al.*, 2020). Meanwhile, research on natural radionuclides in Indonesian waters was conducted by (Sukirno *et al.*, 2003) in the Lemahabang Muria, and Sasongko *et al.* (2012) in the Muria Peninsula. Cirebon is one of the areas potentially polluted by natural radionuclides from various activities, which can result in increased levels of these radionuclides in the water column or sediment surface. Muslim *et al.* (2024) showed that the sediment surface radionuclide of Cirebon CFPS did not show any significant radiological health risk to the ecosystem, but still lacks information on natural radionuclides in the water column and their interconnection in the ecosystem. This research describes the horizontal distribution and initial concentration of specific radionuclides in the water column and the sediment surface of the Cirebon coastal water near the CFPS. Furthermore, it may serve as a basis for future monitoring of Cirebon's CFPS.

2. Materials and Methods

2.1 Materials

2.1.1 The equipment

Sediment equipment used in this research was a Sediment Grab (1,000 cm^2), Van Veen grab sampler (Duncan, Denmark), Sediment Cruiser (Sediment Cruiser Fritsch Pulverisette 14, Landsberger, Berlin), and Automatic Oven (Oven Memmert, Schwabach, Germany), Gamma Spectrometry (Canberra type GX2018, Mirion, Germany). Global Positioning System (Garmin GPS eTrex 10 Sea, Jakarta, Indonesia) was used to locate the accurate position of the sampling station. The early chemical seawater properties used a pH indicator (Universal Indicator, Merck, Germany). Vacuum filtration (Sigma-Aldrich, Merck, Germany) and a Polycarbonate filter (Sigma-Aldrich, Merck, Germany) were used for sample preparation before radionuclide analysis.

2.1.1 The materials

Seawater sample 40-60 liters, sediment sample of 2-3 kg for each station, ammonia (NH_3) 0.25 N (PA) (Sigma-Aldrich, Merck, Germany), $KMnO_4$ 250 µl 0.25 N (PA) (Sigma-Aldrich, Merck, Germany), $MnCl_2$ 100 µL 0.25 N (PA) (Sigma-Aldrich, Merck, Germany), Nitric acid (HNO_3) stock (PA) (Sigma-Aldrich, Merck, Germany), and standard reference (RG-U, RG-Th, RG-K, ^{152}Eu, Merck, Germany).

2.1.3 Ethical approval

This study does not require ethical approval because it does not involve the use of experimental animals.

2.2 Methods

2.2.1 Sampling methods

Sediment and seawater in situ samples were collected once in October 2022. Sediment samples were collected from five stations (Figure 1), while water column samples were collected from six stations (Figure 2) in the Cirebon coastal waters near a potential pollution source (CFPS). The station is designed to predict the impact of the distance variable on the horizontal distribution of radionuclide. The stations were located near the potential pollution source in shallow coastal water with depths of 10 to 20 m. The sampling coordinates were 6 stations for seawater column samples and 5 stations for sediment samples. The station coordinates for sea water column samples were station 1 (6^0 46' 04.75'' S / 108^0 36' 42.48" E), station 2 (6^0 45' 23.55'' S / 108^0 37' 01.35" E), station 3 (6^0 44' 55.44'' S / 108^0 37' 14.48" E), station 4 (6^0 45' 27.41'' S / 108^0 37' 34.24" E), station 5 (6^0 45' 53.39'' S / 108^0 37' 43.81" E), and station 6 (6^0 45' 47.77'' S / 108^0 36' 19.70" E). The station coordinates for sediment samples were station 1 (6^0 46' 04.75'' S / 108^0 36' 42.48" E), station 2 (6^0 45' 23.55'' S / 108^0 37' 01.35" E), station 3 (6^0 44' 55.44'' S / 108^0 37' 14.48" E), station 4 (6^0 45' 27.41'' S / 108^0 37' 34.24" E), and station 5 (6^0 45' 47.77'' S / 108^0 36' 19.70" E).

2.2.2 Sample preparation

Sediment samples were collected as much as 2-3 kg using a sediment grab, and then seawater samples were collected as much as 40-60 litres, acidified to pH <1, stored in a container/zip lock plastic, cooled (<10 °C), and labelled for laboratory analysis. Samples will be analysed in the next two days after sampling.

2.3 Analysis Data

2.3.1 Gamma spectroscopic analysis

Qualitative and quantitative analysis of radionuclide samples performed with a computer-based, High-Purity Germanium (HPGe) γ-spectrometry and connected to Genie-2000 analysis software (Akram *et al*., 2005; Diab *et al*., 2019). System calibration and γ-spectrum analysis were performed with Genie-2000 software (CANBERRA) (Akram *et al*., 2005; Diab *et al*., 2019). System calibration and analysis for efficiency calibration used International Atomic Energy Agency (IAEA) reference standards such as RG-U (4940 ± 30 Bq kg-1) and RG-Th (3250 ± 90 Bq kg-1) (Akram *et al*., 2005). The time spent counting measurements of the samples was approximately 295,000 seconds. The activity concentrations of ^{226}Ra and ^{232}Th were measured through their decay products in radioactive equilibrium. The concentration of ^{226}Ra was measured via γ-particles ^{214}Pb (295 keV, 351.9 keV) and ^{214}Bi (609.3 keV, 1120.3 keV, 1764 keV). The concentration of ^{232}Th was measured via γ-particles ^{212}Pb (238.6 keV), ^{228}Ac (911 keV, 338 keV), and ^{208}Tl (583 keV) (Akram *et al*., 2005).

