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Heavy Metals Contamination in Surface Water Due to Intensive Agricultural Chemical Use: A Case Study of the Hantu River in the Vicinity of Oil Palm Plantations, Banyuasin Sumatera Selatan Indonesia

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Abstract

Water pollution is a serious issue that requires immediate attention, especially when the water serves as a source for household activities. The consequences, such as health disorders or death, may occur if contaminated water is consumed continuously. Polluted water often contains various types of heavy metals. This study highlights changes in the water quality of the Hantu River, located near private oil palm plantations, focusing on the analysis of heavy metal contamination suspected to be present in the river water. The research was conducted by collecting water samples from the upstream and downstream sections of the river, followed by testing using the Atomic Absorption Spectrophotometry (AAS) method to measure heavy metal concentrations. The parameters assessed included heavy metals such as iron (Fe), manganese (Mn), cadmium (Cd), lead (Pb), mercury (Hg), and zinc (Zn). The results showed fluctuations in Fe and Zn contamination during the study period, while Mn and Hg contamination remained consistent each year. However, a startling finding was the concentration of Cd and Pb, which exceeded drinking water quality standards by 200%. This fact rendered the surface water unsuitable for consumption. It is suspected that the contamination occurred due to the use of materials for pest control (pesticides), weed control (herbicides), and the massive and continuous application of Palm Oil Mill Effluent (POME) during the 2019–2023 period. Regression models indicated a significant relationship between the use of pesticides, herbicides, and POME with contamination levels, accounting for 89.6% of Cd pollution and 92.3% of Pb pollution in the water. These findings demonstrate the impact of pesticides, herbicides, and POME on water quality concerning heavy metal pollution parameters. Therefore, managing the use of pollution sources and continuously monitoring water quality are essential to prevent and detect potential pollution in the future.

Keywords: *Atomic Absorption Spectrophotometry (AAS) Analysis, Impacts of Oil Palm Plantations, Surface Water Quality, Heavy Metals, Water Pollution.*

Introduction

Heavy metal contamination in water caused by agricultural activities using chemicals such as pesticides and herbicides is a frequent occurrence. Additionally, industrial waste such as Palm Oil Mill Effluent (POME) contributes significantly as a source of heavy metal pollution in water. Heavy metals like cadmium (Cd) and lead (Pb) present in water are extremely hazardous when consumed continuously. Cd has bioaccumulative properties and can severely damage organs, including causing chronic kidney damage, brittle bones or osteoporosis, liver damage, acute poisoning, cancer, and digestive system problems. Meanwhile, Pb is a potent neurotoxin capable of damaging the central nervous system. It can also lead to serious health issues such as reduced cognitive abilities, behavioral disorders, decreased IQ in children, and kidney and liver damage in adults. At high doses or with prolonged exposure, Pb also poses risks of anemia, hypertension, and reproductive system disorders (Aprile et al., 2019).

On the other hand, the utilization of wetlands for agricultural activities, such as oil palm plantations by private companies, plays a crucial role in driving regional economic growth. This sector not only prioritizes productivity but also creates significant employment opportunities for local communities (Rist et al., 2010).

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However, the degradation of environmental quality resulting from these activities is unavoidable (Shuhada et al., 2020), particularly the decline in water quality (Colchester et al., 2011).

In oil palm plantation operations, the use of fertilizers and pesticides is a common practice. While excessive use may positively impact production, it also poses a significant risk of contaminating nearby water sources and degrading environmental quality (Sheil et al., 2009).

Banyuasin Regency, located in South Sumatra Province, Indonesia, encompasses approximately 14,836.62 km² of wetland areas. Within this province, Banyuasin Regency includes 19 tidal swamp locations and 1 freshwater swamp location (Bappeda Sumsel, 2014). The region features two subdistricts dominated by aquatic areas, namely Pulau Rimau and Selat Penugukan. These areas are also utilized by private entities for oil palm plantation activities. Research findings indicate that wetland use for oil palm plantation activities significantly affects environmental quality. Intensive agricultural practices, such as the massive and continuous application of chemicals by companies, pose a substantial risk of contaminating surface water in the vicinity of their operations (Anyaoha & Zhang, 2022).

