Cadmium (Cd) Contamination in Soil, Leachate, and Air at Sukawinatan Landfill, Palembang, Indonesia: A Risk Assessment Perspective

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Abstract: The Sukawinatan Landfill in Palembang operates using an open dumping system, posing a potential risk of environmental contamination by the heavy metal cadmium (Cd). This study aims to analyze Cd contamination levels in soil, leachate, and air, and assess the potential health and environmental risks. Soil samples were randomly collected from three points at depths of 10 cm, 20 cm, and 30 cm. Leachate sampling followed the grab sampling technique in accordance with SNI 6989.59:2008, while air samples were collected from four cardinal directions using a High Volume Air Sampler (HVAS), based on the SNI 7119-4:2017 standard. Cd concentrations were analyzed using *Atomic Absorption Spectroscopy* (AAS). Results showed that Cd levels in soil at all locations exceeded the quality standard (0.06 mg/kg), with the highest concentration recorded at Location 3 (1.52 mg/kg at 20 cm depth). Leachate samples at several points also exceeded environmental thresholds, while Cd concentrations in air remained within safe limits. These findings indicate a potential Cd contamination risk around the landfill, posing possible health hazards, particularly to workers and nearby residents. Improved waste management and regular monitoring are essential to minimize the environmental impact of heavy metal contamination at the Sukawinatan Landfill.

Keywords: Cadmium (Cd); Soil contamination; Leachate; Air quality; Sukawinatan Landfill

Introduction

The increasing volume of waste significantly impacts waste accumulation at landfill sites. Sukawinatan Landfill is one of the main waste disposal sites in Palembang, located in Sukajaya Village, Sukarami District, and has been in operation since 1994 [1)]. The growing population leads to increased waste generation, contributing to environmental issues [2)]. Every day, approximately 1.200 tons of waste are transported from various areas of Palembang, with around 800 tons disposed of at the 25 hectare Sukawinatan Landfill (Siregar et al., 2022). According to data from the Palembang City Environmental Agency (2024), the composition of waste at Sukawinatan Landfill mainly consists of food waste (53%), followed by plastic (17%), paper (14%), wood or leaves (5.5%), rubber (4%), fabric (3%), metal (1.5%), glass (1%), and other types of waste (1%). The landfill still employs an *open dumping* system [4], where waste is piled up without undergoing proper treatment [5].

One of the heavy metals found in landfills is cadmium (Cd) [6]. Electronic waste (e-waste), which is mixed with other waste in landfills, contributes to toxic pollution, particularly heavy metal toxicity Waste accumulated in landfills undergoes oxidation and decomposition processes, ultimately generating leachate due to rainwater infiltration into the waste pile [7]. Leachate seeps into the soil or flows over the surface, eventually reaching river streams[8]. As a result, the Sukawinatan Landfill becomes a potential source of environmental pollution, primarily through the release of Cd into the soil, leachate, and air. Cd present in soil, leachate, and air can lead to ecosystem contamination, enter the food chain, and pose serious health risks to humans[9].

Cadmium (Cd) is a highly toxic heavy metal commonly found in the environment due to human activities[10], particularly from industrial waste, batteries, metal-coated plastics, and improperly managed electronic waste[11]. Cd is classified as a heavy metal with high carcinogenic potential and can have negative effects on various organs and body systems, including the liver, kidneys, brain, and cardiovascular system[12]. Cd pollution in landfills can have long-term impacts on ecosystems and human health, especially for communities and workers around the landfill[13]

Although various studies have been conducted on heavy metal pollution in landfills, comprehensive research analyzing Cd levels in the three main environmental media—soil, leachate, and air—remains limited, especially at the Sukawinatan Landfill in Palembang. Most existing studies have primarily focused on Cd contamination in soil and leachate, as these are the main pathways for pollutant movement in the environment. However, air pollution due to Cd has not been extensively studied, despite the fact that unawareness of airborne Cd levels poses a significant concern, as inhalation exposure can increase health risks for workers and nearby communities. Therefore, this study aims to fill this gap by analyzing not only Cd concentrations in soil and leachate but also in the air, providing a more comprehensive overview of Cd pollution potential at the Sukawinatan Landfill. This research is expected to provide scientific data that can be used by the government and relevant stakeholders to improve waste management systems and minimize the negative impacts of pollution on health and the environment.

