$PM_{2.5}$ AND HEAVY METAL CONCENTRATIONS IN AMBIENT AIR OF A STEEL INDUSTRIAL ZONE: INFLUENCE OF METEOROLOGICAL FACTORS IN CILEGON, INDONESIA

Purnomosutji Dyah Prinajati*, Lidia Handayani, Nila Astuti

Environmental Engineering, Sahid University, Indonesia

Abstract

This study was to examine the concentrations of $PM_{2.5}$ and associated heavy metals (Fe, Pb, Zn, and Cd) in the ambient air of a steel industrial zone in Cilegon, Indonesia. Cilegon is recognized as a major industrial hub; however, comprehensive assessments of $PM_{2.5}$ pollution in such heavy industry contexts remain limited. Air samples were collected from four strategic locations surrounding PT Krakatau Steel using a Sequential PM Sampler, and meteorological data were simultaneously recorded. Gravimetric analysis was applied to determine $PM_{2.5}$ mass, while heavy metals were quantified via Inductively Coupled Plasma–Atomic Emission Spectroscopy (ICP-AES). The results of the study indicate that the concentrations of $PM_{2.5}$ and related heavy metals (Fe, Pb, Zn, and Cd) in the ambient air of steel industry areas often exceed the WHO guideline (25 µg/m³) and, in some instances, approached or surpassed the Indonesian national standard (65 µg/m³), with higher values typically observed during periods of active industrial operations. Among the metals analyzed, iron (Fe) was dominant, indicating a strong link to steel processing activities. Spearman's correlation revealed a statistically significant positive relationship between ambient temperature and $PM_{2.5}$ concentrations, while no significant correlation was found for relative humidity. These findings highlight the health risks associated with prolonged exposure to fine particulate matter and toxic metals, underscoring the urgent need for targeted air quality management and worker protection strategies in industrial zones. The study contributes local-scale evidence for environmental governance and public health policy in rapidly industrializing regions.

Keywords: *air pollution, Cilegon, heavy metals, $PM_{2.5}$, steel industry*

Introduction

Air pollution remains one of the most pressing environmental challenges worldwide, with serious consequences for both ecological systems and public health (Zhang et al., 2021). This issue is particularly severe in urban and industrialized regions, where emissions from mobile sources (e.g., vehicles) and stationary sources (e.g., factories, power plants) contribute heavily to atmospheric contamination (Manisalidis et al., 2020; Guttikunda & Jawahar, 2018). These emissions contain a complex mix of gaseous pollutants—such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs)—and airborne particulate matter (PM), which may remain suspended or undergo atmospheric transformations before ultimately depositing onto land and water surfaces (Fuzzi et al., 2015). Substantial evidence also shows how emission reductions Influence $PM_{2.5}$ levels and health impacts in China (Zhang et al., 2015).

Among these pollutants, fine particulate matter ($PM_{2.5}$)—particles with aerodynamic diameters of 2.5 microns or less—poses the greatest health threat. Due to its small size, $PM_{2.5}$ can penetrate deep into the lungs and enter the bloodstream,

*)Corresponding Author:
E-mail: dyah_prinajati@usahid.ac.id

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triggering inflammation, respiratory diseases, and even premature mortality (Pope & Dockery, 2006; Lelieveld et al., 2015). Meteorological factors such as temperature, humidity, and wind speed significantly affect $PM_{2.5}$ dispersion and concentration levels, rendering air quality highly responsive to climatic variability (Tai et al., 2010; Wang et al., 2021).

In response to these risks, many countries, including Indonesia, have implemented ambient air quality standards to limit human exposure. However, regional differences in emission sources and meteorological conditions can lead to localized exceedances even when national thresholds are met.

