Potential Radiological Dose of $^{210}$Po to Several Marine Organisms in Coastal Area of Coal-Fired Power Plant Tanjung Awar – Awar, Tuban

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Abstract

NORM (Naturally Occurring Radioactive Material) is a radionuclide element that naturally already exists in the earth. Its concentration can be increased by industrial activities, such as coal-fired power plant (CFPP). Coal-fired power plant activities produce fly ash and bottom ash which will be carried away by the wind and then can enter the CFPP environment, one of which is marine waters and can affect the existence of marine biota. The determination of the radiation dose rate is essential in assessing the risk of radionuclide exposure to the marine environment. This study aims to determine and evaluate the total dose rate of $^{210}$Po to marine biota taken from the Karangsari fish market with catchment areas around the waters of CFPP Tanjung Awar – Awar, Tuban, East Java. This research was conducted in April 2021 in the waters of CFPP Tanjung Awar – Awar. $^{210}$Po measurement activity was carried out using alpha ray spectrometry at the Marine Radioecology Laboratory of PTKMR-BATAN, then the radiation dose rate was calculated using the ERICA Tool software. The value of the total radiation dose of $^{210}$Po on marine biota ranges from 2.70E-1 μGy.h⁻¹ to 39.70E+0 μGy.h⁻¹. The radiation dose of $^{210}$Po on marine biota measured in the waters of CFPP, has a lower value range than the research result carried out in other countries. Based on the Erica Tools software analysis, the total radiation dose measured on marine organisms in the waters of CFPP Tanjung Awar – Awar, does not give a negatively impact to the marine ecosystems and the sustainability of marine organisms in the study area.

Keywords: Radiation dose rate, $^{210}$Po, ERICA tools, marine biota, CFPP waters.

Introduction

Globally, coal is one of the essential energy sources, especially in the power generation sector up to 39%, contributing the electricity production called coal-fired power plant (IAEA, 2010). In Indonesia, Presidential Regulation No. 71/2006 is the basis for constructing a coal-fired power plant (CFPP) known as the 10,000 MW CFPP Acceleration Project.

CFPP Tanjung Awar – Awar, Tuban, East Java is one of the coal-fired power plant included in the 10,000 MW Energy Diversification Acceleration Program (EDAP) Phase 1 with a capacity of 2 x 350 MW (Riadessy, 2015). The fuel used is low-calorie coal from Bontang, Kalimantan, with 160 tons.h⁻¹ of coal consumption to produce 700 MW of electrical energy (Riadessy, 2015).

The use of coal as a power plant fuel can produce releases in fly ash and bottom ash containing natural radionuclides or Naturally Occurring Radioactive Material (NORM) with certain activities (Ozden et al., 2018). In the coal combustion process at CFPP, there will be cracking, which causes natural radionuclides to come out with other emission gases through bottom and fly ash which contain NORM ten times higher than the original value (Hvistendahl, 2007). Natural radioactive elements are also concentrated in this processing and form a radioactive concentrate called TENORM (Pandit et al., 2011).

According to Susiati (2005), the most dominant radioactive pollutants in coal samples are radioactive elements such as $^{210}$Pb, $^{210}$Po, $^{231}$Pa, $^{226}$Ra, $^{238}$U, $^{232}$Th, $^{14}$C, $^{40}$K (Table 1). Radioactive pollutants numbers 1 to 6 belong to the group of heavy metals when it comes in the human body will follow the level route that negatively impacts human health.

$^{210}$Po is one of the natural radionuclides produced in CFPP processing ($T_{1/2} = 138.4$ d) (Alam and Mohamed, 2011). $^{210}$Po is an alpha-emitting...
natural radionuclide produced by the decay chain of $^{238}\text{U}$ through $^{210}\text{Pb}$ and $^{210}\text{Bi}$, but can also be generated by the activation of the neutron $^{209}\text{Bi}$ (Gjelsvik et al., 2012). Various marine organisms can accumulate $^{210}\text{Po}$, it is the main contributor (90%) to the natural radiation dose from alpha-emitting radionuclides received by most marine organisms (Alam and Mohamed, 2011), which make it responsible for the majority of the absorbed dose received by a human from seafood ingestion (Makmur et al., 2020). It may contribute almost 80% of the total dose received by humans (Makmur et al., 2020). Alpha radiation that comes out of $^{210}\text{Po}$ is an internal-radiation hazard, which is very dangerous if it enters the human body through the consumption of marine biota because it has a large ionizing power (Gjelsvik et al., 2012). Natural radionuclides in certain amounts can increase the risk of cancer if it enters the human body (Alam and Mohamed, 2011).

Fly ash has physical properties that are heavier than air (Lockwood and Evans, 2012). At a particular moment, it will fall into the environment around the power plant, which is usually dominated by sea waters (Alviandini et al., 2019). Most radionuclides that accumulate in the marine environment contribute to external radiation sources. The higher the natural radionuclide content in the area is, the higher the radiation dose rate is (Júnior et al., 2017).

Natural radionuclides released into marine waters will generally be spread through abiotic components (water and sediment). Through these components, there is also accumulation into the biota. Thus, this incident can slowly disrupt the life of biota and human life that consumes the marine biota (Suseno and Prihatiningsih, 2014).

