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RESEARCH ARTICLE

Analysis of heavy metal content in emissions from shell, fiber, and empty fruit bunch biomass fuels

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ABSTRACT

Riau Province is one of the largest palm oil producers in Indonesia, where palm oil mills use boilers as a primary component to generate steam energy for processing activities. At PT TH Indo Plantation, particularly at Pulai Palm Oil Mill, biomass fuels such as palm kernel shells, fibers, and empty fruit bunches are commonly used. Boiler operations are often associated with emissions that may pose environmental and health risks. This study aims to analyze the heavy metal content in emissions from these biomass fuels. The research employed quantitative methods, including proximate and ultimate analyses, as well as spatial modeling using AERMOD to observe emission dispersion. The results showed relatively low heavy metal content: 0.01% in palm kernel shells and empty fruit bunches, and 0.02% in fibers. AERMOD simulation indicated that the concentration of PM2.5-type particulate matter reached 3.31311 µg/m³, with dispersion extending up to 3 km from the source. Based on these findings, the use of shell, fiber, and empty fruit bunch fuels at Pulai Palm Oil Mill does not result in significant environmental impact related to heavy metal dispersion and may be considered relatively safe.

1. INTRODUCTION

Indonesia has a total of 6.5 million hectares of land dedicated to oil palm cultivation. Oil palm plantations in Indonesia are spread across 26 provinces, with Riau Province being one of the largest producers (Statistics Indonesia [BPS], 2023; Syafrani et al., 2022). In 2023, the total area of oil palm plantations in Riau Province reached 2.86 million hectares, accounting for approximately 19.62% of the total oil palm plantation area in Indonesia (Syafrani et al., 2022). This indicates that oil palm cultivation dominates the plantations in Riau Province and significantly contributes to Indonesia's palm oil industry.

To meet the high energy demand of palm oil processing, boilers are widely used in palm oil mills. Palm oil mills operate using boilers (Rusdi et al., 2022). A boiler is one of the main components in processing, serving as a source of heat energy. A boiler is a closed tank that converts water into hot water or pressurized steam through heat transfer from combustion. The size of a boiler typically depends on the size of the plant and its production capacity, and a boiler size that is too large will significantly reduce efficiency due to increased cycles (Bennett & Elwell, 2020). The number and capacity of boilers are also influenced by factors such as energy efficiency, the type of fuel used, and company policies regarding maintenance and reserves (Muniandy et al., 2022).

Boilers operate using fuel. The commonly used fuels are palm kernel shells, fibers, and empty fruit bunches. When in operation, boilers produce pressurized steam. This steam is then used in the Steam Power Plant (PLTU) within the mill to drive turbines, meeting the plant's electricity and heat energy needs (Radhiah et al., 2024). During operational processes, boilers generate emissions whose characteristics depend on the type of fuel used (Érces & Kajtár, 2021).

The Ministry of Environment and Forestry of the Republic of Indonesia. (2021), addresses the emission standards produced by palm oil mills. This regulation governs all activities that have the potential to generate emissions, including palm oil mills, by establishing emission standards that must be adhered to. The key parameters of concern in the emissions produced by palm oil mill boilers include Mercury (Hg), Arsenic (As), Antimony (Sb), Cadmium (Cd), Zinc (Zn), and Lead (Pb), which are heavy metals (Lenntech, 2022).

Heavy metals in dispersed emissions can pose various risks to health and the environment (Han et al., 2020). For human health, exposure to heavy metals can lead to skin and lung cancer, circulatory disorders, and other health issues. From an environmental perspective, dispersed heavy metals can contaminate soil and water, damage ecosystems, and negatively impact environmental balance (Tchounwou et al., 2012).