Cilegon City, located in Banten Province, Indonesia, exemplifies this challenge. As one of the country's largest industrial hubs, Cilegon hosts PT Krakatau Steel (PT KS), a major steel production facility covering approximately 2,815 hectares—nearly 16% of the city's total land area. Emissions from industrial operations, vehicular traffic, and residential combustion sources collectively contribute to the degradation of the city's air quality. Moreover, variations in fuel usage, emission control technologies, and stack configurations across industries lead to spatial heterogeneity in pollutant levels (DLHPE, 2009).

Official assessments by the Environmental, Mining, and Energy Agency (DLHPE) have identified nitrogen oxides, particulate matter, sulfur dioxide, carbon monoxide, hydrocarbons, and lead as the primary pollutants in the area, primarily originating from steel manufacturing and transportation emissions (Ruhiat, 2009). To regulate these pollutants, the Indonesian government introduced National Ambient Air Quality Standards (NAAQS) under Government Regulation No. 41 of 1999. These standards define threshold values, beyond which the environment is officially deemed polluted and harmful to human health.

In this context, the present study was to determine the concentration of $PM_{2.5}$ and their associated heavy metal content in the ambient air of Cilegon's steel industrial zone.

Despite Cilegon's status as a critical industrial area with intense manufacturing activity, comprehensive assessments of $PM_{2.5}$ and its chemical composition—particularly heavy metal content—remain limited. Most previous studies in Indonesia have focused on urban vehicular emissions or residential pollution, leaving a significant research gap in understanding the dynamics of air quality within heavy industry zones. Therefore, this study not only contributes valuable empirical data for environmental management in Cilegon but also serves as a reference point for similar steel-producing regions across Southeast Asia.

Research Methodology

Research Location

This study was conducted in Cilegon City, Banten Province, Indonesia—an industrial hub characterized by intensive steel manufacturing activities and elevated levels of air pollution. Sampling locations were selected based on the Indonesian National Standard SNI 19-7119.6-2005, which recommends siting air quality monitors in locations that capture both pollution hotspots and representative ambient conditions.

Air sampling was conducted by the Indonesian National Standard SNI 7119.15:2016, utilizing the Low Volume Sampler (LVS) method. This method collects 24 m^3 of air over 24 hours through 47 mm membrane filters. This method has been validated in previous Indonesian studies for its cost-effectiveness and accuracy in industrial settings (Ermawati et al., 2022), offering a practical tool for routine environmental monitoring and public health risk assessment.

Four representative sites were selected within and surrounding the operational area of PT

Krakatau Steel, aiming to capture spatial variability in $PM_{2.5}$ concentrations.

Figure 1. Sampling sites.

Notes:

- Site 1: Main Entrance Steel Industry (5°59’47.1” S; 106°00’21.3” E)
- Site 2**:** Hot Strip Mill Area Steel Industry (5°59’50.2” S; 106°00’08.1” E)
- Site 3: Billet Pos Area Steel Industry (6°00’32.2” S; 106°00’20.1” E)
- Site 4**:** Blast Furnace Area Steel Industry (6°00’11.9” S; 105°59’36.1” E)

These locations were strategically selected to ensure proximity to primary emission sources while minimizing interference from unrelated anthropogenic activities (Setiawati et al., 2019).

Tools and Materials

Ambient air sampling was conducted on two consecutive weekdays during the standard operating hours of the steel facility. At each location, $PM_{2.5}$ samples were collected using a Sequential PM Sampler (ART Plus APS-1897, Korea) with a constant flow rate of 20 L/min. The samplers were equipped with $PM_{2.5}$ Wins Impactor inlets to capture fine particulate matter selectively.

Pre-conditioned 47 mm glass fiber filter papers were weighed using a microbalance with a sensitivity of ±0.01 mg, both before and after sampling. $PM_{2.5}$. Concentrations were determined through gravimetric analysis, following SNI 7119.15:2016.

Simultaneously, meteorological parameters—including temperature, relative humidity, and wind speed—were measured using Solar Shield temperature-humidity sensors and digital anemometers. Data was logged at 5-minute intervals over a one-hour sampling period at each site to capture real-time atmospheric variation.