Marine organisms risk exposure to internal and external radiation through radionuclide contamination mechanisms is found in the marine environment (Suseno and Prihatiningsih, 2014). External contamination occurs when the radionuclide attaches to the outside of the biota’s body (ERICA, 2021). In contrast, internal contamination occurs when the radionuclide enters the biota’s body through the respiratory tract (inhalation), ingestion, or absorption through the skin (Tsuchiya et al., 2017). The concentration of $^{210}\text{Po}$ in the edible portions of marine organisms may be many folds higher than that in the seawater because of the biological re concentration process (Mustafa and Krishnamoorthy, 2012). This is especially so with filter feeder mussels, which ingest detritus material with a high degree of radionuclide association. It has been recognized internationally that filter-feeding bivalve mollusks act as first-order biological indicators of radioactive pollution (Macklin Rani et al., 2014).

Based on research (Alam and Mohamed, 2011) conducted at the coal-fired power plant industry in the Kapar coastal area of Malaysia, the biota that has potential for public consumption and the highest $^{210}\text{Po}$ activity when compared to other biota is Anadara granosa, it is included in mollusks and Penaeus merguiensis, which is included in crustaceans. Mishra et al. (2009), reported that $^{210}\text{Po}$ was non-uniformly distributed within the Mumbai coastal ecosystem. The highest values were associated with mollusks, the second-highest values with crustacea, and the lowest for fish.

According to Melawati (2003), radiation exposure from natural radionuclide up to 10.48 mSv/48 h resulted in disturbances in the larva stage (sensitive growth stage) of tiger prawn seeds in a mortality rate of as much as 50%. Thus, it is crucial to determine the radiation dose rate in the process of assessing the risk of radionuclide exposure to natural resources in the marine environment.

The $^{210}\text{Po}$ study related to CFPP operations has never been carried out in Indonesia. Many studies on NORM release from CFPP have been carried out, but only for environmental monitoring (Alviandini et al., 2019; Anggarini et al., 2018). Studies of its accumulation in several biotas have also been carried out in Malaysia (Abdullah et al., 2015), Northern Arabian Gulf (Uddin et al., 2017), Korea (Kim et al., 2017), and Vietnam (Duong Van, 2020). On the other hand, the impact of CFPP operations on its accumulation in marine biota based on an increase in the concentration of $^{210}\text{Po}$ has been carried out in Malaysia (Alam and Mohamed, 2011).

A further study of radionuclide monitoring in the marine environment is to examine the impact on marine waters, including marine biota in the research area (Suseno and Prihatiningsih, 2014; Prihatiningsih et al., 2016). Several models have been developed to facilitate the assessment of the radiological impact of ionizing radiation on various species of biota, one of the most widely used models is the Erica Tool (Brown et al., 2004; Brown et al., 2008; Gjelsvik et al., 2012; ERICA, 2021). The use of the Erica Tool has been widely applied in various environmental conditions (Brown et al., 2004; Khan et al., 2014). Using the Erica Tool, radiological studies on marine ecosystems have also been carried out to calculate the radiation impact of $^{134}\text{Cs}$, $^{137}\text{Cs}$, $^{90}\text{Sr}$, and $^{110}\text{Ag}$ caused by the Fukushima nuclear reactor accident on Japanese marine biota (Yu et al., 2015).
Table 1. Dominant Radioactive Pollutants from Coal Burning

| Number | Pollutant          | Symbol | Radiation | Half Life    |
|--------|--------------------|--------|-----------|-------------|
| 1      | Timbal-210         | $^{210}\text{Pb}$ | Beta      | 19.4 Year   |
| 2      | Polonium-210       | $^{210}\text{Po}$ | Alpha     | 138 Days    |
| 3      | Protactinium-231   | $^{231}\text{Pa}$ | Alpha     | $3,43 \times 10^4$ Year |
| 4      | Radium-226         | $^{226}\text{Ra}$ | Alpha     | 1620 Year   |
| 5      | Thorium-232        | $^{232}\text{Th}$ | Alpha     | $1,39 \times 10^{10}$ Year |
| 6      | Uranium-238        | $^{238}\text{U}$ | Alpha     | 4.5 x 10 Year         |
| 7      | Carbon-14          | $^{14}\text{C}$ | Beta      | 57.30 Year   |
| 8      | Potassium-40       | $^{40}\text{K}$ | Alpha     | $1.28 \times 10^3$ Year |

Source: (Susati, 2005)

The same method would be used to assess the impact of $^{210}\text{Po}$, which is thought to come from the CFPP flying ash release on marine biota in the waters of CFPP Tanjung Awar-Awar, Tuban, which is calculated using the Erica tool as the software. Study of radiation dose on biota can provide a complete picture of the effect of these natural radionuclides on the sustainability of natural resources in the marine environment (Brown et al., 2004; Brown et al., 2008; Khan et al., 2014; Mahmood et al., 2021; ERICA, 2021).

Therefore, such a study on the estimation of $^{210}\text{Po}$ dose rate is crucial to assess the level of radiological safety to marine organisms. With that, we have therefore calculated the radiation doses absorbed by diverse marine organisms. Thus, this study aims to determine and evaluate the total dose rate of $^{210}\text{Po}$ to marine organisms using the ERICA Tools Assessment.