To assess the actual impact of oil palm plantation activities on the environment, this study analyzes changes in surface water quality around plantation areas and identifies the sources of pollution. The results of this research are expected to provide recommendations for companies and governments in establishing environmental policies that ensure environmental sustainability and prevent more severe damage in the future.

Method

Water Quality Testing, Water quality testing was conducted in a laboratory accredited by the National Accreditation Committee (KAN) to ensure the reliability and accountability of the results. The testing included various physical and chemical parameters. The analyzed parameters focused on heavy metals, such as iron (Fe), manganese (Mn), cadmium (Cd), lead (Pb), mercury (Hg), and zinc (Zn). The method applied for heavy metal analysis was Atomic Absorption Spectrophotometry (AAS). Previous studies have demonstrated that the AAS method is highly effective in measuring heavy metal concentrations in water (Wilberforce, 2016; Boss & Fredeen, 1997).

Data Analysis, To evaluate the relationship between variables such as the use of agricultural chemicals including fertilizers, pesticides, herbicides, and POME and surface water quality, the researchers employed multiple linear regression analysis. The data included laboratory test results of water samples analyzed using the Atomic Absorption Spectrophotometry (AAS) method to measure heavy metal concentrations, such as iron (Fe), manganese (Mn), cadmium (Cd), lead (Pb), mercury (Hg), and zinc (Zn). Descriptive statistical analysis was used to describe changes in water quality over the study period. In addition to enabling the identification of patterns among the tested variables, multiple linear regression analysis provides insights into the contribution of each type of agricultural chemical to water pollution.

Result and Discussion

Plantation Area Coverage

The private oil palm plantations studied cover a nucleus estate area of 4,492.45 hectares and a plasma estate area of 6,338.28 hectares, with a total of 678,973 oil palm trees in the nucleus area and 862,006 trees in the plasma area. The planting process began in 2006 and was completed in 2018. The average tree density reached 136 trees per hectare. While optimal planting density can significantly boost productivity, inadequate management may accelerate land degradation (Z. B. Yan et al., 2023).

Fresh Fruit Bunch (FFB) Production

The private oil palm plantations began the planting process in 2006 and completed it in 2018, with production starting in 2009. At the time of the study, the plantation age ranged from 6 to 18 years. The

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study revealed FFB production figures categorized by planting year, showing significant fluctuations in production over the period.

FFB production from the 2006 planting group exhibited a decline of 6.36% in average growth, whereas production from the 2007 planting group increased by 11.03%, and the 2008 group showed a rise of 10.82%. Plants from 2009 recorded an 8.08% increase, while the 2010 group experienced an average growth increase of 4.35%. More substantial increases in FFB production were observed in plantings from 2013 to 2018. The 2013 group recorded the highest production growth of 54.07%, while the 2014 group surged by 94.22%, and the 2017 group showed a 40.24% increase.

A particularly drastic rise in FFB production was recorded for the 2015 planting group, with an increase of 128.56%, followed by 194.33% for the 2016 group, and 214.30% for the 2018 group. Total production over the last five years, from 2019 to 2023, demonstrated significant growth, starting at 74,037,937 kg in 2019 and rising to 108,290,400 kg in 2023, representing an average increase of 42.43%. This data highlights the success of private plantation management in achieving sustainable production, evidenced by consistent annual growth in FFB output.

Pollution and Decline in Surface Water Quality

One indicator used to assess the environmental impact of oil palm plantation activities is the quality of surface water surrounding the plantation area, specifically the Hantu River. Water quality testing serves to evaluate the extent to which agricultural activities contribute to environmental pollution. The test results indicated fluctuations in heavy metal pollution parameters, particularly Fe and Zn, from 2019 to 2023. In 2020, Fe concentrations increased by 302.73% compared to 2019, when the concentration was only 2.93 mg/L. Similarly, Zn concentrations rose by 1,515.38% in 2020 compared to the previous year, where Zn was detected at <0.013 mg/L.

In contrast, Mn and Hg concentrations remained consistent at <0.013 mg/L and <0.0004 mg/L, respectively, throughout the study period. However, Cd and Pb concentrations require special attention due to levels exceeding 200% of permissible limits for human exposure. The most concerning levels were recorded in 2019 and 2020, with concentrations surpassing the maximum threshold by 366% and 400%, respectively, as stipulated by the Indonesian Ministry of Health Regulation Number 2 of 2023 regarding the implementation of Government Regulation Number 66 of 2014 on Environmental Health.