Analytical Methods

After sampling, the filters were subjected to acid digestion using a solution of HCl and H_2O_2, followed by dilution with HNO_3. The resulting solutions were analyzed at the Balai Besar Kimia dan Kemasan Laboratory in Jakarta using Inductively Coupled Plasma–Atomic Emission Spectroscopy (ICP-AES).

This method enables a sensitive and accurate quantification of selected trace metals, including Lead (Pb), Cadmium (Cd), and Iron (Fe)

This technique complies with recognized national and international standards for environmental trace metal analysis and has been widely applied in air quality research for industrial zones.

Results and Discussion

$PM_{2.5}$ Concentrations in the Steel Factory Work Environment

Ambient air monitoring was conducted over three distinct periods—3-day, 4-day, and 7-day intervals—between April and June 2024 at PT Krakatau Steel, Cilegon, Indonesia. $PM_{2.5}$ Concentrations were measured using the Sequential PM Sampler (ART Plus APS-1897, Korea) with 24-hour sampling cycles, in accordance with SNI 7119.15:2016. Four strategically selected sampling points were distributed across the industrial complex to capture spatial and temporal variations in $PM_{2.5}$ concentration, adopting a source–receptor framework consistent with methodologies applied in regional studies, which emphasize spatial heterogeneity and seasonal trends in industrial air pollution (Rahman & Meng, 2024; Li et al., 2015).

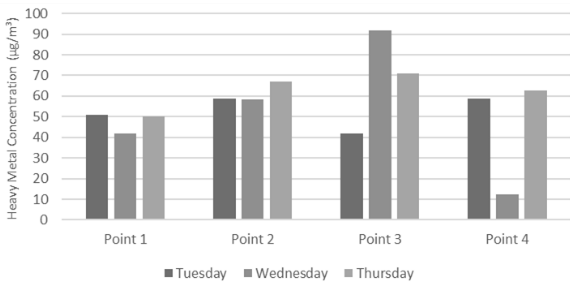

Figure 2. 3-Day $PM_{2.5}$ Concentrations by Sampling Point

As illustrated in Figure 2, $PM_{2.5}$ Concentrations during the 3-day monitoring period exhibited marked spatial variation. The highest concentration was observed at Sampling Point 3 on Wednesday (91.93 µg/m³), while the lowest was recorded at Point 4 on the same day (12.54 µg/m³). The average $PM_{2.5}$ concentration across all locations and days was 55.48 µg/m³—significantly above the 24-hour guideline of 15 µg/m³ set by the World Health Organization (WHO, 2021), indicating a potentially harmful level of exposure to fine particulate matter (WHO, 2021; Lelieveld et al., 2015).

Elevated levels at certain points suggest localized emission sources within the steel production complex, such as sintering plants, rolling mills, or combustion units (Sylvestre et al., 2017; Zhu et al., 2023).

During the 4-day monitoring period, the average $PM_{2.5}$ concentration increased slightly to 60.54 µg/m³ (Figure 3). The peak value occurred at Point 1 on Friday (91.97 µg/m³), possibly due to intensified industrial processes toward the end of the workweek. Conversely, the lowest value was noted at Point 4 on Monday (37.61 µg/m³), likely due to reduced emissions or favorable meteorological conditions (e.g., increased wind speed or humidity), which are known to affect particulate dispersion and atmospheric residence time (Tai et al., 2010; Zhang et al., 2015).