2.3.2 Determination of radioactivity concentration of ^{226}Ra and ^{232}Th

For both samples, the radioactivity concentrations of ^{226}Ra and ^{232}Th were determined through their decay product activities using the following formula:

$$A = \frac{N}{e \times m \times \eta} \qquad \text{(i)}$$

Where :

A = is the concentration of radioactivity to be measured (Bq kg⁻¹) for sediment samples,
Bq/L = for seawater samples,
N = is the peak area per unit of time (counts/s),
e = is the peak abundance in the observed radionuclide,
m = is the mass of the sediment sample (kg),
η = is the efficiency value for each peak of the observed radionuclide (El-Taher *et al.,* 2010; Suseno and Prihatiningsih, 2014).

Extraction of radionuclides from seawater was carried out radiochemically through manganese dioxide (MnO_2) precipitation (Uddin *et al.,* 2017). In detail, 6 drops of 25% ammonia (NH_3) and 250 µL of $KMnO_4$ solution were added to 20 litres of filtered seawater sample. The samples were mixed with 100 µL of $MnCl_2$ solution, and MnO_2 suspension particles were formed. After 8 hours, the suspension was filtered using a 1 µm polycarbonate filter to obtain the MnO_2 precipitate. The precipitates were separated by vacuum filtration and then dried at 100-105 °C in an

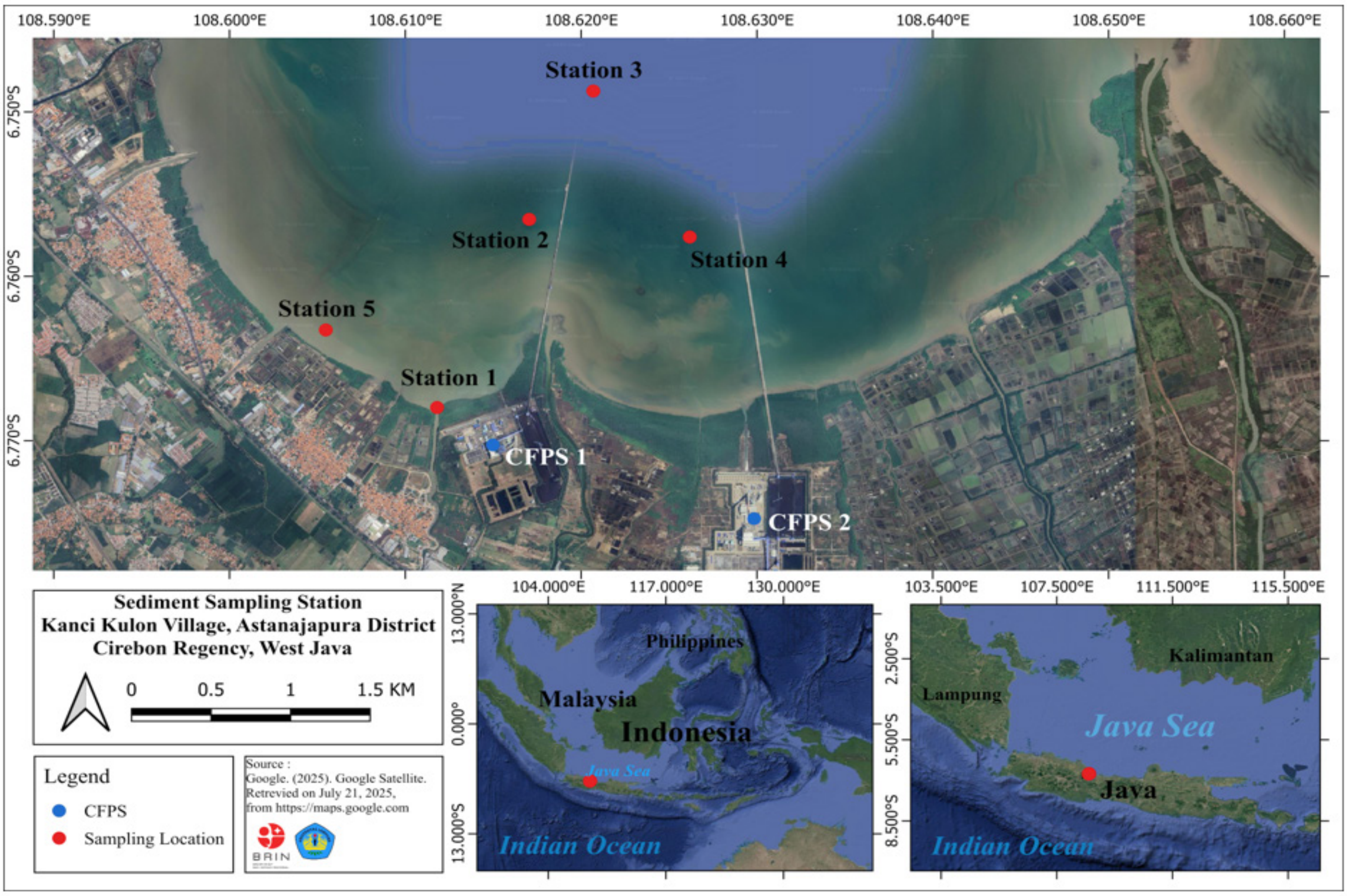

Figure 1. Sediment sampling stations.