Research on emission dispersion from palm oil processing mills has been conducted. In 2019, Sasmitra Ayo investigated the largest sources of emissions from palm oil mills and found that boilers contributed 81% of the total emissions from these mills (Ayo & Reza, 2019). In 2020, Jamian studied the particulate emission concentrations produced by five palm oil mills and found an average concentration of 2.2±0.9 g/Nm³ (Jamian et al., 2020). In 2022, Prabasari modeled the dispersion of emissions from palm oil mill boilers and found that emissions spread up to 10 km from the source (Prabasari & Pusparani, 2022). These studies indicate that the highest emission dispersion occurs near the source, namely the boiler. Despite various studies conducted, there has been no specific research analyzing the heavy metal content in palm kernel shell, fiber, and empty fruit bunch (EFB) fuels, nor the dispersion distance of emissions produced by palm oil mill boilers using these fuels. Therefore, the aim of this study is to analyze the heavy metal content in palm kernel shell, fiber, and EFB fuels, and to investigate the dispersion distance of emissions produced by the palm oil mill boiler.

The aim of this study is to analyze the heavy metal content in palm kernel shell, fiber, and empty fruit bunch (EFB) fuels, and to investigate the dispersion distance of emissions produced by the palm oil mill boiler using these three types of fuel.

2. MATERIALS AND METHODS

The study is a descriptive research type. It employs a mixed-methods approach, consisting of quantitative and spatial methods. The research methods used to analyze the metal content in palm kernel shells, fibers, and empty fruit bunches are illustrated in Figure 1.

The research location for analyzing heavy metal content in fuels and emission dispersion was conducted at PT TH Indo Plantation, a crude palm oil processing mill located in Pelangiran District, Indragiri Hilir Regency, Riau Province. PT TH Indo Plantation consists of 6 Palm Oil Mills (PMKS), each equipped with 1 boiler. This study was carried out at PKMS Pulai, which has a capacity of 120 tons of Fresh Fruit Bunches (FFB) per hour, with the boiler as the emission source located at coordinates 0°13'17.76"N and 103°9'45.70"E. A map of PT TH Indo Plantation with a focus on the PMKS Pulai can be seen in Figure 2, the map was modeled using ArcGIS 9.3.

In 2023, the vulnerability assessment of Pekanbaru City to climate change was also conducted using ArcGIS 9.3 to identify areas susceptible to climate change (Fitri et al., 2023). ArcGIS facilitates the creation of comprehensive maps with accurate geographic information, aiding in the identification and visualization of focal points. Samples were collected from one of the locations at PT TH Indo Plantation, specifically from PMKS Pulai, using a random sampling method to ensure representativeness. The collected samples included palm kernel shells, fibers, and empty fruit bunches, each weighing 1 kg. These samples were then further analyzed to determine their heavy metal composition.

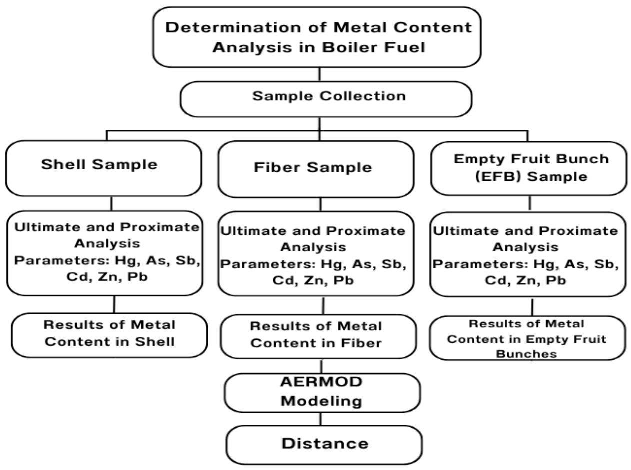

Figure 1: Research flow of the study, starting from sample collection (shell, fiber, and empty fruit bunch), proximate and ultimate analysis, and determination of heavy metals (Hg, As, Sb, Cd, Zn, Pb) using Atomic Absorption Spectroscopy (AAS). The results were then used as input for AERMOD dispersion modeling with meteorological data to estimate PM2.5 concentration and dispersion distance.