Materials and Methods

Sample collection

A sampling of marine biota was carried out in March 2021. The samples used are biota that has potential for public consumption. Referring to the researches (Alam and Mohamed, 2011; Suseno and Prihatiningsih, 2014; Kim et al., 2017), samples of popular seafood (fish, shrimp, cuttlefish, squid, and crab) were collected from fresh catch sold in the local fish market in the study area. The catch location was verified with the interviews by fishermen who carried out ship unloading activities near the local fish market. The research location can be seen in (Figure 1) samples were taken from the Karangasari traditional fish market, Tuban. There are ten (10) samples of biota were divided into four groups which are: crustaceans (shrimp, Litopenaeus setiferus; crab, Portunus pelagicus), molluscs (squid, Loligo gahi; cuttlefish, Sepia aculeata), demersal fish (groupers, Epinephelus epistictus; Japanese threadfin bream, Nemipterus japonicus; Indian halibut, Psettodes erumei; pink ear emperor, Lethrinus lentjan), and pelagic fish (anchovy, Stolephorus commersonni; yellowtail fish Caesio cuning). The samples were transported to the laboratory for further analysis.

Analysis of $^{210}\text{Po}$

The method used to determine $^{210}\text{Po}$ in biota is based on The International Atomic Energy Agency’s Marine Environmental Laboratories (IAEA-MEL) (Alam and Mohamed, 2011) with several modifications. The organism samples were dissected to obtain the edible part (muscle) and oven-dried at 60°C temperature. About 1 gram of the dried sample was digested with HNO$_3$ 10 mL, heat until the sample was digested. Add H$_2$O$_2$ 1 mL (drop by drop) and evaporate to dryness. Add HNO$_3$ 6mL; H$_2$O$_2$ 1mL and evaporate to dryness. Repeat this procedure twice. Add HCl 2 mL in residue and evaporate to dryness. Repeat this procedure twice. Then, the samples were dissolved in 0.1 M HCl with a pinch of ascorbic acid to reduce Fe (III), and $^{210}\text{Po}$ was spontaneously deposited on brightly polished silver discs (2 cm diameter) for 3-4 hours at a temperature of 70-90°C. The clamp with the silver disc was then removed from the solution, rinsed with deionized water and ethanol, and then aired. The discs were counted for $^{210}\text{Po}$ activities with an alpha spectrometer.

Sample counting using alpha spectrometry

The measurement of $^{210}\text{Po}$ was carried out by using alpha spectrometry for 24 hours. $^{210}\text{Po}$ activity concentration was corrected to the time of sample collection. The alpha spectrometry counting was equipped with alpha Passivated Implanted Planar Silicon (PIPS) detectors with 450 mm$^2$ active area. The relative efficiency of each detector is about 25% for a detector-to-source distance less than 10 mm. The background count for each spectroscopy channel was less than one count per hour for energies above 3 MeV. The system was calibrated for energy and efficiency using multineucleide calibration standards comprising $^{234}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, and $^{241}\text{Am}$ supplied by Analytics, USA (SRS 67943-121) (Mahmood et al., 2021).
**Data analysis**

The concentration of $^{210}\text{Po}$ was determined by using the following equation (Makmur et al., 2020). With notes, $N_{\text{net}}$ is the net count area, $f_1$ is a correction factor for tracer decay during sample counting, $f_2$ is a correction factor for tracer decay between a separation start date and counting start date, and $f_3$ is a correction factor tracer decay between sampling and separation date.

**Calculation of total dose rate using the Erica Tool**

The radiation dose rate was calculated using the Erica Tool (software used to assess radiological impacts on non-human biota) (Brown et al., 2008). The value of the total radiation dose to marine organisms was determined by the concentration ratio between the environmental concentration and the concentration absorbed by the organism (Abbasi et al., 2021). Various studies have recorded a range of concentration ratios in various aquatic organisms called concentration factors (CF) recorded in the Erica Tool database (ERICA, 2021). In addition, radionuclides dissolved in water can be adsorbed in suspended sediment particles until they finally settle in the bottom sediments of the waters due to the movement of currents, wind, or dispersion (Suseno and Prihatiningih, 2014). The Kd is the ratio of the concentration of an element on a solid phase (soil or sediment) divided by the equilibrium concentration in the contacting liquid phase (water) (Sheppard et al., 2011). The factor concentration equation (CF) and distribution coefficient (Kd) are respectively described by ERICA (2021).

Radionuclide concentrations can be converted into radiation exposure values for each aquatic organism produced by a radionuclide.

Exposure to radiation dose to organisms is divided into two pathways: internal dose ($D_{\text{int}}$) and external dose ($D_{\text{ext}}$) (Abbasi et al., 2021b). Internal dose is the value of radiation dose absorbed by the organism from the radionuclide concentration that the body has absorbed. In contrast, external dose illustrates the value of radiation exposure from the concentration of radionuclides in the environment that is not absorbed in the organism's body (Ciesielski et al., 2015). The total dose rate can then be calculated by ERICA, (2021) and Table 2.