2. Materials and Methods

Research Design

Sampling locations for soil, leachate, and air at the Sukawinatan Landfill, Palembang. This study employs a quantitative descriptive approach with laboratory analysis of soil, leachate, and air samples from the Sukawinatan Landfill in Palembang. The cadmium (Cd) concentration in leachate and air was tested at the Analytical Chemistry and Instrumentation Testing Laboratory, Faculty of Mathematics and Natural Sciences, Sriwijaya University, using the *Atomic Absorption Spectrophotometry* (AAS) method.

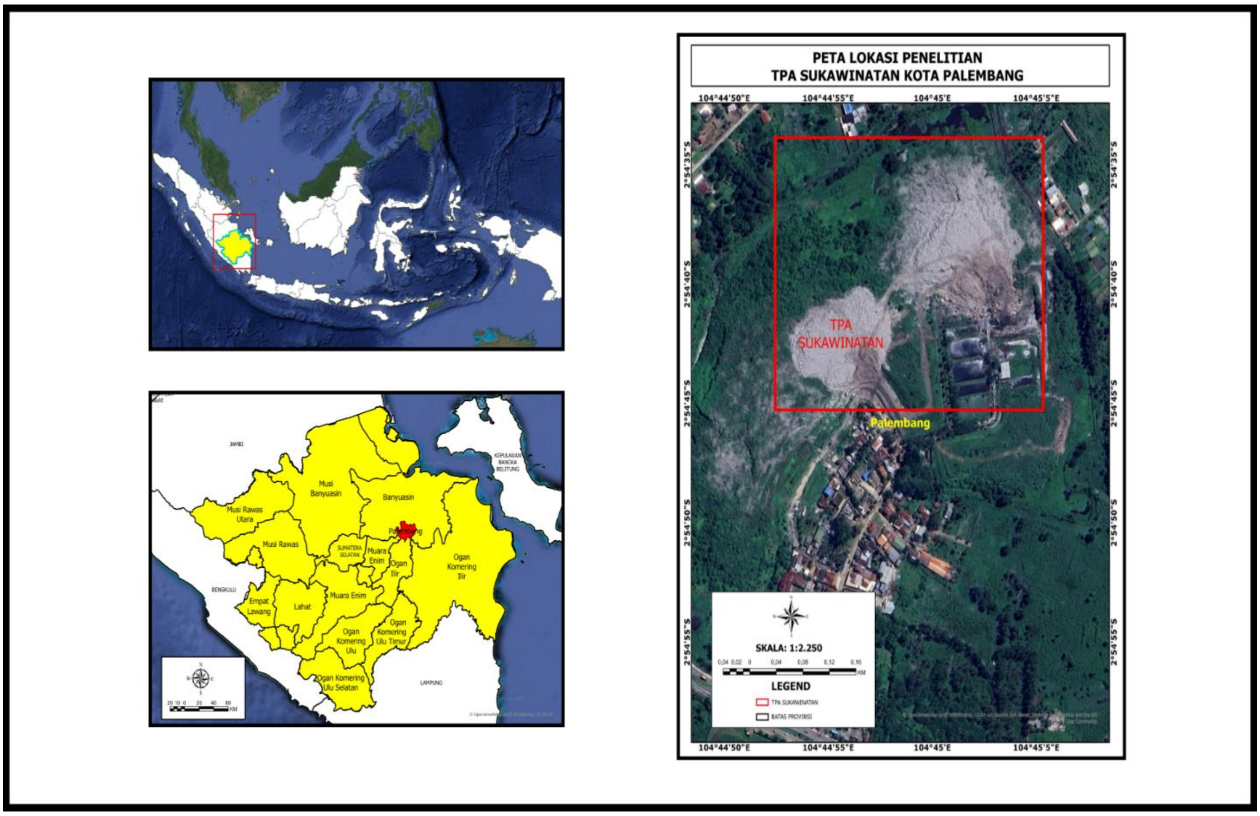

Fig. 1: Location of Sukawinatan Landfill, Palembang
Source: compiled by the authors.