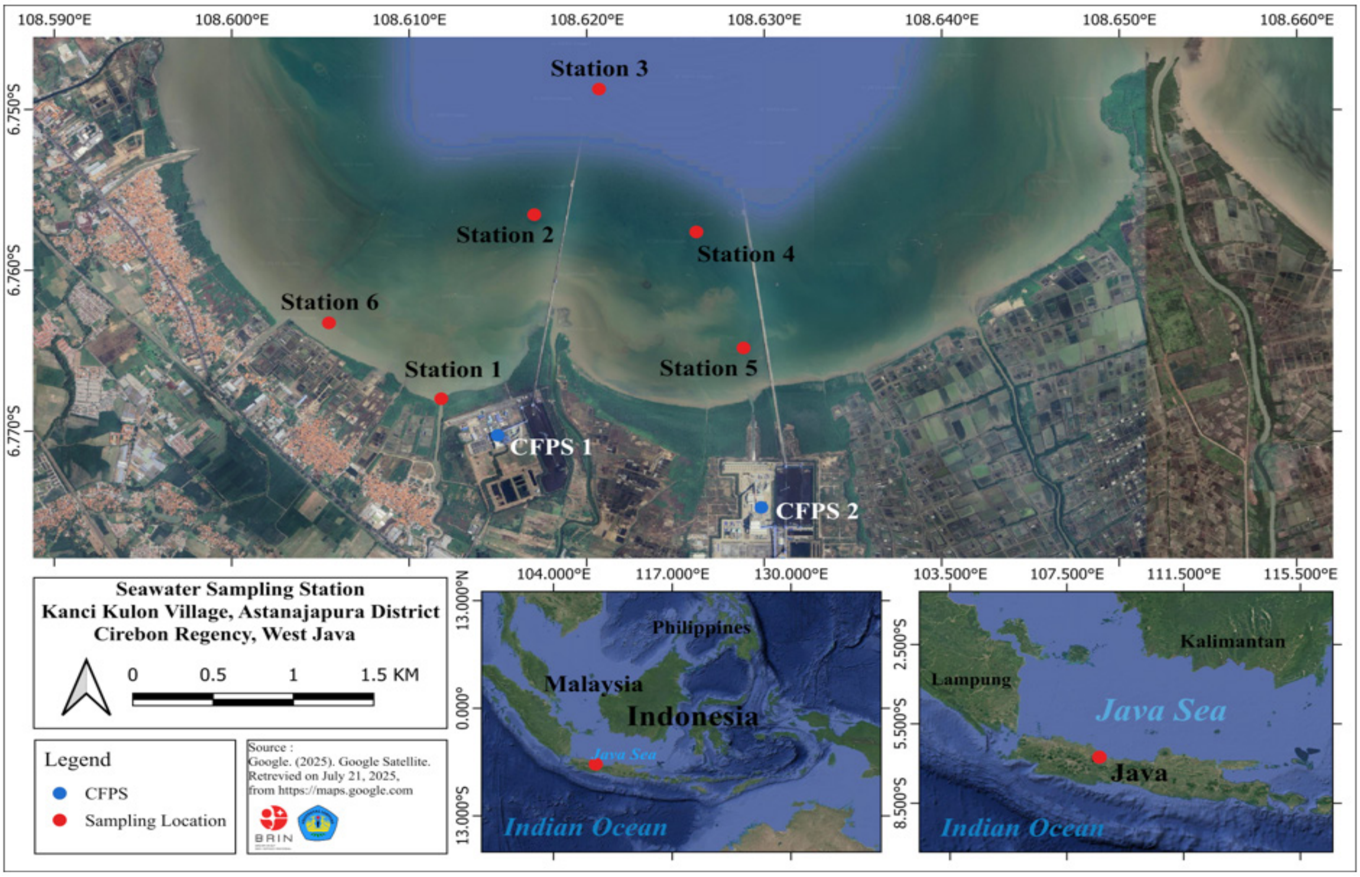

Figure 2. Seawater sampling station.

oven until they reached a constant weight. After the precipitate reached room temperature (25°C), the total precipitate was weighed and equated to the standard geometry (Loeff and Moore, 1999). The use of resins with MnO_2 can increase the concentration of the sample before it enters the radionuclide analysis or detection stage (Varga, 2007). The initial radioactivity concentrations of ^{226}Ra and ^{232}Th were too low to detect; the concentrations were determined from the average concentrations of their decay products. The total initial concentration of ^{226}Ra was determined by measuring the average radioactivity concentration of its decay element, i.e., ^{214}Pb and ^{214}Bi. Meanwhile, the total initial concentration of ^{232}Th was determined by measuring the average radioactivity concentration of, i.e., ^{212}Pb, ^{208}Tl, and ^{228}Ac (Hamby and Tynybekov, 2002).

2.3.3 Analysis and visualization of radioactivity concentration of ^{226}Ra and ^{232}Th

The horizontal distribution of each radionuclide was analyzed and visualized using Ocean Data View (ODV) online version 5.8.2 at https://webodv-egi-ace.cloud.ba.infn.it/. Spatial analysis was conducted using *Ocean Data View* (v5.8.2) with inverse distance weighting (IDW) interpolation at a 0.01° grid resolution. All measurements were performed in triplicate, with results expressed as mean ± 1 SD. Quality assurance was verified using IAEA-315 reference material with recovery rates of 95-103%.

3. Results and Discussion

3.1 Results

3.1.1 Radioactivity concentration

The radioactivity concentrations of ^{226}Ra and ^{232}Th in sediments worldwide (Table 2) and seawater worldwide (Table 3) can be compared with our samples (Table 1) from several stations (Figures 1 - 2). The highest radioactivity concentration for ^{226}Ra in sediment was detected at station 2 at 25.9 Bq/kg, and in seawater at station 1 at 0.0033 Bq/L. The lowest radioactivity concentration for ^{226}Ra in sediment was detected at station 4 at 23.7 Bq/kg, and in seawater at station 3 at 0.0014 Bq/L. The highest radioactivity concentration for ^{232}Th in sediment was detected at station 3 at 28.89 Bq/kg, and in seawater at station 3 at 0.0082 Bq/L. The lowest radioactivity concentration for ^{232}Th in sediment was detected at station 4 at 24.47 Bq/kg, and in seawater at station 2 at 0.0069 Bq/L. The average values of ^{226}Ra and ^{232}Th were 10,000 and 3,800 times higher than those in seawater samples, respectively. These were in line with the results of studies in other regions that report that the concentration of ^{226}Ra and ^{232}Th radioactivity in sediment samples is higher than in seawater samples (Sasongko *et al.*, 2012; Antovic and Ivanka, 2014; Tham *et al.*, 2022).