**Results and Discussion**

$^{210}\text{Po}$ activity results in organisms consisting of crustaceans (shrimp, Litopenaeus setiferus; crab, Portunus pelagicus), mollusks (squid, Loligo gahi; cuttlefish, Sepia aculeata), demersal fish (grouper, Epinephelus epistictus; Japanese threadfin bream, Nemipterus japonicus; Indian halibut, Psettodes erumei; pink ear emperor, Lethrinus lentjan), and pelagic fish (anchovy, Stolephorus commersonni; yellowtail fish, Caesio cuning), were used as input data in the Erica Tool software. The results of $^{210}\text{Po}$ measurement in the marine biota samples use a spectrophotometer Alpha shown in Table 4.

Based on the monitoring results, in moving contaminants in the food chain, transfer factor data is used in the ERICA tool database (Brown et al., 2008; ERICA, 2021). The database comes from experimental results in various countries and has been published in reputable international journals. The movement of contaminants in the food chain is illustrated in Figure 2. In Figure 2, if the radionuclide concentration value is known in one component, the radiation dose can be predicted in the other components (ERICA, 2021).
Table 2. Equation of radiation value per unit of radionuclide concentration

| Organism Group     | F Equation |
|--------------------|------------|
| Phytoplankton      | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Macroalgae         | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |
| Vascular plant     | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |
| Zooplankton        | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Polychaeta         | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} - \text{DCC}_{\text{skl}}, K_\rho \right] \) |
| Mollusks dan Bivalves | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |
| Crustacea          | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |
| Demersal Fish      | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |
| Pelagic Fish       | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Bird               | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Sea Mammal         | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Reptile            | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + \text{DCC}_{\text{skl}} \right] \) |
| Anemone dan Reef   | \( F = \left[ \text{DCC}_{\text{int}} - \text{CR} + 0.5 \cdot \text{DCC}_{\text{skl}}, (1 + K_\rho) \right] \) |

\( R = \text{Concentration Ratio}\) (Bq,kg\(^{-1}\), fresh weight per Bq,kg\(^{-1}\)), \( Kd = \text{Distribution Coefficient}\) (1 kg\(^{-1}\)), \( \text{DCC} = \text{Dose Conversion Coefficient}\) (\( \mu \text{Gy.h}^{-1}\) per Bq,kg\(^{-1}\)).

Source: (ERICA, 2021).

Table 3. Risk Degree: Criteria of risk measurement (Risk characterization)

| Dose Rate (D)      | Risk Degree      | Effect                                      |
|--------------------|------------------|---------------------------------------------|
| \( D > 100 \text{ mGy.hr}^{-1} \) | Extremely High Risk | High mortality of roe; acute lethal of fish; decrease in diversity |
| 10 \text{ mGy.hr}^{-1} < D < 100 \text{ mGy.hr}^{-1} | High Risk | Mortality of roe and plankton; fish die within a few days |
| 400 \text{ µGy.hr}^{-1} < D < 10 \text{ mGy.hr}^{-1} | Medium Risk | Some organisms such as zooplankton will be affected |
| 10 \text{ µGy.hr}^{-1} < D < 400 \text{ µGy.hr}^{-1} | Low Risk | Some sensitive organisms at embryonic and larval stages will be affected |
| < 10 \text{ µGy.hr}^{-1} | No-Risk | Safe |

Source: (Ye et al., 2017)

Table 4. The activity of 210Po in Marine biota

| Marine Biota      | Concentration average of Po-210 (Bq,kg\(^{-1}\)) |
|-------------------|-----------------------------------------------|
| Pelagic Fish      | 103.86                                        |
| Demersal Fish     | 42.79                                         |
| Mollusks          | 107.87                                        |
| Crustaceans       | 354.85                                        |

The radiation dose level of marine biota was calculated using the Erica Tool software. The study results of external and internal radiation doses on marine biota in the waters of CFPP Tanjung Awar-Awar Tuban are shown in Table 5.

Based on the Erica Tool software calculations, total radiation dose rate received by marine organisms in the waters of CFPP Tanjung Awar – Awar, Tuban ranges between 2.70E-1–39.70E+0 \( \mu \text{Gy.hr}^{-1} \). Gray (Gy) is an international unit used to express the amount of radiation dose received by a material (Brown et al., 2008). The highest value of total radiation dose obtained by biota was found in true corals - colony (39.70E+0 \( \mu \text{Gy.hr}^{-1} \)), and the lowest for macroalgalae (2.70E-1 \( \mu \text{Gy.hr}^{-1} \)). Some marine organisms have a total radiation dose value above the screening level (10E+0 \( \mu \text{Gy.hr}^{-1} \)), including (crustaceans, phyttoplankton, true corals - colony, and true corals – polyp) (11.00E+0; 13.30E+0; 39.70E+0; 21.00E+0) \( \mu \text{Gy.hr}^{-1} \), respectively. Based on Ye et al. (2017), the dose rate value under screening level 10E+0 \( \mu \text{Gy.hr}^{-1} \) is safe, and under chronic irradiation of 400E+0 \( \mu \text{Gy.hr}^{-1} \), which is the screening dose rate used in biota, there will be no significant effect observed on organisms in coastal areas.