3. Sample Collection

3.1 Soil Sample Collection

The sampling locations for soil were determined using GPS. Samples were randomly collected from three sampling points within the active landfill zone. Soil was taken using a hand auger at three depth intervals: 10 cm, 20 cm, and 30 cm. From each depth, 0.5 kg of soil was collected, placed in labeled plastic bags, and transported to the laboratory for Cd concentration analysis[14]. The quality standard for cadmium in soil is 0.06 mg/kg (Government Regulation of the Republic of Indonesia No. 101 of 2014)[15]. The tested parameter also included soil pH.

Fig 2: Map of Soil Sampling Points at Sukawinatan Landfill, Palembang
Source: compiled by the authors.

3.2 Leachate Sample Collection

The leachate sampling method was conducted using a water sampler and followed the grab sampling technique in accordance with SNI 6989.59:2008[1)]. Sampling points were determined using Global Positioning System (GPS) and were selected based on the flow direction of the leachate[16)].

The data analysis method followed the Indonesian National Standard (SNI) for water and wastewater testing, utilizing the *Atomic Absorption Spectroscopy* (AAS) instrument. The cadmium concentration threshold for leachate is 0.1 mg/L (Regulation of the Minister of Environment and Forestry No. 59 of 2016)[17)]. The measured parameters included pH, *Biochemical Oxygen Demand* (BOD), *Chemical Oxygen Demand* (COD), and *Total Suspended Solids* (TSS).

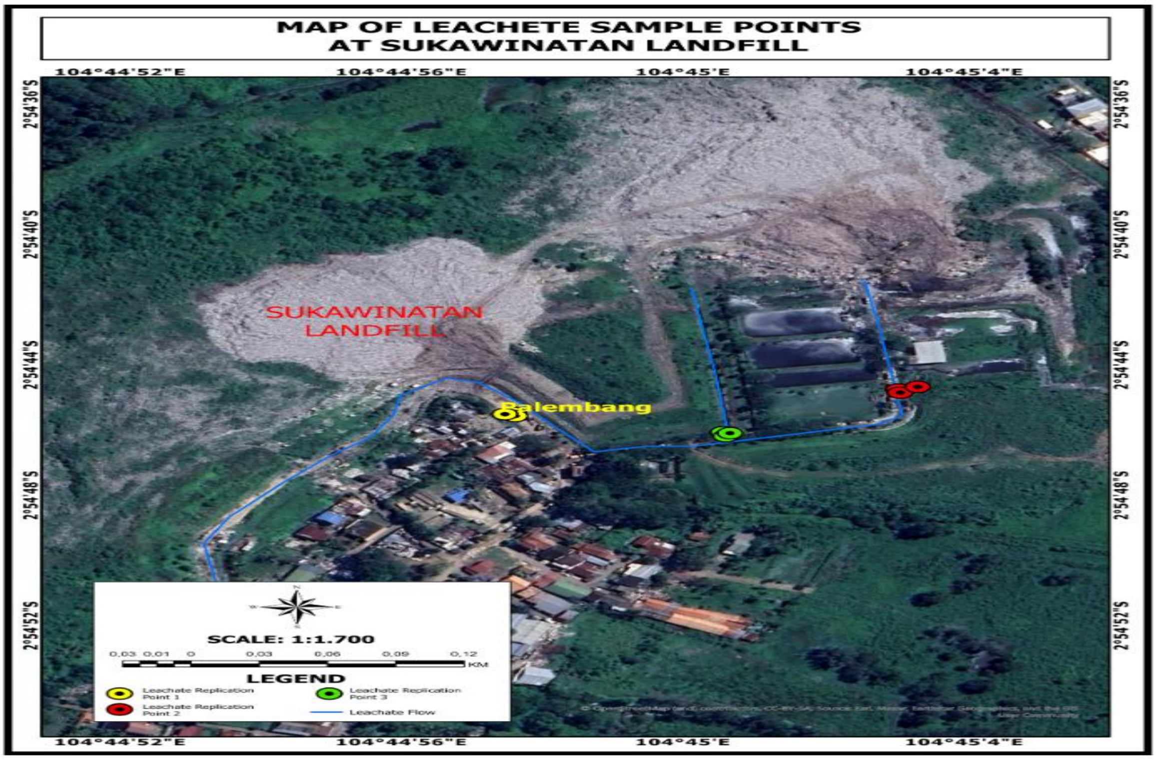

Fig 3: Map of leachate Sampling Points at Sukawinatan Landfill, Palembang
Source: compiled by the authors.