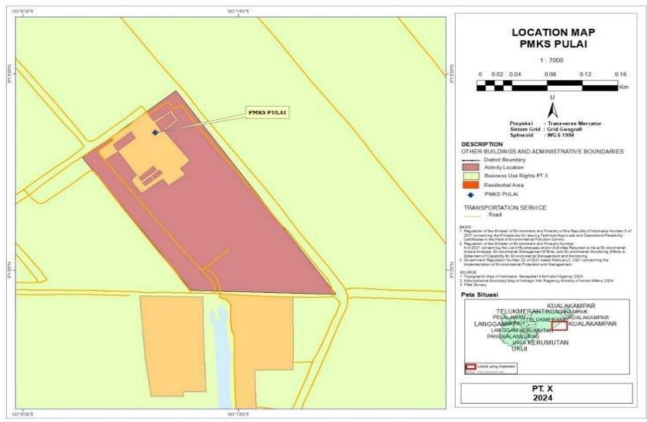

Figure 2: Map of the Research Location PT TH Indo Plantation (PMKS Pulai)

In 2023, the vulnerability assessment of Pekanbaru City to climate change was also conducted using ArcGIS 9.3 to identify areas susceptible to climate change (Fitri et al., 2023). ArcGIS facilitates the creation of comprehensive maps with accurate geographic information, aiding in the identification and visualization of focal points. Samples were collected from one of the locations at PT TH Indo Plantation, specifically from PMKS Pulai, using a random sampling

method to ensure representativeness. The collected samples included palm kernel shells, fibers, and empty fruit bunches, each weighing 1 kg. These samples were then further analyzed to determine their heavy metal composition.

The metal content analysis was conducted at the Environmental Quality Management Laboratory, Department of Environmental Engineering, FTSPK ITS. The methods used to determine the basic composition of the samples were proximate and ultimate analysis (Mongkito et al., 2020; Zahar, 2021). Heavy metal content in each sample was measured using Atomic Absorption Spectroscopy (AAS). The selected parameters—Mercury (Hg), Arsenic (As), Antimony (Sb), Cadmium (Cd), Zinc (Zn), and Lead (Pb)—were based on the Indonesian Ministry of Environment and Forestry Regulation No. 22 of 2021, which sets emission standards for palm oil mill boilers. These metals were chosen due to their toxicity and environmental relevance, as shown in Table 1. The results obtained from the laboratory were used as parameters in emission modeling to examine the dispersion pattern in the air.

Table 1: Metal Test Parameters Based on Indonesian Ministry of Environment and Forestry Regulation No. 22 of 2021

Parameters	Symbol	Unit (AAS detection)
Mercury	Hg	mg/kg
Arsen	As	mg/kg
Antimony	Sb	mg/kg
Cadmium	Cd	mg/kg
Zinc	Zn	mg/kg
Lead	Pb	mg/kg

Source: Ministry of Environment and Forestry of the Republic of Indonesia. (2021).

Emission dispersion modeling was performed using the AERMOD dispersion model. The modeling aims to predict the dispersion patterns of heavy metal emissions in the air at the study location (Alam et al., 2019). In 2024, methane (CH_4) emission estimation at the municipal waste processing site in Pekanbaru was also conducted using the AERMOD dispersion model to ensure consistency in the application of AERMOD (Lestari et al., 2024).

Meteorological data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) and NASA Langley Research Center (NASALARC), which provide weather and climate reanalysis data, including parameters such as wind direction and speed, air temperature, solar radiation, air humidity, air pressure, and precipitation (Kaiser-Weiss et al., 2019). The meteorological data cover two monsoon periods: the eastern monsoon (March to August) and the western monsoon (September to February), with the aim of providing a more comprehensive and representative overview of the weather and climate conditions in the region. The collected data were processed and compiled in Microsoft Excel. Subsequently, the data were converted to SAMSON (.sam) format using AERMET software and further processed with WRPLOT View software to obtain the wind direction pattern for the study location (Windrose) (Sundari et al., 2020).

The windrose can describe the direction and speed of the wind from all cardinal directions in the study area over a specific time period. The windrose provides information on the dispersion of wind direction and speed, which is crucial for understanding the movement of emission particles (Roubeyrie & Celles, 2018).