Based on (ERICA, 2021), each marine organism has a certain effect on the value of the radiation dose received on each biota. The total radiation dose obtained in crustaceans is 11.00E+0 \( \mu \text{Gy.hr}^{-1} \). This value exceeds the screening level set by the Erica Tool (10 \( \mu \text{Gy.hr}^{-1} \)). Still, based on ERICA (2021) the interval value, 0 – 50E+0\( \mu \text{Gy.hr}^{-1} \) on crustaceans, has no significant effect statistically on DNA chain damage. According to (Harshitha et al., 2016), the crustacean is an important part of coastal ecosystems in maintaining the balance of ecosystems in the marine environment. Including in

Potential Radiological Dose of 210Po (C.A. Aryanti et al.)
Tabel 5. The estimated value of the total radiation dose rate $^{210}$Po on marine biota in the waters of CFPP Tanjung Awar – Awar, Tuban was calculated using the ERICA Tool

| No | Marine Organism              | External Dose Rate $^{210}$Po ($\mu$Gy hr$^{-1}$) | Internal Dose Rate $^{210}$Po ($\mu$Gy hr$^{-1}$) | Total Dose Rate $^{210}$Po ($\mu$Gy hr$^{-1}$) |
|----|------------------------------|-------------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| 1  | Bird                         | 3.83E-11                                        | 8.78E+0                                         | 8.78E+0                                       |
| 2  | Benthic Fish                 | 1.39E-4                                         | 3.87E+0                                         | 3.87E+0                                       |
| 3  | Benthic Mollusks             | 1.45E-4                                         | 3.34E+0                                         | 3.34E+0                                       |
| 4  | Crustacean                   | 1.32E-4                                         | 1.00E+0                                         | 1.00E+0                                       |
| 5  | Macroalgae                   | 1.51E-4                                         | 2.70E-1                                         | 2.70E-1                                       |
| 6  | Mammal                       | 2.01E-11                                        | 5.12E+0                                         | 5.12E+0                                       |
| 7  | Pelagic Fish                 | 4.02E-11                                        | 3.22E+0                                         | 3.22E+0                                       |
| 8  | Phytoplankton                | 2.83E-5                                         | 1.33E-0                                         | 1.33E+0                                       |
| 9  | Polychaeta worm              | 2.96E-4                                         | 5.87E+0                                         | 5.87E+0                                       |
| 10 | Reptile                      | 2.10E-11                                        | 5.96E+0                                         | 5.96E+0                                       |
| 11 | True corals–colony           | 1.32E-4                                         | 39.70E+0                                        | 39.70E+0                                      |
| 12 | True corals–polyp            | 1.48E-4                                         | 21.00E+0                                        | 21.00E+0                                      |
| 13 | Vascular plant              | 1.45E-4                                         | 3.1E-1                                          | 3.1E-1                                        |
| 14 | zooplankton                  | 4.47E-11                                        | 5.08E+0                                         | 5.08E+0                                       |

Figure 2. Schematic illustration of the measurement model of the radiation dose rate on natural resources in the marine environment by the ERICA Tool software (ERICA, 2021).

dead corals (Ulfah et al., 2019). One of them, crustaceans alive by making a hole in the substrate nest of sediment. This activity can improve air circulation sediment to prevent and reduce the formation of phytotoxin, such as H$_2$S that can harm marine organisms (Handayani et al., 2016). Thus, based on the total radiation dose value in crustaceans, it will not harm the sustainability of crustacean life, which can maintain the balance of ecosystems in the marine environment (ERICA, 2021).

The total radiation dose on true corals–colony and polyps were 39.70E+0 and 21.00E+0 Gy/hr$^{-1}$. These values exceeded the screening level set by the Erica Tool (10 µGy.hr$^{-1}$). In contrast, based on (ERICA, 2021), the interval value was 0–85E+0 µGy.hr$^{-1}$ on true corals–colony and polyp where there were no significant effects on growth inhibition. The assessment (ERICA, 2021) indicates no negative impact on the balance of the marine ecosystem around the waters of the CFPP Tanjung Awar – Awar, Tuban. Consider coral reefs have a high conservation value function (ecological-process supporting, coastal-life supporting, coastal-sediment sources, and beach protecting from the abrasion threat) (Hoegh-Guldberg et al., 2017).

Phytoplankton has a total radiation dose value (external + internal) of 13.30E+0 µGy.hr$^{-1}$. The total radiation dose (external + internal) obtained by phytoplankton exceeds the screening level set by the Erica Tool (10 µGy.hr$^{-1}$) but based on (ERICA, 2021), the total radiation dose with an interval of 0 – 50E+0 µGy.hr$^{-1}$ on phytoplankton only gives small stimulatory effect on phytoplankton growth. Thus, it
will not interfere with the growth and sustainability of phytoplankton life. Referring to (Effendi et al., 2016), phytoplankton has a crucial role in the food chain because these organisms are a food source for pelagic fish, so the abundance is often associated with these organisms the quality of aquatic fertility.