Fig 4: Map of air Sampling Points at Sukawinatan Landfill, Palembang, Indonesia
Source: compiled by the authors.

3.3 Air Sampling

The air sampling technique refers to the SNI 7119-4:2017 standard[18)]. The air measurement points were determined based on the main wind directions (West, East, North, and South) using a compass, while the coordinates were recorded using GPS. Air samples were collected using High Volume Air Sampler (HVAS). The measurement results were then compared with the ambient air quality standards set in Government Regulation of the Republic of Indonesia No. 22 of 2021[19)].

4. Results And Discussion

Waste management at the Sukawinatan Landfill in Palembang has the potential to pollute the environment, particularly due to the presence of the heavy metal Cadmium (Cd). Cd can contaminate soil, leachate, and air through the decomposition of waste and the breakdown of toxic materials. To evaluate this pollution, Cd levels in soil, leachate, and air at the Sukawinatan Landfill were measured and compared with environmental quality standards. The following are the results of Cd concentration measurements in the Sukawinatan Landfill environment.

Table 1. Measurement Results of Cadmium (Cd) Concentration in Soil at Sukawinatan Landfill in Three Locations.

Location	**Depth (cm)**	**pH**	**Cd Concentration (mg/kg)**	**Average Cd Concentration (mg/kg)**	***Cadmium Quality Standard (mg/kg)**	**Remarks**
Location 1 (A)	A1 (10 cm)	**7**	**0,36**			
	A2 (20 cm)	6,5	**1,07**			
	A3 (30 cm)	6,9	**0,37**	**0,6**	**0,06**	Exceeds quality standard
Location 2 (B)	B1 (10 cm)	6,8	**0,50**			
	B2 (20 cm)	6,8	**0,50**			
	B3 (30 cm)	6,9	**0,61**	**0,53**	**0,06**	Exceeds quality standard
Location 3 (C)	C1 (10 cm)	6,9	**1,43**			
	C2 (20 cm)	6,9	**1,52**			
	C3 (30 cm)	6,7	**1,41**	**1,45**	**0,06**	Exceeds quality standard

Remarks: * Threshold limit of cadmium concentration in soil according to the Government Regulation of the Republic of Indonesia No. 101 of 2014.

Based on Table 1, the measurement results indicate that cadmium (Cd) levels in the soil at Location 1 (A) vary between 0.36 mg/kg and 1.07 mg/kg, with an average of 0.6 mg/kg. This average value significantly exceeds the established quality standard of 0.06 mg/kg, indicating heavy metal contamination in this area.

The soil pH at Location 1 ranges from 6.5 to 7, indicating that the soil is in a slightly acidic to neutral condition. A study conducted by Huang et al. (2021) found that Cd concentrations in soils near waste management areas tend to be higher than in soils unaffected by waste activities[20)], particularly when the soil pH is within the slightly acidic to neutral range[21)]. In this pH range, Cd is more soluble and more readily distributed within the soil, increasing its potential mobility in the surrounding environment[22)]. At lower pH conditions, Cd solubility increases[23)], which can elevate the risk of Cd accumulation in plants and the environment[24]. Additionally, high organic matter content can increase soil pH and reduce Cd solubility[25] by stimulating microbial reduction of oxidized soil components[26].

The soil pH at Location 2 and Location 3 remains relatively stable, ranging between 6.8 and 6.9, which is close to neutral conditions. At near-neutral pH, Cd is more easily adsorbed by soil particles such as clay, iron oxides, and organic matter, reducing its presence in soil solution[27]. The cadmium content in neutral soil tends to be lower compared to acidic soil[28]. In low pH soil conditions, cadmium dissolves more easily in groundwater, increasing the potential for it to be transported to deeper soil layers during rainfall or absorbed by plant roots during nutrient uptake[29].

Cd metal is one of the heavy metals in soil that is hazardous to humans because, over the long term, it can accumulate in the body. Figure 5 presents Cd levels in the soil based on location and depth.