3. RESULTS AND DISCUSSION

3.1 Analysis of metal content

3.1.1 Palm kernel shell samples

The analysis data for palm kernel shell samples can be seen in Table 2. The palm kernel shell fuel samples were tested using proximate and ultimate analysis. The ultimate analysis results indicated a total composition of 100%, which aims to ensure the accuracy of the compositional data contained in the shells. This approach also applied to the fiber and empty fruit bunch (EFB) fuel samples.

a) Proximate Analysis

The proximate analysis shows that palm kernel shells have a moisture content of 24.63% according to ASTM D3173-03. This moisture content is relatively high and can Freaffect combustion efficiency. Additionally, the volatile solid content is recorded at 88.37% based on ASTM D3175-07. Both moisture and volatile solid content may vary due to environmental factors such as humidity and storage temperature.

b) Ultimate Analysis

The ultimate analysis of the palm kernel shell fuel indicates high carbon and hydrogen content in the shell samples, with values of 50.09% C and 5.75% H, respectively, suggesting a good energy potential and effective combustion performance. The relatively high oxygen content of 20.93% in this sample can affect combustion efficiency and the emissions produced, necessitating strict control to minimize pollutant formation. The measured ash content in the shell sample was 11.63%, which was a concern for combustion performance, as high ash content can lead to issues in the boiler such as deposition and erosion. Additionally, the low chlorine and fluorine content in this sample, at 0.00% and 0.02% respectively, was advantageous, as high levels of these elements can cause corrosion of equipment and the formation of hazardous compounds during combustion (Alam et al., 2019).

Table 2: Data Analysis of Palm Kernel Shell

Parameter	Unit	Analysis Result	Analysis Method
Proximate Analysis			
Moisture Content	%	24.63	ASTM D3173-03
Volatile Solid	%	88.37	ASTM D3175-07
Ultimate Analysis			
Carbon (C)	%	50.09	ASTM D 5373-2002
Fixed Carbon (C)	%	10.65	ASTM D 5373-2002
Nitrogen (N)	%	0.91	ASTM D 5373-2002
Hydrogen (H)	%	5.76	ASTM D 5373-2002
Oxygen (O)	%	20.93	ASTM D 3174-04
Sulfur (S)	%	0.00	ASTM D 3177-2002
Ash	%	11.63	Balance
Chlorine (Cl_2)	%	0.00	Iodimetri
Flourine (F)	%	0.02	Spektrofotometri
Mercury (Hg)	%	0.00	AAS
Arsenic (As)	%	0.00	AAS
Cadmium (Cd)	%	0.00	AAS
Zinc (Zn)	%	0.01	AAS
Lead (Pb)	%	0.00	AAS
Antimony (Sb)	%	0.00	AAS

The analysis revealed that hazardous metals such as mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb) were not detected in the palm kernel shell fuel, indicating that this fuel was relatively free from heavy metal contamination that could be harmful to the environment and health. The only metal detected was zinc (Zn) at 0.01%, which was considered very low and does not pose a significant threat. The low zinc content may be due to several factors, such as the source of the raw materials from zinc-poor soil, the processing method reducing heavy metals, or natural variation in metal content. (Mongkito et al., 2020).

3.1.2 Palm Fiber Samples

The analysis data for palm fiber samples were presented in Table 3. This table shows the results of the proximate and ultimate analyses for palm fibers, with the ultimate analysis results indicating a total composition of 100%.

a) Proximate Analysis

The analysis of palm fiber as a boiler fuel revealed several characteristics that reflect its potential as an energy source. The relatively high moisture content of 36.57% indicated that a significant portion of the combustion energy will be used to evaporate water. The high volatile solid content, reaching 94.00%, suggested that the fiber has a rapid and effective combustion capability, making it an efficient choice for use in boilers.

Table 3: Analysis Data for Palm Fiber

Parameter	Unit	Analysis Results	Analysis Methods
Proximate Analysis			
Moisture Content	%	36.57	ASTM D3173-03
Volatile Solid	%	94.00	ASTM D3175-07
Ultimate Analysis			
Carbon (C)	%	54.52	ASTM D 5373-2002
Fixed Carbon (C)	%	5.51	ASTM D 5373-2002
Nitrogen (N)	%	1.30	ASTM D 5373-2002
Hydrogen (H)	%	6.27	ASTM D 5373-2002
Oxygen (O)	%	26.33	ASTM D 3174-04
Sulfur (S)	%	0.04	ASTM D 3177-2002
Ash	%	6.00	Balance
Chlorine (Cl_2)	%	0.00	Iodimetri
Flourine (F)	%	0.01	Spektrofotometri
Mercury (Hg)	%	0.00	AAS
Arsenic (As)	%	0.00	AAS
Cadmium (Cd)	%	0.00	AAS
Zinc (Zn)	%	0.02	AAS
Lead (Pb)	%	0.00	AAS
Antimony (Sb)	%	0.00	AAS