The relationship among individuals in the marine environment is complex and mutually influences each other (reciprocity). The reciprocal relationship among biological elements forms an ecosystem's ecological system (Kwak and Park, 2020). In ecosystems, there are food chains, energy flows, and biogeochemical cycles (Kwak and Park, 2020). The food chain is the transfer of energy at its source (plants) through a series of prey-predatory organisms (Trites, 2003). The food chain that occurs in marine ecosystems in the form of phytoplankton as primary producers is considered as trophic level I, zooplankton eating phytoplankton as trophic level II, carnivores eating zooplankton as trophic level III, and so on (Trites, 2003). The growth process of phytoplankton is influenced by the availability of nutrients, while zooplankton is a predator, its growth is influenced by the availability of phytoplankton, and so on (Trites, 2003). The function of the food chain is to maintain the number of an organism in an ecosystem (Kwak and Park, 2020). An ecosystem imbalance will occur if one experiences extinction due to pollution in the sea (Islam and Tanaka, 2004). One of the pollutants that can be released into marine bodies is natural radionuclide $^{210}$Po which can be produced from CFPP (Alam and Mohamed, 2011). Natural radionuclides released into marine waters will generally be spread through abiotic components (water and sediment). Through these components, there is also accumulation into the biota network so that this incident can slowly disrupt the life of biota and human that consumes the marine biota (Suseno and Prihatiningsih, 2014).

The value of the total radiation dose in this study was compared with the total radiation dose to marine biota in other countries, Norwegian waters, which was carried out by (Brown et al., 2004). The comparison results based on the diversity of marine biota species show that the total radiation dose in the waters of CFPP Tanjung Awar - Awar, Tuban, Indonesia is smaller than in Norwegian waters. Variations in the value of the total radiation dose can be influenced by several factors such as the type and size of the biota, feeding habits, input of pollutants, and location (Štrok and Smodiš, 2011; Aközcan, 2013;).

Based on the assessment (ERICA, 2021), the total radiation dose of $^{210}$Po on the biota in the study area shows that there is no significant hazard impact from the operation of the coal-fired power plant (CFPP) on the biota in the waters. Thus, it will not harm marine ecosystems and the sustainability of marine life in the waters of CFPP Tanjung Awar - Awar, Tuban.

### Conclusion

The radiation dose of $^{210}$Po was non-uniformly distributed in marine organisms, variations in the value of the total radiation dose can be influenced by several factors such as the type and size of the biota, feeding habits, input of pollutants, and location. The Erica Tools software analysis showed that the probability of exceeding the selected screening dose rate for each marine organism was well below the chronic irradiation value. This indicates that the $^{210}$Po activity concentration in the waters of CFPP Tanjung Awar - Awar, Tuban was far below the screening value. This poses no risk to the marine ecosystems and the sustainability of marine biota.

### References

Abbasi, A., Zakaly, H.M.H. & Badawi, A. 2021. The Anthropogenic Radioactive Element of $^{137}$Cs Accumulate to Biota in the Mediterranean Sea. Mar. Poli. Bull., 164: 25-30. https://doi.org/10.1016/j.marpolbul.2021.

Abdullah, A., Hamzah, Z., Saat, A., Wood, A.K. & Alias, M. 2015. Accumulation of Radionuclides in Selected Marine Biota from Manjung Coastal Area. AIP Conf. Proc., 1659: 1-11. https://doi.org/10.1063/1.4916879

Aközcan, S. 2013. Levels Of $^{210}$Po in Some Commercial Fish Species Consumed in the Aegean Sea Coast of Turkey and the Related Dose Assessment to the Coastal Population. J. Environ. Radioact., 118: 93–95. https://doi.org/10.1016/j.jenvrad.2012.11.014

Alam, L. & Mohamed, C.A.R. 2011. Natural Radionuclide of Po$^{210}$ in the Edible Seafood

| Marine Organism   | Total Dosis Radiasi $^{210}$Po ($\mu$Gy.hr$^{-1}$) |
|-------------------|-----------------------------------------------|
| Benthic Fish      | 9.00                                          |
| Benthic Mollusks  | 37.00                                         |
| Crustacean        | 50.00                                         |
| Macroalgae        | 2.10                                          |
| Mammal            | 20.00                                         |
| Pelagic Fish      | 11.00                                         |
| Phytoplankton     | 2.50                                          |
| Zooplankton       | 25.00                                         |

Table 6. Comparison of total radiation doses from Norwegian coastal waters (Brown et al., 2004)
Affected by Coal-Fired Power Plant Industry in Kapar Coastal Area of Malaysia. *Environ. Health: Glob. Access Sci. Source*, 10(1): 1–10. https://doi.org/10.1186/1476-069X-10-43

Alviandini, N.B., Muslim, M., Prihatiningsih, W.R. & Wulandari, S.Y. 2019. Aktivitas NORM pada Sedimen Dasar di Perairan PLTU Tanjung Jati Jepara dan Kaitannya dengan Ukuran Butir Sedimen serta TOC. *Ekspoliorum*, 40(2): 115–126. https://doi.org/10.17146/ekspoliorum.2019.40.2.5662

Anggarini, N.H., Iskandar, D. & Stefanus, M. 2018. Studi Peningkatan Radionuklida Alam Karena Lepasan Abu Terbang di Sekitar PLTU Labuan. *J. Sains Dan Teknologi Nuklir Indonesia*, 19(1): 29. https://doi.org/10.17146/jstni.2018.19.1.378

Araújo dos Santos Júnior, J., dos Santos Amaral, R., Simões Cesar Menezes, R., Reinaldo Estevez Alvarex, J., Marques do Nascimento Santos, J., Herrero Fernández, Z., Dias Bezerra, J., Antônio da Silva, A., Francis Rodrigues Damascena, K. & de Almeida Maciel Neto, J. 2017. Influence of Terrestrial Radionuclides on Environmental Gamma Exposure in a Uranium Deposit in Paraíba, Brazil. *Ecotoxicol. Environ. Saf.*, 141: 154–159. https://doi.org/10.1016/j.ecoenv.2017.02.004