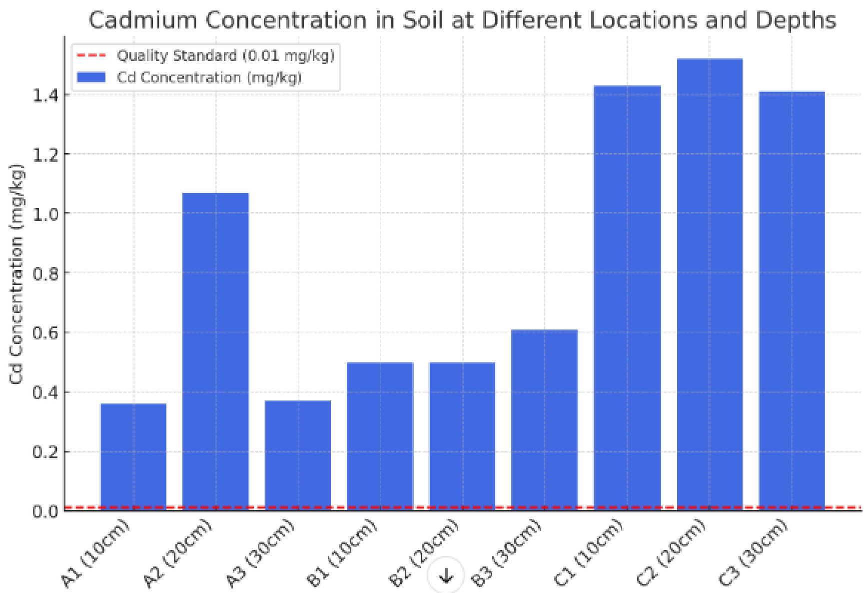

Fig 5: Cadmium (Cd) Concentration in Soil by Location and Depth.

The research results indicate that Cd levels in the soil at all locations have exceeded the established quality standard of 0.06 mg/kg. This condition suggests a significant level of contamination in the area. Exceeding the specified limit indicates a potential hazard to the environment and health, as exposure through the food chain or direct contact with the soil may pose risks to living organisms[30].

At Location 1 (A), the highest Cd concentration was found at a depth of 20 cm (1.07 mg/kg). At Location 2 (B), Cd distribution remained relatively stable across all depths, with the highest concentration recorded at 30 cm (0.61 mg/kg). Meanwhile, at Location 3 (C), Cd levels were significantly high at all depths, peaking at 20 cm (1.52 mg/kg). In general, Cd concentrations in the soil tended to increase or accumulate at a depth of 20 cm in each location. This is due to the accumulation of organic matter in this soil layer, which has the ability to absorb heavy metals significantly[31]. High organic matter content in the soil can enhance its cation-binding capacity, including cadmium. Landfill soils often have low pH due to the decomposition of organic matter, which produces acids[32].

The high Cd levels in the soil at the Sukawinatan Landfill may be attributed to the types of waste accumulated at the site. The composition of waste in this landfill primarily consists of food waste (53%), followed by plastic (17%), paper (14%), wood or leaves (5.5%), rubber (4%), fabric (3%), metal (1.5%), glass (1%), and other waste types (1%)[33]. The Sukawinatan Landfill still employs an open dumping system[4] and does not implement waste segregation, allowing hazardous waste such as electronic waste and hazardous and toxic materials (B3 waste) to mix with other waste types.

Waste in the landfill undergoes oxidation and decomposition, producing leachate due to rainwater infiltration into the waste piles[7]. Consequently, waste materials containing heavy metals in large amounts contaminate the soil[34]. High rainfall infiltration can increase the mobility of heavy metals and accelerate the movement of pollutants through soil layers. This process allows heavy metals to dissolve and migrate to deeper soil layers or groundwater sources[35].

Location 3 has the highest Cd concentration compared to Locations 1 and 2, indicating a greater potential for contamination. The increased presence of heavy metals in contaminated soil suggests that these metals have accumulated within the soil[36]. Soil contamination can also occur indirectly through water that has already been polluted, which then infiltrates into the soil[37]. Hazardous substances contaminating the soil surface can be transported by rainwater or volatilize, eventually penetrating the soil layers[38].