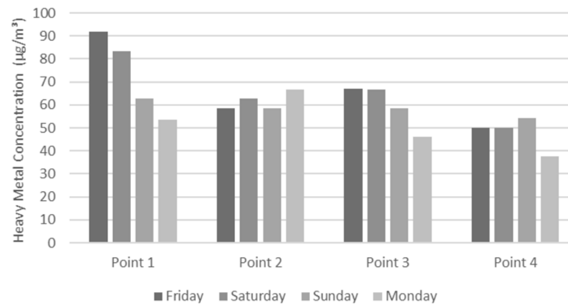

Figure 3. 4-Day $PM_{2.5}$ Concentrations by Sampling Point

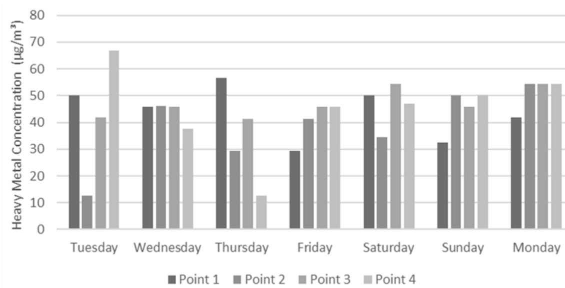

Figure 4. 7-Day $PM_{2.5}$ Concentrations by Sampling Point

The 7-day monitoring campaign resulted in a lower average concentration of 43.50 µg/m³ (Figure 4), which may reflect variations in weather—such as precipitation events that enhance particulate removal through wet deposition—or reduced production cycles during weekends (Fuzzi et al., 2015). Notably, point 4 recorded the highest single-day concentration on Tuesday (66.86 µg/m³), while the lowest value (12.54 µg/m³) was observed at Points 2 and 4 on different days. The broader temporal scope offered by the 7-day monitoring provides a more comprehensive profile of exposure risk, aligning with previous studies that observed strong temporal variability in $PM_{2.5}$ levels near industrial facilities, particularly due to operational cycles and meteorological influences (Sylvestre et al., 2017).

Heavy Metal Content in $PM_{2.5}$ Samples

To gain a deeper understanding of air pollution within the steel manufacturing zone, $PM_{2.5}$-laden filter samples collected during each monitoring period were subjected to heavy metal analysis. Each sample underwent acid digestion using a standardized protocol involving hydrochloric acid (HCl, 1:2) and hydrogen peroxide (H_2O_2), followed by dilution with nitric acid (HNO_3, 2:98). The resulting solutions were analyzed at the Balai Besar Kimia dan Kemasan Laboratory (Jakarta) using Inductively Coupled Plasma–Atomic Emission Spectroscopy (ICP-AES), a technique widely recognized for its high sensitivity in quantifying trace metals in environmental matrices (Jia et al., 2018)

Figures 4, 5, and 6 present the distribution of heavy metals across four sampling locations for the 3-day, 4-day, and 7-day monitoring periods, respectively.

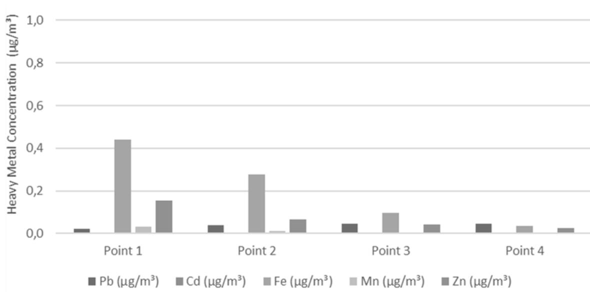

Figure 4. Metal Distribution During 3-day Monitoring

During the 3-day observation period, Fe was the most abundant metal, particularly at Sampling Point 1 (0.46 µg/m³) and Point 2 (0.29 µg/m³), indicating influence from sintering and rolling operations, both known for emitting metallic particulates due to combustion and high-temperature processes (Jia et al., 2018). Pb also peaked at Point 4, suggesting contributions from industrial fuel combustion and vehicular activities. Cd levels remained minimal, reaffirming their limited presence under standard operational conditions. Taken together with the spatial variation observed for Fe, Pb, Mn, and Zn, these findings highlight that emission intensity and the proximity of sampling sites to specific industrial operations—such as furnaces, rolling units, and transport zones—are key determinants of heavy metal distribution patterns in ambient air (Hu et al., 2016; Sylvestre et al., 2017; Jia et al., 2018).