The horizontal distribution maps of radionuclides were processed using Ocean Data View (ODV)

Table 2. Comparison of radioactivity concentrations in sediments world wide

Region	Results of Natural Radionuclide Measurements (Bq/kg)		Source
	^{226}Ra	^{232}Th	
Cirebon Waters	23.75 – 25.94	24.47 – 28.89	Present Study
South Kalimantan	9.83 – 53.46	16.88 – 32.91	(Prihatiningsih *et al.*, 2020)
Banda Sea, Central Sulawesi	62.10	50.05	(Siregar *et al.*, 2021)
Coast of South Sulawesi	16.55 – 47.29	20.16 – 52.73	(Prihatiningsih and Makmur, 2021)
Tanjung Jati Jepara	42.42 – 77.77	99.19 – 212.34	(Alviandini *et al.*, 2019)
Coast of Bangka Island	18.69 – 627.17	74.78 – 2333.50	(Prihatiningsih *et al.*, 2012)
Potenga Sea, Bangladesh	94.39	121.9	(Yasmin *et al.*, 2018)
Nansha Sea, South China Sea	14.60 – 38.51	15.81 – 49.21	(Liu *et al.*, 2021)
Barents Sea, Russia	0.50 – 48.30	3.60 – 54.00	(Yakovlev and Puchkov, 2020)
Aliağa Bay, İzmir (Türkiye)	23.54 – 59.46	37.54 – 64.37	(Özden and Pehlivanoglu, 2021)
Baltic Sea, Finland	45 – 98	75 – 83	(Salahel and Vesterbacka, 2012)

Table 3. Comparison of radioactivity concentrations in seawater world wide

Region	Results of Natural Radionuclide Measurements (Bq/L)		Source
	^{226}Ra	^{232}Th	
North Coast of The Sea of Oman	2.19 – 2.82	1.66 – 2.17	(Zare *et al*., 2015; Darabi-Golestan *et al*., 2017)
Eastern Black Sea Coast, Turkiye	0.0022 – 0.00468	0.00289 – 0.00483	(Kiris and Baltas, 2019)
Gulf of Tonkin (Quang Ninh), Vietnam	0.00703 – 0.0113	0.00162 – 0.00232	(Tham *et al*., 2022)
Muria Peninsula Beach Waters	0.02 – 0.65	0.01 – 0.14	(Sasongko *et al.,* 2012)
Southern Adriatic Sea (Boka Kotorska Bay)	0.08	0.10	(Antovic and Ivanka, 2014)
Mediterranean Sea Coast, Egypt	5.4	3.1	(Ramadan *et al*., 2017)
Republic of Montenegro	0.00161 – 0.0198	0.00109 – 0.00775	(Andjelic *et al*., 2003)
Wanasa Beach, Kuwait	4.21	1.02	(Abbas *et al*., 2020)
Cirebon Waters	0.0014 – 0.0033	0.0069 – 0.0082	This research

Table 1. Radioactivity concentration in Cirebon coastal water

	Sediment Radioactivity Concentration (Bq/kg)		Seawater Radioactivity Concentration (Bq/L)	
Elemen	^{226}Ra	^{232}Th	^{226}Ra	^{232}Th
Mean	25.05 ± 0.7982	27.8 ± 1.8526	0.0025 ± 0.0006	0.0073 ± 0.0005
Range	23.75 – 25.94	24.47 – 28.89	0.0014 – 0.0033	0.0069 – 0.0082

software. Spatial distribution maps generated using *Ocean Data View* revealed slightly elevated activities at offshore stations, suggesting lateral sediment transport dominates over direct inputs from the CFPS dis charge. Variations in the concentration of natural radioactivity ^{226}Ra and ^{232}Th were detected from samples in the Cirebon Coastal Waters area facing the CFPS (Figures 4 and 5). Figure 3 presents a spectrum sample

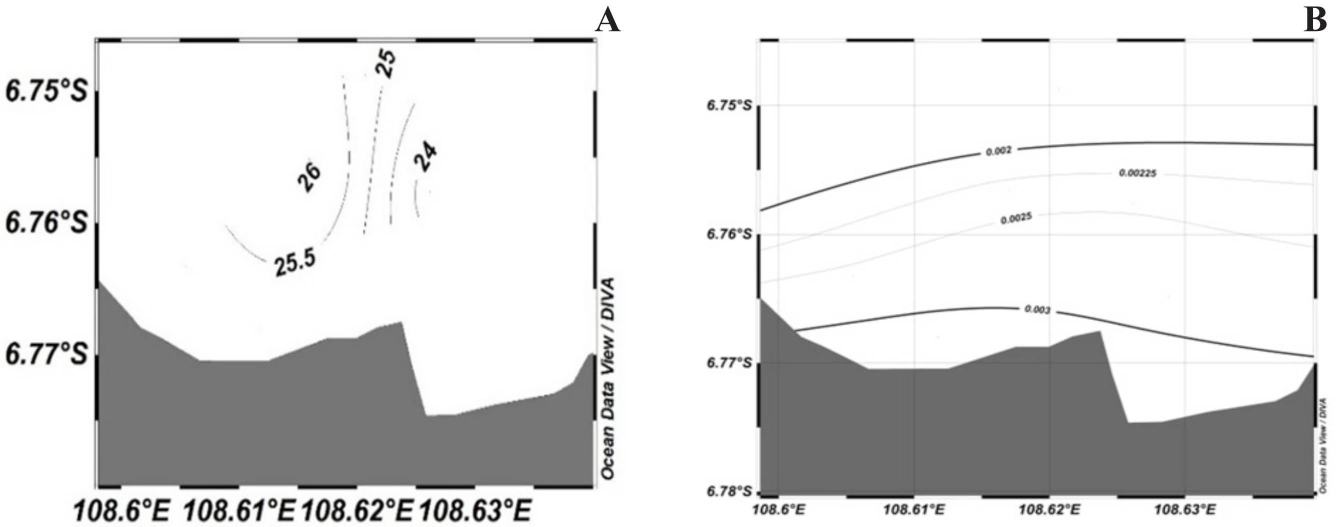

Figure 4. Distribution map of ^{226}Ra in Cirebon waters (a) sediments (b) waters.