Supporting Factors for Production and Potential Pollutants

Fertilizer Usage

Fertilizers play a crucial role in the growth and productivity of oil palm plantations. The study revealed data on the use of organic and chemical fertilizers by the company from 2019 to 2023. The findings showed significant fluctuations in fertilizer use. In 2020, usage increased by 12,851.84% from the previous year, rising from 42,479.45 kg/year in 2019. However, fertilizer use decreased by 11.31% in 2021 and further declined by 20.79% in 2022. In 2023, fertilizer usage rebounded, increasing by 62.86% to 6,294,109 kg/year.

The total increase in organic fertilizer use over the study period reached 14,716.8%. This evidence indicates that the company's efforts to boost FFB production were conducted intensively, with fertilizer application being a key strategy employed to optimize FFB yields.

Plant Pests and Diseases (PPD) and Weeds

Controlling PPD and weeds is a critical factor in maintaining the productivity of oil palm plantations. In the research area, various pests such as nettle caterpillars, rats, and rhinoceros beetles frequently attack the plants, leading to decreased fresh fruit bunch (FFB) production. Research data revealed significant changes in pesticide usage during the study period. In 2019, the amount of pesticide used reached 12,209.12 liters/kg, followed by a substantial increase of 187.75% in 2020. However, usage declined by 78.72% in

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2021, 37.89% in 2022, and 65.82% in 2023. Overall, there was a significant reduction of approximately 87.01% in pesticide usage from 2019 to 2023.

The decrease in PPD control measures correlates with improved weed management practices. Weed management efforts aim to eliminate factors that may hinder growth or fruiting, including removing pest habitats. The research found notable changes in the use of liquid and solid herbicides. In 2019, herbicide usage was recorded at 655.87 liters/kg. In 2020, usage increased significantly by 1,860.12%, followed by a further 38.91% increase in 2021. However, a 34.76% decline occurred in 2022, followed by a 37.99% increase in 2023. Overall, herbicide use during the study period showed an increase of approximately 2,351.48%.

Utilization of POME

The company continuously utilizes Palm Oil Mill Effluent (POME), as indicated by data from 2019 to 2023. The trend of using POME as a by-product to serve as organic fertilizer and alternative energy for enhancing land productivity is deemed effective in reducing environmental impacts. In 2019, the company recorded POME usage of 919,980 m^3/year. Usage surged by 2,323.76% in 2020, but a sharp decline followed in subsequent years: 99.63% in 2021 and 91.04% in 2022. However, a 406.90% increase was recorded in 2023.

Rainfall

Rainfall data in the plantation area of PT. CLS during the 2019–2023 period shows significant variations in both the number of rainy days and the total annual rainfall. Research findings indicate that in 2019, the total recorded rainfall was 3,150 mm with 119 rainy days. In 2020, rainfall increased to a total of 3,238 mm with 142 rainy days. However, a decline in rainfall occurred in 2021, with a total of 2,883 mm recorded over 114 rainy days. A significant surge was observed in 2022, with total rainfall reaching 3,950 mm over 116 rainy days. Conversely, in 2023, a sharp decline was noted, with total rainfall recorded at only 1,867.3 mm and 95 rainy days. Researchers found that peak rainfall generally occurs in the early and middle months of the year, while the months with the lowest rainfall vary from year to year.

Relationship Between Chemical Usage and Water Quality

The use of materials such as fertilizers, pesticides, and herbicides by oil palm plantation operators, as discussed in this study, has a significant impact on surface water quality. During periods of high rainfall, the potential for chemical residues to be carried into water sources through surface runoff is substantial. These residues influence various water quality parameters such as Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and the presence of heavy metals like lead (Pb), zinc (Zn), and cadmium (Cd) (Syakira Che Nadzi et al., 2019; Formaglio et al., 2020). An increase in nitrate (NO3-N) concentration in surface water is one of the indicators of excessive nitrogen fertilizer use, a condition that significantly contributes to eutrophication, where excessive algal growth triggers a reduction in dissolved oxygen levels in the water (Bashir et al., 2013).