b) Ultimate Analysis

The ultimate analysis reveals that palm fiber is rich in carbon and hydrogen, with values of 54.52% and 6.27%, respectively. These levels indicated a strong potential for generating high thermal energy during combustion. The relatively high oxygen content of 26.33% presents a challenge for combustion efficiency, as it can lower the calorific value and affect the chemical reaction balance during the process (Basu, 2018). On the other hand, the low ash content of only 6.00% provides a significant advantage by reducing the risk of deposition and fouling, thereby minimizing potential damage to boiler equipment (Basu, 2018).

The analysis reveals that palm fiber contains almost no hazardous heavy metals, such as mercury, arsenic, cadmium, lead, and antimony, all of which were undetectable in the samples. The only metal found was zinc (Zn), but at a very low concentration of 0.02%. The analysis reveals that palm fiber contains almost no hazardous heavy metals, such as mercury, arsenic, cadmium, lead, and antimony, all of which were undetectable in the samples. The only metal found was zinc (Zn), but at a very low level of 0.02% as reported by the laboratory. Although expressed in percentage, this value corresponds to a very low concentration, suggesting that the fiber can be considered relatively free from heavy metal contamination. The low metal content may be attributed to various factors, including favorable soil conditions, minimal chemical use during growth, and a clean processing method.

3.1.3 Empty Fruit Bunch Samples

The analysis data for empty fruit bunch samples are presented in Table 4. This table shows the results of the proximate and ultimate analyses for empty fruit bunches, with the ultimate analysis results indicating a total composition of 100%.

Table 4: Analysis Data for Empty Fruit Bunches

Parameter	Unit	Analysis Results	Analysis Methods
Proximate Analysis			
Moisture Content	%	81.47	ASTM D3173-03
Volatile Solid	%	91.22	ASTM D3175-07
Ultimate Analysis			
Carbon (C)	%	52.91	ASTM D 5373-2002
Fixed Carbon (C)	%	8.22	ASTM D 5373-2002
Nitrogen (N)	%	1.39	ASTM D 5373-2002
Hydrogen (H)	%	6.08	ASTM D 5373-2002
Oxygen (O)	%	22.51	ASTM D 3174-04
Sulfur (S)	%	0.07	ASTM D 3177-2002
Ash	%	8.78	Balance
Chlorine (Cl_2)	%	0.00	Iodimetri
Flourine (F)	%	0.03	Spektrofotometri
Mercury (Hg)	%	0.00	AAS
Arsenic (As)	%	0.00	AAS
Cadmium (Cd)	%	0.00	AAS
Zinc (Zn)	%	0.01	AAS
Lead (Pb)	%	0.00	AAS
Antimony (Sb)	%	0.00	AAS

a) Proximate Analysis

The proximate analysis of empty fruit bunches (EFB) reveals a very high moisture content of 81.47% (ASTM D3173-03). This high moisture content was expected to reduce combustion efficiency, as additional energy is required to evaporate the water before the fuel can fully combust (Basu, 2018). Nevertheless, the volatile solid content of 91.22% (ASTM D3175-07) indicates that a significant portion of this material is highly combustible, suggesting effective combustion potential following adequate drying.

b) Ultimate Analysis

The ultimate analysis reveals that the carbon (C) content in empty fruit bunches (EFB) was 52.91% (ASTM D5373-2002), while the hydrogen (H) content was 6.08% (ASTM D5373-2002). These two elements are key indicators of fuel energy potential, suggesting that EFB has the capacity to produce significant heat energy during combustion. However, the relatively high oxygen (O) content, at 22.51% (ASTM D3174-04), should be noted as it may lower the calorific value and affect combustion efficiency, since oxygen is already chemically bound within the biomass structure, which in turn may contribute to the formation of undesirable emissions (Basu, 2018).