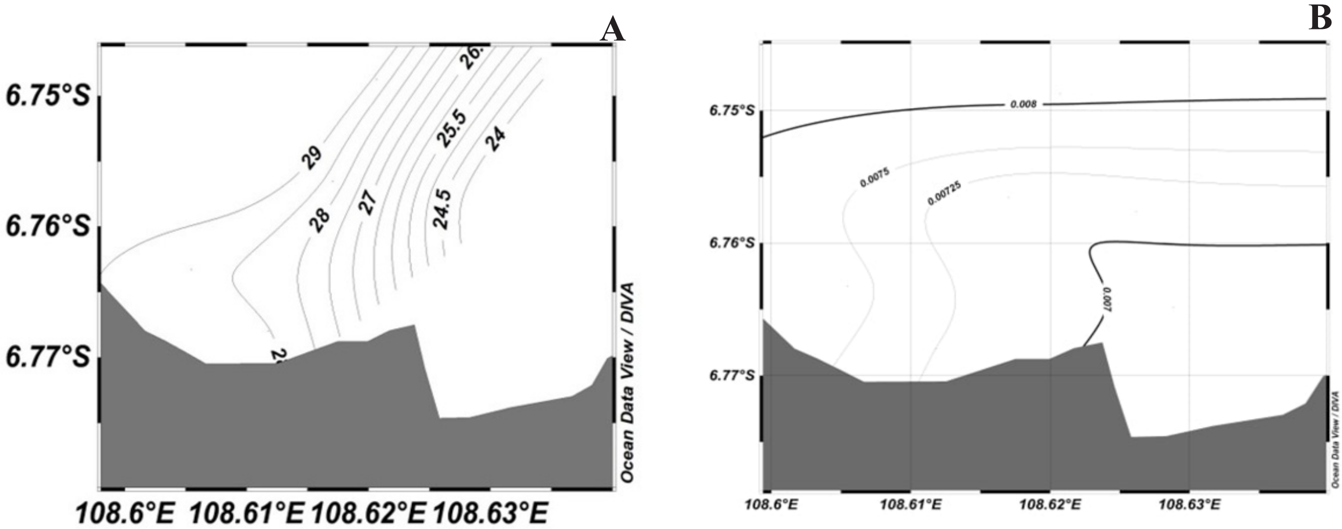

Figure 5. Distribution map of ^{232}Th in Cirebon waters (a) sediments (b) waters.

from the Gamma Spectrometer, which shows energy peaks of radionuclides as described in the methods. Figures 4 and 5 illustrate the distribution patterns of the natural radionuclides ^{226}Ra and ^{232}Th in the waters of Cirebon, highlighting distinct behaviours in sediment and water. In Figure 4b, it is evident that the concentration of ^{226}Ra tends to be higher in the southern part of the study area, which is closer to the coastline. Near the shore, the concentration reaches 0.003 Bq kg^{-1}, while at the farthest point from the land, it is recorded at 0.002 Bq kg^{-1}. The concentration of ^{226}Ra in the water column is lower than that of ^{232}Th (Figures 4b and 5b). In contrast, Figure 5b indicates that ^{232}Th concentrations are relatively higher at locations farther from the shore, reaching up to 0.008Bq kg^{-1}, compared to 0.007 Bq kg^{-1} near the coast. Both radionuclides exhibit a similar trend, with their concentrations in sediments being higher than in the water column, as shown in Figures 4 and 5. However, they also display relatively uniform concentration values across the study area. This uniformity may be attributed to differences in the origin and mobility of the two radionuclides in the marine environment.

3.1.2 Influence of depth

Figure 6 illustrates the relationship between depth and the concentrations of radioactivity for ^{226}Ra (a) and ^{232}Th (b) in sediment. Each point on the graphs corresponds to a specific sampling station at a given depth. The data suggest that there is no linear relationship between depth and radionuclide concentration in the sediment. However, points 1 and 5, which represent the shallowest depths, along with point 3, the deepest station, show relatively similar levels of radioactivity for both ^{226}Ra and ^{232}Th.