The variation in Cd levels in the soil is influenced not only by activities and soil properties at a specific location but also by the distance from the source of contamination. Location 3 is the closest to the pollution source, as it is near the open dumping pit. Research indicates that the farther the sampling site is from the contamination source, the lower the concentration of heavy metals in the soil tends to be[39]. This finding aligns with the study by Anjanapriya et al. (2021), which reported that heavy metal contamination in soil and water near landfill sites is higher compared to areas farther away[39]

Leachate contains various organic and inorganic compounds, such as hydrocarbons, sodium, potassium, sulfate, nitrogen, and heavy metals. Its composition becomes more complex and difficult to treat over time[40]. Below are the measurement results of cadmium (Cd) levels in the leachate at the Sukawinatan Landfill, Palembang. The obtained data were compared with the quality standards set by the Indonesian Ministry of Environment and Forestry Regulation No. 59 of 2016, which establishes a cadmium concentration limit of 0.1 mg/L, to assess pollution levels and compliance with environmental standards.

Table 2. Measurement Results of Cadmium (Cd) Levels in Leachate at Sukawinatan Landfill at 3 Locations

No	Parameter	Average Measurement Results at Each Location			* Quality Standard
		Location 1	Location 2	Location 3	
1	pH	8,2	8,2	7,4	6-9
2	BOD (mg/l)	244	400	251	150
3	COD (mg/l)	1.023	1.675	1.008	300
4	TSS (mg/l)	183	1.992	652	100
5	Kadmium (mg/l)	0,015	0,023	0,024	0,1

Note: *Cadmium concentration limit according to the Regulation of the Ministry of Environment and Forestry No. 59 of 2016.

The pH measurement results at the three locations ranged from 7.4 to 8.2, indicating that the leachate tends to be alkaline. In alkaline conditions, certain metals are more stable and less likely to dissolve[41]. Under these conditions, cadmium can form insoluble compounds such as $Cd(OH)_2$, reducing its solubility[42]. When the pH of water increases, the solubility of metals decreases because they can transition from carbonate to hydroxide forms in aquatic systems[43].

Biological Oxygen Demand (BOD) measures the amount of dissolved oxygen required by microorganisms to break down organic matter in leachate[44]. In this study, BOD levels at all three locations were relatively high, with Location 2 recording the highest value at 400 mg/L, significantly exceeding the standard limit of 150 mg/L. High BOD values indicate a large presence of organic matter[45], which can lead to a decrease in dissolved oxygen levels in water bodies[46]. The decomposition of organic waste contributes to increased BOD concentrations in leachate[47], suggesting a rising accumulation of organic waste in landfill piles[48].

The COD levels at all locations significantly exceeded the standard limit of 300 mg/L, with Location 2 recording the highest value of 1,675 mg/L. High COD levels indicate the presence of large amounts of organic and inorganic compounds that require chemical oxidation, which may suggest severe contamination from industrial or domestic waste. Similar results were found in the study by Royani et al. (2021), where COD levels were extremely high in the leachate at Kaliori Landfill, Banyumas Regency[44)]. Very high COD levels indicate that the leachate contains organic and inorganic substances that are difficult for microorganisms to decompose[49)].

The TSS values at all three locations exceeded the standard limit of 100 mg/L. In contrast to the study by Aufinal Muna & Sigit Ardisty Sitogasa (2023), where the TSS levels in the leachate at Griyo Mulyo Landfill remained below the standard limit, the increase in fine sand, silt, and insoluble organic compounds carried by the leachate flow contributed to the high TSS levels[50)]. According to Meyrita et al. (2023), a decrease in TSS levels occurs when leachate undergoes optimal treatment processes at a wastewater treatment plant (WWTP), such as filtration, sedimentation, coagulation, and flocculation[51)]

One of the pollutant parameters that must be considered in leachate is the presence of heavy metals, such as cadmium (Cd), which can have negative impacts on the environment and human health. Cd is a toxic metal that can contaminate groundwater and aquatic ecosystems if its concentration exceeds the established threshold.