Excessive pesticide use can also increase heavy metal concentrations, such as Pb and Zn, in surface water, threatening aquatic ecosystems (Ahmed et al., 2021; Adil et al., 2023). In addition to heavy metals, the use of both organic and chemical substances in agricultural activities can elevate COD and BOD levels. This increase signals the presence of organic and chemical materials that are difficult to degrade in water, worsening pollution and reducing the quality of aquatic habitats (Qi et al., 2023). Therefore, several studies recommend the adoption of sustainable agricultural practices, including the use of organic fertilizers and effective water management systems, to mitigate environmental impacts. This approach is expected to maintain water quality and ensure the sustainability of palm oil production without harming the surrounding ecosystem (Tanaka et al., 2021).

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Relationship with Increased Heavy Metals

Cd Model

$$Cd = 0.015 + 1.163\times10^{-6}P + 0.000PT - 0.003HB + 1.714\times10^{-6}PO - 6.765\times10^{-7}CH$$
$R^2 = 89.6\%$

This model explains 89.6% of the variation in Cd concentration in water. The constant coefficient of 0.015 represents the baseline Cd concentration when all independent variables are zero. The fertilizer (P) coefficient of 1.163×10^{-6} indicates an increase in Cd concentration by 1.163×10^{-6} mg/L for each additional unit of fertilizer. The pesticide (PT) coefficient of 0.000 shows that changes in pesticide use do not have a significant effect on Cd concentration in this model. The herbicide (HB) coefficient of -0.003 indicates a decrease in Cd concentration by 0.003 mg/L for each additional unit of herbicide. The POME (PO) coefficient of 1.714×10^{-6} explains an increase in Cd concentration by 1.714×10^{-6} mg/L for each additional unit of POME, while the rainfall (CH) coefficient of -6.765×10^{-7} indicates that each additional unit of rainfall reduces Cd concentration by 6.765×10^{-7} mg/L. Overall, the regression results indicate that the use of fertilizers and POME contributes to an increase in Cd concentration, whereas the use of herbicides and rainfall have the potential to reduce Cd levels in water.

Pb (Lead) Model

The regression model for lead (Pb) concentration in water is expressed in the following equation:

$$Pb = 0.012 - 5.781\times10^{-6}P + 3.600\times10^{-2}PT + 1.600\times10^{-2}HB - 1.371\times10^{-5}PO - 1.664\times10^{-6}CH$$

$R^2 = 92.3\%$

This model explains 92.3% of the variation in Pb concentration in water. The constant coefficient of 0.012 represents the baseline lead concentration when all independent variables are zero. The fertilizer (P) coefficient of -5.781×10^{-6} indicates a decrease in Pb concentration by 5.781×10^{-6} mg/L for each additional unit of fertilizer. Pesticide use (PT) causes an increase in Pb concentration by 3.600×10^{-2} mg/L for each additional unit of pesticide.

For herbicide (HB), the contribution is an increase of 1.600×10^{-2} mg/L for each additional unit of herbicide. Meanwhile, the POME (PO) coefficient of -1.371×10^{-5} indicates a decrease in Pb concentration by 1.371×10^{-5} mg/L for each unit of POME. The rainfall (CH) coefficient of -1.664×10^{-6} explains a reduction in Pb concentration by 1.664×10^{-6} mg/L for each additional unit of rainfall. Overall, the regression results indicate that pesticide and herbicide use contribute to an increase in Pb concentration, while the use of fertilizer, POME, and increased rainfall have the potential to reduce Pb levels in water.

Discussion

The issue of environmental pollution caused by oil palm plantations is a major concern in the context of environmental protection and public health worldwide, particularly in countries that are key producers of CPO. Research analyzing the surface water quality around private oil palm plantation areas revealed significant fluctuations in heavy metal pollution parameters such as Fe and Zn, while the concentrations of Cd and Pb were found to exceed the acceptable water quality standards for consumption.

The concentrations of Cd and Pb in the Hantu River water were detected to be above the quality standards. For Cd, with a standard of 0.003 mg/L, the levels detected in 2019 were 466.67% above the threshold, 500.0% in 2020, 300.0% in 2021, 300.0% in 2022, and 300.0% above the standard in 2023. For Pb, with a quality standard of 0.01 mg/L, concentrations detected in 2019 were 260.0% above the threshold, 260.0% in 2020, 300.0% in 2021, 300.0% in 2022, and 300.0% in 2023.