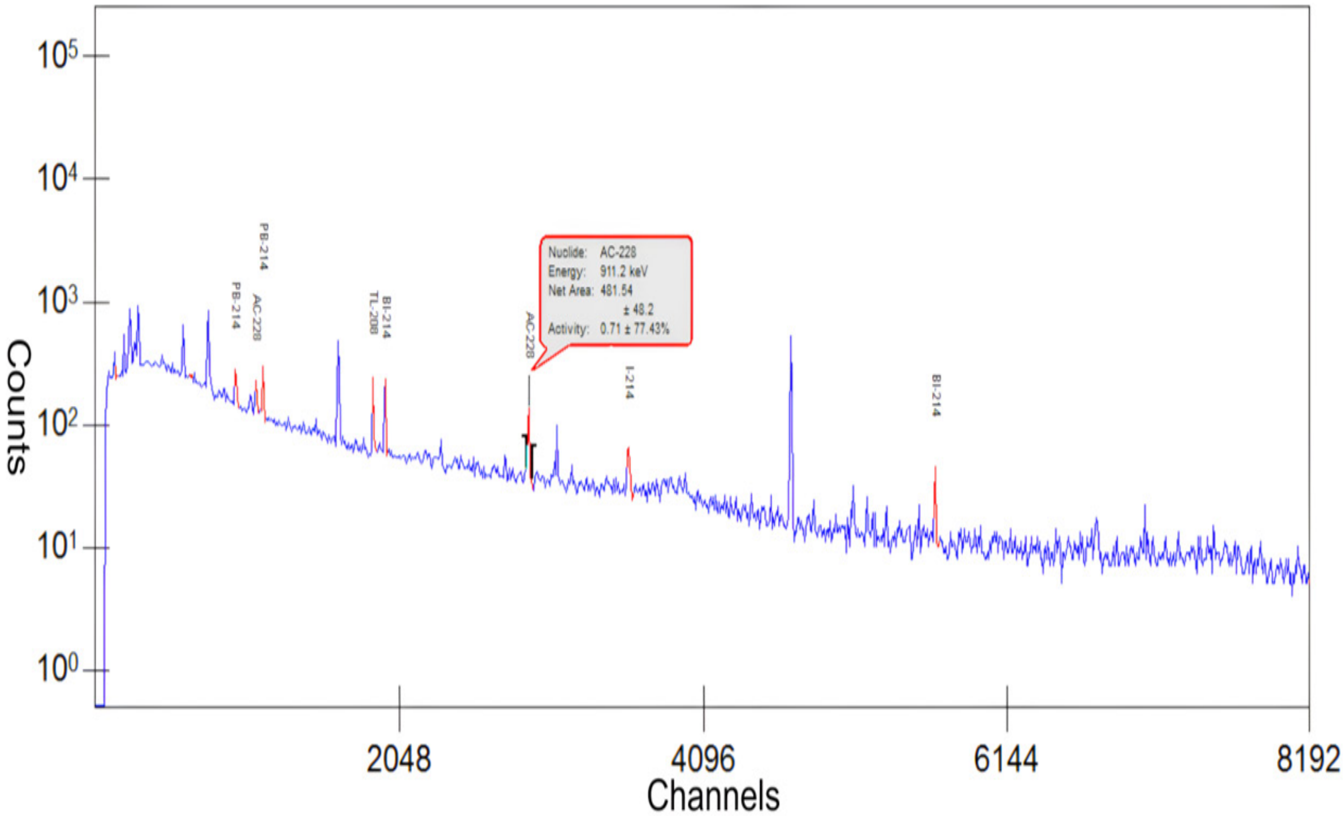

Figure 3. Sampel spectrum of gamma spectrometer.

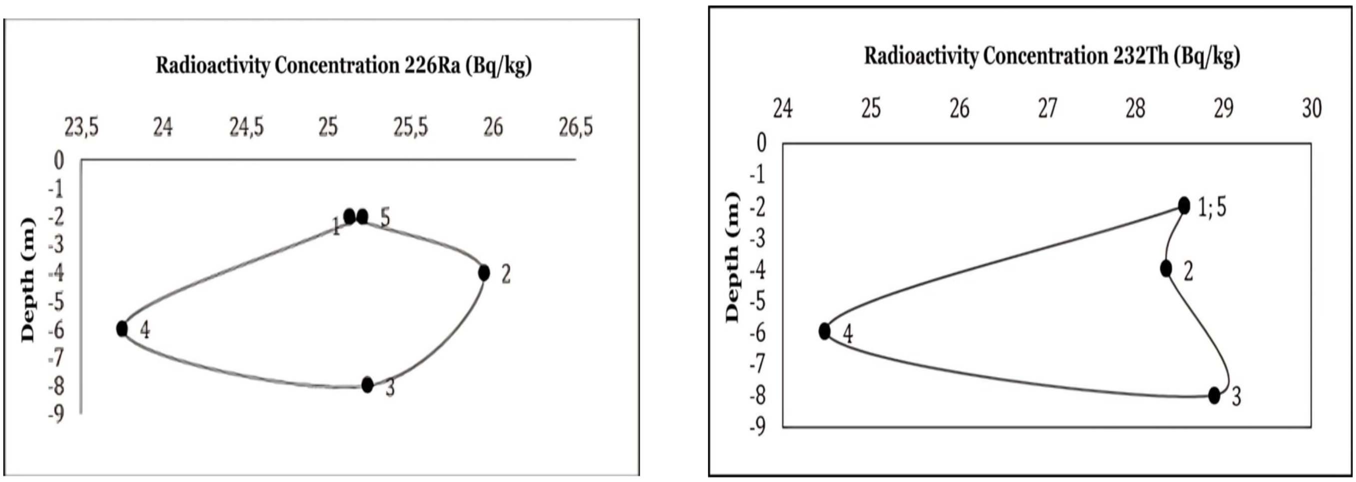

Figure 6. Graph of the relationship between the concentration of radioactivity in sediments at each station (•) and the depth (a) ^{226}Ra and (b) ^{232}Th.

3.2 Discussion

3.2.1 ^{226}Ra and ^{232}Th behaviour

The presence of ^{226}Ra in the seawater column may drive its concentration in sediments of Cirebon waters, which are dominated by fine silt sand (Muslim *et al.*, 2024; A. A. Ramadan and Diab, 2013; Ramasamy *et al.*, 2011). Fine silt sand has a wider layer of adsorption than other larger sediment fractions, so it can bind more elements according to the coarse-grained size (Yii *et al.*, 2007; Alviandini *et al.*, 2019; Pappa *et al.*, 2016; Patiris *et al.*, 2016). In addition, high activity values at some station points may also be associated with radionuclide sources originating from fly ash as waste from CFPS activities (Pandit *et al.*, 2011) stated that natural radionuclides in fly ash are two to five times higher than raw coal, so stations close to CFPS activities around Cirebon waters have the potential to obtain higher activity values. (Pandit *et al*., 2011) stated that natural radionuclides in fly ash are two to five times higher than in raw coal, so stations close to CFPS activities around Cirebon waters have the potential to obtain higher activity values. The activity value of ^{226}Ra is influenced by the chemical properties of the element (Marwoto *et al*., 2019), such as its high solubility in sediment (Ramasamy *et al*., 2011; Suresh *et al*., 2011; Alfonso *et al*., 2014; Al-Absi *et al*., 2016; Alviandini *et al*., 2019; Fallah *et al*., 2019; Suliman and Alsafi, 2021); volatility; and condensation (Hasani *et al*., 2014). ^{226}Ra is mobile (Papaefthymiou *et al*., 2017) and undergoes chemical reduction, and it can be deposited in sediments (Zheng *et al*., 2002; Papaefthymiou *et al*., 2017).