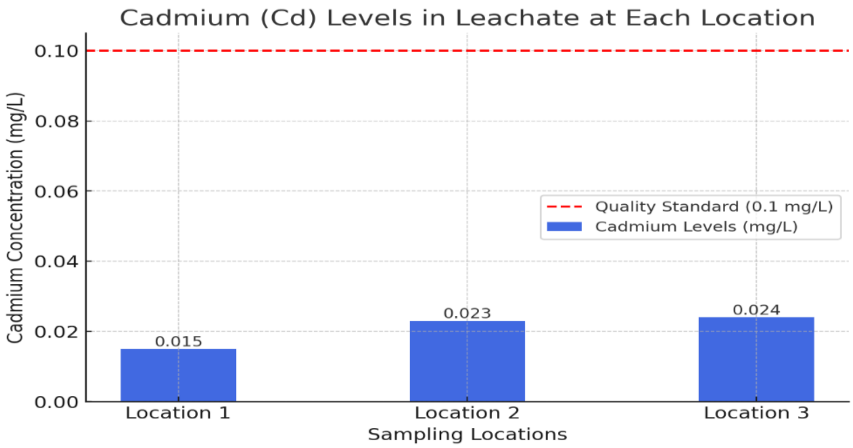

Fig 6: Cd Levels in Leachate at Sukawinatan Landfill at Three Locations.

Based on the figure above, the Cd concentration at the three locations shows variation. At Location 1, the average cadmium concentration is 0.015 mg/L. This location has the lowest cadmium concentration compared to the others. This may be due to the high pH of the leachate (8.2–8.3), which supports the formation of insoluble hydroxide compounds, such as $Cd(OH)_2$. These compounds tend to be insoluble in an alkaline environment, reducing the amount of cadmium dissolved in water[52)].

At Location 2, the average cadmium concentration is 0.023 mg/L. This can be attributed to the high concentration of COD (*Chemical Oxygen Demand*)[53)]. The presence of organic matter in the leachate can influence the solubility of heavy metals by forming organic-metal complexes, thereby increasing the mobility of heavy metals in water[54)].

At Location 3, the average cadmium concentration is 0.024 mg/L, making it the highest among all locations. This is influenced by the lower pH compared to other locations (7.4–7.5). Under these conditions, Cd has higher solubility due to the reduced formation of $Cd(OH)_2$ compounds[42)]. Additionally, the relatively high Total Suspended Solids (TSS) value at this location may indicate a high presence of suspended materials that have the potential to carry heavy metals[55)].

The Cd concentration at all locations remains below the quality standard threshold (0.1 mg/L) set by the Indonesian Ministry of Environment and Forestry Regulation No. 59 of 2016. This indicates that Cd levels in the leachate at Sukawinatan Landfill are still within safe limits. However, the presence of Cd in leachate still requires attention due to its accumulative nature in the environment, which can lead to long-term impacts.

Until now, no data or previous publications have been found that specifically report the measurement results of Cd levels in the air at the Sukawinatan Landfill site. Therefore, this study serves as an initial investigation that directly measures Cd concentrations in the air around the active zone of the Sukawinatan Landfill. The following are the results of Cd measurements in the air at the Sukawinatan Landfill:

Table 3. Measurement Results of Cadmium (Cd) Levels in the Air at Sukawinatan Landfill, Palembang.

Wind Direction	**Cd concentration (μg/m³)**	**Temperature (°C)**	**Time**	**Wind Velocity (m/s)**	**Air pressure (mmHg)**	**Humidity (%)**	***Quality standards (μg/m³)**
North	< 0,0021 (Below the detection limit	29,3	morning	1,8	760	75	0,005
South	< 0,0021 (Below the detection limit)	33,6	afternoon	0,4	758,5	60	0,005
West	< 0,0021 (Below the detection limit)	32,4	afternoon	1,8	760	64	0,005
East	< 0,0021 (Below the detection limit)	28,6	evening	4,9	754	72	0,005

Note: *Quality Standard: Threshold value refers to Government Regulation (PP) No. 22 of 2021 on ambient air quality standards.

Based on Table 3, cadmium (Cd) levels in the air were not detected in all four cardinal directions (north, south, west, and east) during the measurement period. However, this does not necessarily mean that Cd is entirely absent in the air at the landfill; rather, its concentration is below 0.005 μg/m³. This indicates that the potential for air pollution by Cd at the Sukawinatan Landfill is relatively low. Mujahid & Subositi (2020), stated that cadmium presence is more influenced by soil conditions than by air pollution[56)]. Additionally, since there is no waste burning at the Sukawinatan Landfill, cadmium emissions into the air can be minimized. The combustion of waste containing heavy metals or chemicals can release cadmium into the air[57)]. The burning process can generate fine particles containing cadmium, which are released into the atmosphere[58)].