The detected sulfur (S) content was 0.07% (ASTM D3177-2002), which was relatively low but still important to monitor, as it can lead to the formation of corrosive SOx gases. Additionally, the ash content of 8.78% indicated that EFB has the potential to produce a significant amount of solid residues, which may cause issues such as deposition and damage to boiler equipment if not properly managed.

Analysis of heavy metal content reveals that mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb) were not detected in this sample, indicating that EFB was relatively free from hazardous heavy metal contamination. Only zinc (Zn) was detected, with a concentration of 0.01% (AAS). The low levels of heavy metals are consistent with findings from the palm kernel shell sample, suggesting that both the shell and EFB are safer and more environmentally friendly fuel options.

Thus, despite the high moisture content in EFB, which may reduce combustion efficiency, its high energy potential particularly due to its carbon and hydrogen content and the low levels of heavy metals still make it a viable fuel option for combustion applications, provided that adequate drying is performed.

3.2 Emission Dispersion Modeling

3.2.1 Windrose Diagram of Wind Direction and Speed

Figures 3 and 4 illustrate the windrose patterns at PT TH Indo Plantation, specifically at PMKS Pulai, representing the East Monsoon (Figure 3) and West Monsoon (Figure 4) periods. The windrose shows that during the East Monsoon (March to August), the wind predominantly blows from the Southeast to the Northwest, with a maximum wind speed of 1.60-3.40 m/s occurring less than 13% of the time, and a minimum speed of 8.00-10.80 m/s occurring 60% of the time. The frequency of calm wind, with speeds below 0.30 m/s, is 0.02%. During the West Monsoon (September to February), the wind at PMKS Pulai continues to blow predominantly from the Southeast to the Northwest. Although the wind direction remains similar, there is variation in wind speed distribution. The highest wind speeds were recorded in the range of 1.60-3.40 m/s, contributing less than 13%, while the highest speeds reach 8.00-10.80 m/s with a frequency of 60%. Additionally, calm wind conditions, where the wind speed was below 0.30 m/s, occur only 0.02% of the time.

3.2.2 Emission Dispersion

In the emission analysis, zinc (Zn) was detected with a concentration of 0.01% in the shell and empty fruit bunch fuel samples, and 0.02% in the palm fiber samples. Although the concentration is relatively low, the presence of zinc can still impact air quality and health, as zinc has the potential to contribute to the formation of fine particulate matter such as PM2.5.

Zinc (Zn), when dispersed into the atmosphere through the combustion of these fuels, can bond with fine particles or undergo oxidation processes to form new particles with sizes below 2.5 micrometers. These particles can remain suspended in the air and contribute to the PM2.5 fraction, which is hazardous to human health due to its very small size, making it easy to inhale and reach the deeper parts of the respiratory system (Arba, 2019).