Song *et al*. (2017) stated that the farther away the pollutant source, the smaller the concentration of radium radioactivity because it is affected by the process of dilution and radioactive decay. The detection of ^{226}Ra in Cirebon waters is related to the highly soluble nature of ^{226}Ra in water (Khandaker *et al*., 2015; Suliman and Alsafi, 2021), the ability to maintain its presence after being released into seawater (Charette *et al*., 2007), the process of dissolution and desorption in water (Kiro *et al*., 2014), the decay of the parent nuclide in seawater (Yi *et al*., 2019) and the dissolution of mineral grains containing radium (Kraemer *et al*., 2014). The horizontal distribution of ^{226}Ra in Cirebon Coastal Waters was higher in waters close to the pollutant source and lower as the distance from the source increased. The high concentration of ^{226}Ra in some stations may be associated with the nearest station position to CFPS Cirebon. The waste products from CFPS are known to be a natural source of radionuclides that enter the environment (Cevik *et al*., 2007; Papp *et al*., 2002). In accordance with the statement of Bhangare *et al*. (2014), coal-fired CFPS releases natural radionuclides during the combustion process that can cause high radioactivity.

The value of ^{232}Th activity can be associated with geochemical properties (Ramasamy *et al*., 2011; Suresh *et al*., 2011; Alfonso *et al*., 2014; Alviandini *et al*., 2019). Thorium is insoluble in seawater (Jurina *et al*., 2013; Suresh *et al*., 2011), and it is often associated with solid materials (El-Taher and Madkour, 2011; Alfonso *et al*., 2014; Ravisankar *et al*., 2015; Al-Absi *et al*., 2016; Papaefthymiou *et al*., 2017; Fallah *et al*., 2019), so the thorium activity value obtained in sediments was higher. The presence of ^{232}Th may be influenced by sediment properties in Cirebon waters, which are dominated by silt sand. Grain size with fine texture has a larger surface area (Ramadan and Diab, 2013; Ramasamy *et al*., 2011), so it can bind stronger elements than coarse-grained size (Yii *et al*., 2007; Alviandini *et al*., 2019; Pappa *et al*., 2016; Patiris *et al*., 2016). Pandit *et al*. (2011) stated that natural radionuclides in fly ash are two to five times higher than in raw coal. We may assume that the CFPS Cirebon activity may generate potentially higher radionuclide activity values around the Cirebon coastal water.

Thorium is a reactive particle (Lippold *et al*., 2012; Santschi *et al*., 2006) of a larger size (Kenny *et al*., 2019; Rehman *et al*., 2013) that can be removed quickly in the water column, then it is deposited in the sediments (Lippold *et al*., 2012). Thorium is insoluble in water or almost completely insoluble (Khandaker *et al*., 2015; Suliman and Alsafi, 2021) and easily dissolves in non-polar substances (Cotton and Wilkinson, 1988 in Ma *et al*., 2016). These phenomena are also related to the location of Cirebon waters, located in the northern coastal waters of Java, making the area widely used for shipping activities (Nurkhasanah *et al*., 2019) and becoming an international gateway to the region (Jaelani, 2016; Muslim *et al*., 2024). Cirebon City has a port that plays an active role in national and international trade, which cannot be separated from shipping activities (Astuti, 2018). It is assumed that the high concentration of ^{232}Th radioactivity at station 3 was influenced by shipping activities that can cause sediment resuspension in these waters. It is well known that the resuspension process is one of the sources of radionuclides detected in seawater (Darabi-Golestan *et al*., 2017; Muslim *et al*., 2024; El-Saharty, 2013).

3.2.2 Distribution of ^{226}Ra and ^{232}Th

The highest concentration of ^{226}Ra radioactivity was detected at a depth of (-6 m), while the highest concentration of ^{232}Th radioactivity was detected at a depth of (-8 m). Water depth affects the resuspension and deposition of radionuclide material (Marwoto *et al*., 2019). In addition, depth also affects particle sedimentation time. Putra and Nugroho, (2017) in Pawitra *et al*. (2022) stated that sediment distribution correlated with depth, while the deeper sediment is relatively finer. Finer sediment particles are found in suspension over a longer time and distance. In line with the increase in the weight of sediment particles, particles are likely to quickly settle in areas close to the source (Ikhwan *et al*., 2015; Selim *et al*., 2022). According to Kurniawan *et al*. (2014) and Marwoto *et al*. (2019), water conditions, such as current speed and bathymetry, result in continuous stirring. The stirring potentially caused sediment resuspension and provided radionuclides bound to sand-textured sediments into the air. The release of radionuclides from sediments reduced the activity value of radionuclides in sediments (Muslim *et al.*, 2015; Marwoto *et al.*, 2019).