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D., Pröhl, G. & Ulanovsky, A. 2008. The ERICA Tool. *J. Environ. Radioact.*, 99(9): 1371–1383. https://doi.org/10.1016/j.jenvrad.2008.01.008

Brown, J.E., Jones, S. R., Saxén, R., Tharring, H. & Vives i Batlle, J. 2004. Radiation Doses to Aquatic Organisms from Natural Radionuclides. *J. Radiol. Prot.*, 24(4A): pA63. https://doi.org/10.1088/0952-4746/24/4A/004

Ciesielski, T., Göral, M., Szefier, P., Jenssen, B.M. & Bojanowski, R. 2015. 137Cs, 40K and 210Po in Marine Mammals from the Southern Baltic Sea. *Mar. Poll. Bull.*, 101(1): 422–428. https://doi.org/10.1016/j.marpolbul.2015.09.052

Van, D.H. 2020. Assessment of the Annual Committed Effective Dose Due to the 210Po Ingestion from Selected Sea-Food Species in Vietnam. *Chemosphere*, 252: 45-50. https://doi.org/10.1016/j.chemosphere.2020.126519

Effendi, H., Kawaroe, M., Lestari, D.F., Mursalin. & Permadi, T. 2016. Distribution of Phytoplankton Diversity and Abundance in Mahakam Delta, East Kalimantan. *Procedia Environ. Sci.*, 33: 496–504. https://doi.org/10.1016/j.proenv.2016.03.102

ERICA. 2021. ERICA Assessment Tool Help Documentation. Manual Book.

Gjelsvik, R., Brown, J., Holm, E., Roos, P., Saxen. R. & Outila, I. 2012. Polonium-210 and Other Radionuclides in Terrestrial, freshwater and brackish environments. *Stralevern Raport*, 1–45.

Handayani, O.T., Ngabeki, S. & Martuti, N.K.T. 2016. Keanekearagaman Crustacea di Ekok sistem Mangrove Wilayah Tapak Kelurahan Tugurejo Kota Semarang. *Unnes J. Life Sci.*, 5(2): 100–107.

Harshitha, U.P., Apoorva, M.D., D’Silva, P. & D’Lima P. 2016. Crabs Diversity in Mangrove and Coastal Ecosystem. *Lake 2016 : Conf. Conserv. Sustain. Manage. Ecol. Sensitive Reg. Western Ghats (The 10 th Biennial Lake Conference) December 28-30, 2016. 360-366p

Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W. & Dove, S. 2017. Coral Reef Ecosystems Under Climate Change and Ocean Acidification. *Front. Mar. Sci.*, 158(4); 1-20. https://doi.org/10.3389/fmars.2017.00158

Hvistendahl M. 2007. Coal Ash Is More Radioactive Than Nuclear Waste. *Scientific American.*

IAEA. 2010. Opportunities To Transform the Electricity Sector in Major Economies. *Transform*, 13(3): 239–256.

Islam, M.S. & Tanaka, M. 2004. Impacts of Pollution on Coastal and Marine Ecosystems Including Coastal and Marine Fisheries and Approach for Management: A Review And Synthesis. *Mar. Poll. Bull.*, 48(7–8): 624–649. https://doi.org/10.1016/j.marpolbul.2003.12.004

Khan, F.M., Godwin Wesley, S. & Rajan, M.P. 2014. Polonium-210 in Marine Mussels (Bivalve Molluscs) Inhabiting the Southern Coast of India. *J. Environ. Radioact.*, 138: 410–416. https://doi.org/10.1016/j.jenvrad.2014.06.004

Kim, S.H., Hong, G.H., Lee, H.M. & Cho, B.E. 2017. 210Po In the Marine Biota of Korean Coastal Waters and the Effective Dose from Seafood Consumption. *J. Environ. Radioact.*, 174: 30–37.https://doi.org/10.1016/j.jenvrad.2016.11.001
Kwak, I.S. & Park, Y.S. 2020. Food Chains and Food Webs in Aquatic Ecosystems. Applied Sciences (Switzerland), 10(14): 1–5. https://doi.org/10.3390/app10145012

Lockwood, A. & Evans, L. 2012. Ash in Lungs. How Breathing Coal Ash is Hazardous to Your Health. EarthJustice, 150–190p.

Macklin, R.L., Jeevanram, R.K., Kannan, V. & Govindaraju, M. 2014. Estimation of Polonium-210 Activity in Marine and Terrestrial Samples and Computation of Ingestion Dose to the Public in and Around Kanyakumari Coast, India. J. Radiat. Res. Appl., 7(2): 207–213. https://doi.org/10.1016/j.jrras.2014.02.006

Mahmood, U.W.M., Yii M.W., Norfaizal, M., Nooradilah, A., Mohd, Z.M.S, Nurrul, A.M.J. & Kamarudin, S. 2021. Potential Radiological Dose of 210Po to Marine Fishes and Their Consumer in Peninsular Malaysia. Global Scientific J, 1(9): 160-174.