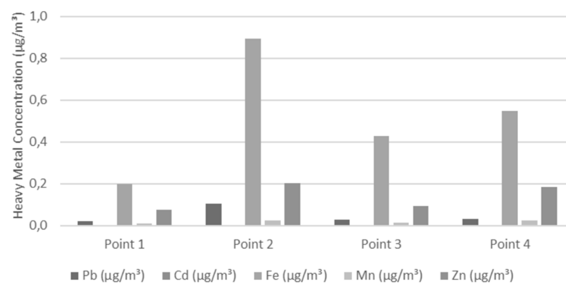

Figure 5. Metal Distribution During 4-day Monitoring

During the 4-day monitoring period, Fe concentrations surged sharply at Sampling Point 2 (~0.9 µg/m³), possibly due to increased industrial activity, particularly from rolling or furnace operations. Mn and Zn also exhibited moderate elevations at this point, likely due to alloying processes or wear on machinery. Cd concentrations remained low and stable across all points, while Pb showed a modest presence, most notably at Point 1. The distinct metal concentration peaks at specific locations underscore the influence of micro-locational factors—such as proximity to furnace units, transport corridors, and material loading areas—in determining pollutant dispersion patterns (Sylvestre et al., 2017; Rahman & Meng, 2024).

In the 7-day results (Figure 6), iron levels remained dominant, again with the highest concentration observed at Point 2 (~0.67 µg/m³). Interestingly, Mn and Zn were relatively stable but more evenly distributed across all points, indicating broader dispersion likely due to consistent emission activities or atmospheric mixing. At the same time, Pb showed a mild increase at Points 3 and 4, possibly linked to traffic-related emissions or delayed atmospheric deposition, a pattern previously noted in studies involving industrial-adjacent zones and diesel traffic impacts (Sylvestre et al., 2017).

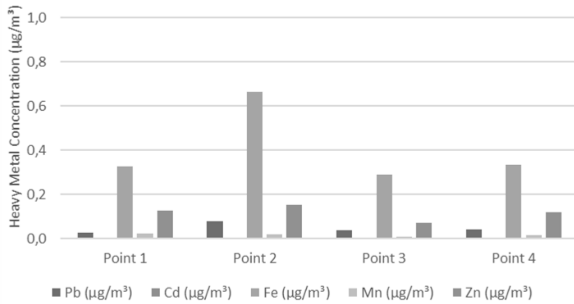

Figure 6. Metal Distribution During 7-day Monitoring

Overall, Fe consistently emerged as the most abundant metal, reflecting its central role in the steel production process, especially during sintering and rolling stages (Jia et al., 2018). The presence of Mn and Zn supports their association with alloying components and mechanical equipment wear (Sylvestre et al., 2017). In contrast, Cd and Pb were detected at relatively low concentrations. Nevertheless, their toxicological significance warrants continued monitoring due to their potential for bioaccumulation and chronic health risks, even at low exposure levels (Hu et al., 2016).

Meteorological Influence and Regulatory Comparison of $PM_{2.5}$ Concentrations

This study further examined the relationships between $PM_{2.5}$ concentrations and meteorological parameters—specifically ambient air temperature and relative humidity—across three monitoring periods using Spearman's rank correlation coefficient. The results indicated a statistically significant positive correlation between temperature and $PM_{2.5}$ concentrations for all durations: $r = 0.596$ ($p = 0.041$) for the 3-day period, $r = 0.514$ ($p = 0.042$) for the 4 days, and $r = 0.391$ ($p = 0.032$) for the 7 days. These findings suggest that increased temperatures may enhance the atmospheric persistence of $PM_{2.5}$ through drier air conditions, increased convection, and potentially more intense solar radiation. This finding is consistent with studies by Tai et al. (2010) and Liu et al. (2017), which found that elevated temperatures promote the formation of secondary aerosols and the suspension of pollutants due to increased photochemical activity.