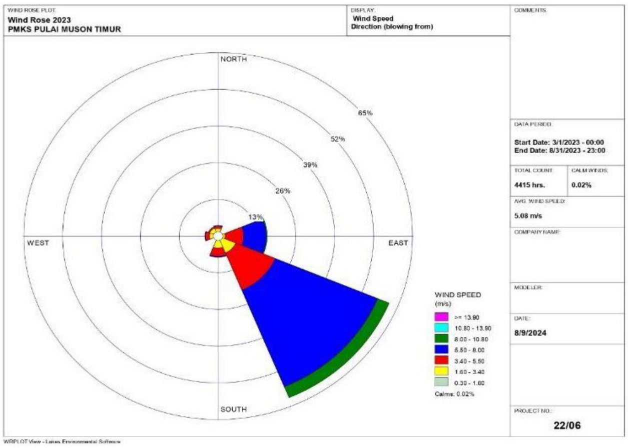

Figure 3: Windrose for PMKS Pulai East Monsoon

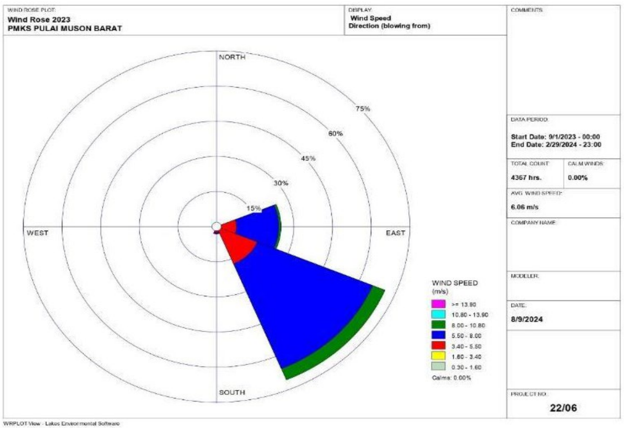

Figure 4: Windrose for PMKS Pulai West Monsoon

Figure 5 displays the PM2.5 dispersion results for the shell and empty fruit bunch (EFB) palm oil samples, which exhibit similar levels of metal content analysis. In contrast, the PM2.5 emission dispersion resulting from the combustion of palm oil fibers can be observed in Figure 6.Figures 5 and 6 illustrate the PM2.5 emission dispersion modeling results from the PMKS Pulai smokestack at PT TH Indo Plantation. In Figure 5, the concentration value is 3.31311 µg/m³ with a dispersion distance of 1.92 km. Figure 5 depicts emission dispersion during the eastern monsoon, characterized by stronger and more stable winds, resulting in a shorter dispersion distance for the emission particles.

Figure 6 also detects the same maximum concentration value of 3.31311 µg/m³, although there is a 0.01% difference in metal content. Figure 6 illustrates the emission dispersion during the western monsoon, with a broader dispersion distance of up to 3 km. This is attributed to slower winds and a tendency for wind direction to change during the western monsoon, which allows emission particles to disperse further before settling. The direction and speed of the wind influence the dispersion of small airborne particles. Stronger winds lead to wider pollution dispersion, particularly following the rainy season (Kumar et al., 2022).

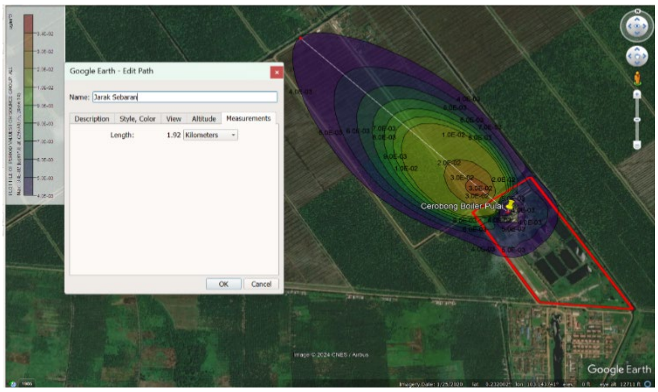

Figure 5: PM2.5 Emission Distribution East Monsoon

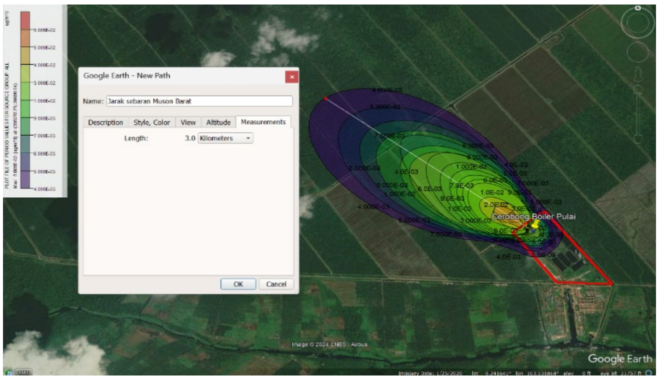

Figure 6: PM2.5 Emission Distribution West Monsoon

4. CONCLUSION

Based on the research conducted, it can be concluded that at PMKS Pulai in PT TH Indo Plantation, the boiler, which uses palm shell, fiber, and empty fruit bunches as fuel, shows very low concentrations of heavy metals, ranging from 0.01% to 0.02%. The dispersion of these heavy metal emissions, classified as PM2.5, indicates a detected concentration of 3.31311 µg/m³, with the maximum dispersion distance reaching up to 3 km from the emission source. This demonstrates that the use of palm shell, fiber, and empty fruit bunches in PT TH Indo Plantation's operations does not result in significant environmental impact, particularly concerning the dispersion of heavy metals in the air. Therefore, these fuels can be considered relatively safe in terms of heavy metal emissions.

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