The data also show temperature variations at different times of the day. The highest temperature was recorded at midday in the southern direction (33.6°C), while the lowest temperature was measured in the evening in the eastern direction (28.6°C). Temperature differences can be influenced by solar radiation intensity and local conditions around the landfill. The intensity of solar radiation affects environmental temperatures[59)]. According to Zahra et al (2024), as sunlight becomes more intense during the day, temperatures increase due to higher solar radiation exposure[60)]

Additionally, land cover also affects temperatures around the landfill. Open land cover in the main disposal area can significantly increase local temperature[61)]. Areas with lower vegetation density tend to have higher surface temperatures because less sunlight is absorbed by plants, which typically help reduce temperatures through evapotranspiration[62)]. Wind speed measurements at the landfill showed significant variations based on direction and time. The highest recorded wind speed was 4.9 m/s from the east in the evening, while the lowest wind speed was 0.4 m/s from the south at midday.

Wind speed influences the dispersion of pollutants in the atmosphere[63]; as wind speed increases, pollutants can be dispersed further from their source, reducing local concentrations but potentially affecting a wider area[64].

Air pressure is one of the meteorological parameters that can influence the dispersion of air pollutants, including cadmium (Cd) levels. Based on measurements at the Sukawinatan Landfill in Palembang, air pressure varied between 757 mmHg and 760 mmHg in different directions. In general, air pressure tends to be lower when air temperature is higher, as observed in the eastern and southern directions, where the pressure was lower compared to the north and west. In the context of air pollution, higher air pressure can compress atmospheric layers and hinder pollutant dispersion, whereas lower air pressure can allow pollutants to spread more easily[49]

The highest air humidity was recorded in the morning in the northern direction (75%), while the lowest humidity was observed in the southern direction at midday (60%). When air humidity is high, air dispersion becomes slower due to theincreased presence of water vapor in the mosphere. The abundance of water vapor slows down air movement both horizontally and vertically, leading to higher pollutant concentrations[65].

The study of air pollution at landfill sites has evolved over the past few decades, but it remains less comprehensive than research focused on water and soil contamination. Studies on air pollution in landfills have primarily highlighted greenhouse gas emissions such as methane (CH_4) and carbon dioxide (CO_2)[66][41], as well as hazardous gases like hydrogen sulfide (H_2S)[67] and ammonia (NH_3), which are produced from the decomposition of organic waste[68]. In the context of Indonesia, research specifically examining air pollution caused by heavy metals, particularly cadmium (Cd), remains very limited. One relevant study by Abidin et al., (2024), found that workers at the Piyungan Landfill in Indonesia are at risk of exposure to heavy metals, including cadmium, through the air they inhale while working[34]. To date, there is no national standard that specifically regulates the permissible Cd concentration in the air at landfill environments. However, Cd exposure through inhalation can pose serious health risks, including lung dysfunction [69] and kidney disorders[70], particularly for landfill workers and nearby residents. Therefore, this study, which directly measures Cd levels in the air around the active zone of the Sukawinatan Landfill, represents an important first step in expanding the understanding of heavy metal air pollution risks. These findings not only fill a significant gap in scientific data but also provide a strong foundation for supporting environmental management policies and establishing a more integrated air quality monitoring system in landfill areas.

5. Conclusion

This study reveals that cadmium (Cd) contamination at the Sukawinatan Landfill in Palembang has reached concerning levels, particularly in soil and leachate. The analysis results indicate that Cd concentrations in soil at all sampling locations exceed the established quality standards, with the highest concentration found at a depth of 20 cm in Location 3 (1.52 mg/kg). Overall, Cd levels in landfill leachate remain within safe limits, but other parameters such as BOD, COD, and TSS significantly exceed the regulatory standards. This suggests a high potential for environmental pollution, particularly affecting water sources around the Sukawinatan Landfill. On the other hand, Cd concentrations in the air were below the detection limit (<0.005 µg/m^3), indicating that the risk of air pollution from Cd at the landfill is relatively low. A key factor minimizing Cd emissions into the air is the absence of waste burning at this site, which is typically a major source of Cd release into the atmosphere. Overall, these findings confirm that the Sukawinatan Landfill has the potential to be a source of Cd contamination, primarily through soil and leachate, posing potential health risks to workers and nearby communities. Therefore, improved management strategies are necessary, including routine monitoring, enhancements in waste management systems, and the implementation of remediation technologies to mitigate contamination risks.

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