In contrast, no significant correlation was found between relative humidity and $PM_{2.5}$ concentrations in any observation period. Correlation values were low and statistically insignificant ($r = 0.098$, 0.018, and 0.152 for the 3-, 4-, and 7-day periods, respectively, with p-values well above 0.05). High humidity has been shown to support particle scavenging and deposition, reducing ambient $PM_{2.5}$ levels through hygroscopic growth and wet deposition mechanisms (Zhang et al., 2015; Wang et al., 2022).

Time-series comparisons further supported these findings, showing that $PM_{2.5}$ levels often rose during periods of higher temperatures, especially during active industrial hours. For instance, Sampling Point 3 peaked at 68.25 µg/m³ despite a local temperature drop to 29.7°C, indicating microclimatic and emission source variability can override general meteorological patterns.

Conversely, comparisons between $PM_{2.5}$ and relative humidity showed a consistent trend of lower $PM_{2.5}$ during more humid periods, reinforcing the moisture-removal hypothesis.

To evaluate health risk implications, $PM_{2.5}$ concentrations were compared to Indonesia's National Ambient Air Quality Standards (65 µg/m³, 24-hour average) and the WHO guideline (25 µg/m³, 24-hour average). While most readings were within national limits, many exceeded WHO thresholds. For example, 68.25 µg/m³ at Point 3 (3rd day) and 74.19 µg/m³ at

Point 1 (4th day) far surpassed WHO limits, supporting earlier findings by Pope & Dockery (2006) which stress that long-term exposure, even below national thresholds, can significantly increase risks of respiratory and cardiovascular diseases.

Conclusions

This study evaluated ambient air quality in the steel industrial zone of Cilegon, Indonesia, by assessing $PM_{2.5}$ concentrations, heavy metal content, and key meteorological parameters. The results demonstrated that the average $PM_{2.5}$ levels exceeded both the WHO guideline of 25 µg/m³ and, in several cases, approached or surpassed the Indonesian national standard of 65 µg/m³. The highest concentrations were observed during operational hours and in proximity to core production areas, suggesting that industrial emissions, vehicular activity, and internal combustion processes are the primary contributors to particulate pollution.

Chemical characterization of $PM_{2.5}$ revealed the presence of heavy metals including iron (Fe), lead (Pb), zinc (Zn), and cadmium (Cd), suggesting significant contributions from anthropogenic sources such as metallurgical operations, fuel combustion, and machinery wear. The elevated concentrations of these metals during working periods underscore the influence of production intensity on air quality. Additionally, comparative analysis between working and non-working days further confirmed the dominant role of human activity in driving $PM_{2.5}$ fluctuations.

Meteorological conditions were also found to influence the behavior of pollutants. Air temperature showed a positive and statistically significant correlation with $PM_{2.5}$ levels, likely due to enhanced atmospheric persistence and reduced humidity. In contrast, relative humidity had no significant effect, supporting the hypothesis that rainfall and moisture primarily contribute to pollutant removal rather than accumulation.

These findings raise critical concerns regarding occupational and environmental health risks faced by workers and residents in surrounding areas. Prolonged exposure to delicate particulate matter and toxic trace metals may lead to respiratory and cardiovascular illnesses. Factors such as inadequate ventilation, limited emission control technologies, and insufficient use of personal protective equipment (PPE) further amplify exposure risks within the industrial setting.

Therefore, this study underscores the urgent need for: Strengthened air quality monitoring programs, Enhanced emission control measures targeting particulate and metal emissions, Worker protection policies, including mandatory PPE and exposure limits, and public health surveillance and epidemiological research to evaluate the long-term impacts of industrial air pollution in the Cilegon region.

By integrating scientific evidence with policy-oriented recommendations, this research provides a foundation for more effective environmental governance and sustainable industrial development.

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