Makmur, M., Prihatiningsih, W.R. & Yahya, M.N. 2020. Baseline Concentration of Polonium-210 (210Po) in Several Biota from Jakarta Bay. IOP Conf. Ser. Earth Environ. Sci., 429(1):p012061. https://doi.org/10.1088/1755-1315/429/1/012061

Melawati. 2003. Ajan Dampak Lepasan Radionuklida dari Pengoperasian PLTU Batubara dan PLTN ke Lingkungan. IPTEK Nuklir: Bunga Rampai Presentasi Ilmiah Jabatan Peneliti, 197–230p.

Musthafa, S.M. & Krishnamoorthy, R. 2012. Estimation of 210Po and 210Pb and its Dose to Human beings due to Consumption of Marine Species of Ennore Creek, South India. Environ. Monit. Assess., 184(10), 6253–6260. https://doi.org/10.1007/s10661-011-2417-8

Ozden, B., Guler, E., Vaasma, T., Horvath, M., Kiisk, M. & Kovacs, T. 2018. Enrichment of Naturally Occurring Radionuclides and Trace Elements in Yatagan and Venikoy Coal-Fired Thermal Power Plants, Turkey. J. Environ. Radioact., 188: 100–107. https://doi.org/10.1016/j.jenrad.2017.09.016

Pandit, G.G., Sahu, S.K. & Puranik, V.D. 2011. Natural radionuclides from Coal Fired Thermal Power Plants - Estimation of atmospheric release and inhalation risk. J. Radiol. Prot., 46(6): 173-179. https://doi.org/10.1051/radiopro/20116982s

Prihatiningsih, W.R., Suseno, H., Zamani, N.P. & Soedharma, D. 2016. Bioaccumulation and Retention Kinetics of Cesium in the Milkfish Chanos chanos from Jakarta Bay. Mar. Poll. Bull., 110(2): 647–653. https://doi.org/10.1016/j.marpolbul.2016.04.058

Riadessy, 2015. Analisis Konsumsi Batubara Pada Pltu Tanjung Awar-Awar Unit 1 Dengan Menggunakan Metode Least Square Analysis of Coal Consumption in the Power Plant Tanjung Awar-Awar Unit 1 By Using the Least Square Method. [Skripsi]. Institut Teknologi Sepuluh Nopember. Surabaya.

Sheppard, S., Sohlenius, G., Omberg, L.-G., Borgiel, M., Grolander, S. & Nordén, S. 2011. Solid/Liquid Partition Coefficients (Kd) and Pant/Soil ConcentrationRatios (CR) for Selected Soils, Tills and Sediments at Forsmark. Skb, November. www.skb.se

Štrok, M. & Smodiš, B. 2011. Levels of 210Po and 210Pb in Fish and Molluscs in Slovenia and the Related Dose Assessment to the Population. Chemosphere, 82(7): 970–976. https://doi.org/10.1016/j.chemosphere.2010.10.075

Suseno, H. & Prihatiningsih, W.R. 2014. Monitoring 137Cs and 134Cs at Marine Coasts in Indonesia between 2011 and 2013. Mar. Poll. Bull., 88(1–2): 319–324. https://doi.org/10.1016/j.marpolbul.2014.08.024

Susiati. 2005. Studi Potensi Peningkatan Paparan Unsur Radioaktif Alam Akibat Pembakaran Batubara. J. Pengembangan Energi Nuklir, 7(2): 24-39.

Trites, A.W. 2003. Food Webs in the Ocean: Who Eats Whom and How Much? Responsible Fisheries in the Marine Ecosystem, December, 125–141. https://doi.org/10.1079/9780851996332.0125

Tsuchiya, R., Taira, Y., Orita, M., Fukushima, Y., Endo, Y., Yamashita, S. & Takamura, N. 2017. Radionuclide Contamination and Estimated Internal Exposure Doses in Edible Wild Plants in Kawauchi Village Following the Fukushima Nuclear Disaster. Plos One, 12(12): 1–13. https://doi.org/10.1371/journal.pone.0189398

Uddin, S., Fowler, S.W., Behbehani, M. & Metian, M. 2017. 210Po Bioaccumulation and Trophic Transfer in Marine Food Chains in the Northern Arabian Gulf. J. Environ. Radioact., 174: 23–29. https://doi.org/10.1016/j.jenvrad.2016.08.021

Ulfah M., Tawakkal M., Devira C.N., Nurfadillah N.,...
Mellisa S., Sembiring A., Kurniasih E.M., Ambariyanto, A. & Meyer C. 2019. Composition of brachyura cryptic organism (crustacea) on the dead coral of Pocillopora in Sabang. IOP Conference Series: Earth and Environmental Science, 348(1): 012073, doi: 10.1088/1755-1315/348/1/012073

Ye, S., Zhang, L. & Feng, H. 2017. Marine Ecological Risk Assessment Methods for Radiation Accidents. J. Environ. Radioact., 180: 65–76. https://doi.org/10.1016/j.jenvrad.2017.09.024

Yu, W., He, J., Lin, W., Li, Y., Men, W., Wang, F. & Huang, J. 2015. Distribution and Risk Assessment of Radionuclides Released by Fukushima Nuclear Accident at the Northwest Pacific. J. Environ. Radioact., 142: 54–61. https://doi.org/10.1016/j.jenvrad.2015.01.005