The results of radionuclide activity values obtained in Cirebon waters near CFPS are compared with other studies (national and international). The range of ^{226}Ra and ^{232}Th activity values in Cirebon waters is much lower than the values reported in South Kalimantan, Central Sulawesi, Banda Sea, South Sulawesi Coast, Tanjung Jati Jepara, and Bangka Island Coast, Nansha Sea, Russian Barents Sea, Aliağa Bay, İzmir, Turkey, Potenga Sea, Bangladesh, and Baltic Sea. However, based on the comparison with other studies (national and international), the highest activity value is found in the coastal area of Bangka Island. The high activity value is due to the tin mining activity and geological formations (Prihatiningsih *et al.*, 2012). Tin ore contains uranium and thorium that bind to various minerals (Prihatiningsih *et al.*, 2012), so it has the potential to increase natural radionuclides ^{226}Ra and ^{232}Th in the environment around the coast of Bangka Island.

Differences in activity values are influenced by geological formations (Salahel and Vesterbacka, 2012; Ravisankar *et al.*, 2015; Yasmin *et al.*, 2018), the process of deposition of radionuclides and heavy minerals along the coastline at high tide (Alshahri, 2017; Zorer, 2019; Wais and Najam, 2021), chemical properties (Onjefu *et al.*, 2017; Ramasamy *et al.*, 2011), physical, and geochemical properties and their environment (Agbalagba and Onoja, 2011; Al-Trabulsy *et al.*, 2011; El-Taher and Madkour, 2011; Alfonso *et al.*, 2014; Al-Absi *et al.*, 2016; Ravisankar *et al.*, 2015; Uosif *et al.*, 2016; Zakaly *et al.*, 2019). Differences in particle size distribution also affect the variation of natural radionuclide activity values in marine sediments (Jurina *et al.*, 2013; Ravisankar *et al.*, 2015; Ulyantsev *et al.*, 2023). The amount of radionuclide accumulation in marine sediments depends on the chemical properties of the radionuclide, the physical and chemical properties of the sediment: sediment type, grain size, and organic content, and geography: flow direction and flow rate (Khuntong *et al.*, 2015; Muslim *et al.*, 2024).

In Southeast Asian regions, such as Indonesia and Vietnam, the radioactivity concentration of ^{226}Ra ranged from 0.00703 Bq/L to 0.65 Bq/L, and ^{232}Th ranged from 0.00162 Bq/L to 0.14 Bq/L. The highest radioactivity concentration was found in Indonesia's Muria Peninsula region. The candidate area of a nuclear power plant on the Muria Peninsula (Asmara, 2020), a power plant in Tanjung Jati (Kurniawan *et al.*, 2014), and mining activities that are potential resources on the Muria Peninsula (Wiyono dan Sunarto, 2016) are known to be natural sources of radioactivity in the region. The detection of ^{226}Ra and ^{232}Th in Vietnam is attributed to mining activities that are well known to produce radioactive elements in the form of dust (Csavina *et al.*, 2012). The Rare Earth Elements (REE) mining activities are well known to spread in Vietnam, especially in northern Vietnam (Van *et al.*, 2019). In West Asian regions such as Oman, Turkey, and Kuwait, radioactivity concentrations of ^{226}Ra ranged from 0.0022 Bq/L to 4.21 Bq/L, and ^{232}Th ranged from 0.00289 Bq/L to 2.17 Bq/L. The high concentration of radioactivity detected in the Oman region is related to mining activities, which were the most common industrial activities in the region (Palanivel and Victor, 2020). Potential natural sources of radionuclides in Turkey originate from plutonic and volcanic rocks that are common in certain areas of Turkey (Temizel *et al.*, 2020). Plutonic rock types such as granodiorite and granite are also found in other areas of Turkey (Kaygusuz *et al.*, 2021). Plutonic rocks are rock types with high levels of natural radioactivity (Yalcin *et al.*, 2020).

Moving to the European region, Montenegro has higher radioactivity concentrations of ^{226}Ra, ranging from 0.00161 Bq/L to 0.08, and ^{232}Th, of 0.00109 Bq/L to 0.10 Bq/L. Montenegro is a region with many rocks, e.q. sediments, metamorphic, and magmatic rocks were highly associated with thorium (Dragovic *et al.*, 2006). Moreover, the coastal part of Montenegro has active volcanoes such as Mount Lovcen (Žebre and Stepisnik, 2014) and Mount Orjen (Woodward *et al.*, 2014). It may contribute to the concentration of ^{226}Ra and ^{232}Th radioactivity in Montenegro. Moving to northern Africa, the ^{226}Ra and ^{232}Th radioactivity concentrations found in Egypt were 5.4 Bq/L and 3.1 Bq/L. Egypt is known to have a phosphate rock industry with a smaller activity level, which affects the level of radioactivity (Abbady *et al.*, 2005). The concentration activity of radionuclide detected in Cirebon coastal waters tends to be lower than the concentration activity value of radionuclide in seawater samples from several regions of the world.

4. Conclusion

Based on the research conducted in the coastal waters of Cirebon near CFPS, it was concluded that the concentration of ^{226}Ra and ^{232}Th radioactivity detected in the sediment is higher than in the water column. These higher concentrations of them in sediment may indicate higher accumulation processes of them in sediment. The radionuclides' activity monitoring should be provided to ensure they are managed according to government regulations and decrease further impact on biota and humankind.

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Authors' Contributions

All authors have contributed to the research project. Each author's contribution is as follows: MM; Conceptualization, Supervision, Writing – original draft, review & editing, resources, formal analysis. WRP; conceptualization, funding acquisition, resources, methodology, writing – original draft, review & editing. MNY; investigation, formal analysis, resources, methodology. YP; investigation, formal analysis, resources, methodology. ADP; writing – original draft, formal analysis, visualization. SMA; writing – original draft, formal analysis, visualization. MM; investigation, formal analysis, resources. DIPP; investigation, formal analysis, resources. AW; formal analysis, methodology.

Conflict of Interest

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

Declaration of Artificial Intelligence (AI)

We affirm that no artificial intelligence (AI) tools, services, or technologies were employed in the creation, editing, or refinement of this manuscript. All content presented is the result of the independent intellectual efforts of the authors, ensuring originality and integrity.

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