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It is important to note that the long-term accumulation of these heavy metals can lead to serious health risks, such as neurological disorders and developmental issues in children (Chandravanshi et al., 2021; Lidsky & Schneider, 2003). Therefore, despite the relatively low Pb concentration in the Hantu River water, regular monitoring is essential to prevent further potential pollution.

Mercury, known as one of the most hazardous heavy metals, showed consistent test results of <0.0004. However, continuous consumption, even at low levels, can still pose health risks, despite the World Health Organization (WHO) setting the maximum permissible mercury level in drinking water at 0.001 mg/L. Concentrations lower than this threshold, such as 0.0004 mg/L, are typically considered safe in the short term and do not pose significant health risks. However, mercury has cumulative properties, meaning it can accumulate in the human body from long-term exposure, even in very small amounts. Long-term exposure to mercury can cause damage to the nervous system, kidneys, and other organs. The risk is even higher for vulnerable groups such as children, pregnant women, and individuals with specific health conditions (World Health Organization, 2022).

Zinc concentrations exhibited more dramatic fluctuations, peaking at 0.210 mg/L in 2020, followed by a decrease in the subsequent years. This fluctuation suggests that zinc levels in surface water may be influenced by agricultural activities and the use of fertilizers, which often contain heavy metal elements (B. Yan et al., 2023).

The concentration of cadmium (Cd) showed a significant relationship, with an R^2 of 89.6%, while the concentration of lead (Pb) showed an R^2 of 92.3%. These regression results explain that the use of fertilizers, herbicides, and POME has a direct impact on heavy metal concentrations in water. This reinforces the argument for the importance of sustainable agricultural practices and the management of palm oil mill waste (Qiu et al., 2016).

In the context of sustainability, the significant increase in fertilizer use in 2023, which rose by 14.716% to 42,479.45 kg, compared to 42,479.45 kg in 2019, demonstrates the company's commitment to sustainable agricultural practices and contributes to improving water and soil quality.

The reduction in pesticide use, which decreased from 12,209.12 liters/kg/year in 2019 to 1,586.85 liters/kg/year in 2023, may be due to a decrease in pests in the plantation area, alongside an increase in the number of herbicide materials that serve as habitats for plant pests. However, from another perspective, this fact may indicate that the company has taken the right steps to minimize environmental pollution.

The increase in herbicide usage, which rose by 2,351.48% from 655.87 liters/kg/year in 2019, poses a significant potential risk for contamination. It is crucial for every palm oil plantation operator to ensure that the use of agricultural chemicals remains within safe limits to prevent various negative impacts on the environment.

Therefore, regulations governing the use of pollutant sources should be carried out continuously. Additionally, periodic environmental monitoring is essential to ensure that metal concentrations in water, suspected to be caused by the use of agricultural chemicals, remain below the established quality standards. Moreover, educating and advising the surrounding community is important to prevent negative health impacts. Other actions that need to be taken include monitoring water quality to detect potential pollution and prevent environmental damage that could occur in the future (Mudyawabikwa & Musuna-Garwe, 2014).

In general, the findings of this study emphasize the need for prevention and mitigation of environmental impacts by using sustainable agricultural practices, reducing chemicals as pollutants, educating the surrounding community, and conducting regular environmental monitoring to ensure that heavy metal contamination in surface water around plantation areas does not exceed quality standards and does not cause harm to the environment or public health.

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Conclusion

This study reveals that the water quality of the Hantu River, located in the private oil palm plantation area between 2019 and 2023, showed fluctuations in Fe and Zn contamination, while Mn and Hg contamination remained consistent. However, the concentrations of Cd and Pb were found to be more than 200% above the drinking water quality standard, making the surface water unsuitable for consumption.

This contamination occurred due to the use of substances for pest and disease control, weed management, and the extensive and continuous utilization of POME from 2019 to 2023. This assumption is supported by the regression model, which shows a significant relationship between pesticide, herbicide, and POME use, accounting for 89.6% of Cd contamination and 92.3% of Pb contamination in water. Therefore, the management of these substances, along with reducing the sources of pollution and continuous monitoring of water quality, is essential to prevent and detect potential pollution in the future.

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