

## ORIGINAL ARTICLE

# Impacts of Imported Waste Processing Industries on the Ambient Air Quality in Kuala Langat, Malaysia

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## ABSTRACT

**Introduction:** The growth of imported waste processing industries in Malaysia has become a concern due to its impacts to the environment and public health. This study aims to measure the ambient air quality particularly the particulate matter (PM<sub>2.5</sub>) level and heavy metals near paper, plastic and e-waste processing facilities. **Methods:** An ambient air monitoring was conducted at four locations near waste processing facilities and one control area for a month. The real-time concentration of PM<sub>2.5</sub> was measured using Purple Air devices while a low-volume air sampler was used to collect air samples on a glass fibre filter for a heavy metals analysis. **Results:** The results showed that the daily concentration of PM<sub>2.5</sub> at all locations, except for S1(A), exceeded the Malaysian Ambient Air Quality Standards for PM<sub>2.5</sub> which is 35 µg m<sup>-3</sup>. The highest PM<sub>2.5</sub> concentration was recorded near to plastic and e-waste processing facilities (S3) (41.41 ± 6.37 µg m<sup>-3</sup>). Diurnal analysis showed that the PM<sub>2.5</sub> concentration was higher during the early morning (00:00 – 05:00), ranging from 33.94 to 53.78 µg m<sup>-3</sup>, and late evening (18:00 – 23:00), ranging from 37.00 µg m<sup>-3</sup> to 46.14 µg m<sup>-3</sup>, which may be associated with overnight pollutant accumulation. Statistical analysis has shown a significantly higher (p < 0.05) PM<sub>2.5</sub> concentrations at all sampling locations compared to the paper waste processing facilities, as well as between plastic and e-waste processing facilities with the control area. In addition, an analysis of heavy metals has shown the presence of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni) and lead (Pb) at all sampling locations. However, Pb at plastic waste processing facilities (S2) was the only one found to exceed the permissible exposure limit (PEL) by WHO (0.5 µg m<sup>-3</sup>) at 1.03 µg m<sup>-3</sup>. **Conclusion:** These findings provide early evidence of the declined air quality near the imported waste processing facilities and indicate the potential of health risks such as respiratory and cardiovascular effects due to prolonged exposure to PM<sub>2.5</sub> and heavy metals. Immediate actions should be taken by identifying all illegal facilities as well as conducting health risk assessments for the communities nearby to minimize the exposure and protect the public health.

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## INTRODUCTION

In Malaysia, there are extremely low post-consumer recycling practices. The solid waste is often disposed of in both sanitary and unsanitary landfills due to the procedures involved in recycling being expensive, time-consuming, and needing a lot of energy resources especially when processing mixed, multi-layered, and contaminated plastic (1). However, when China started to completely close its doors to plastic waste importation in 2018, there were reports of hundreds of small-scale

Chinese plastic recycling companies relocating to countries in Southeast Asia. This has led to a booming number of illegal plastic recycling facilities which began operating in Malaysia with 170 of them having been identified and subsequently closed down by the authorities in a series of raids in 2019 (2, 3). The plastic waste took a significant detour throughout Southeast Asia and Malaysia became the world's largest importer of plastic waste overnight due to the increase of plastic waste purchased by the local recycling industry (3).

In addition, due to the rising demand for paper-based packaging goods from the industrial and culinary sectors, paper recycling is also becoming increasingly popular in the paper and paper board sectors (4). However, following the National Sword policy's introduction

in 2017, small Chinese paper mills had their import permits for recycled paper revoked which caused a significant drop in the amount of recycled paper from the United States that was sent to China and Southeast Asian nations were among the new destinations that the U.S. recycled paper sector created for recyclable solid waste (5-7).

Apart from the rise of legal recycling factories to deal with the overwhelming plastic waste imports, there were reports of unregulated recycling facilities which operated without Approved Permit (AP) and have inadequate pollution control measures, resulting in environmental and public health concerns (8). This expansion created a need to better understand the air quality implications of waste-processing activities, particularly emissions of  $PM_{2.5}$  and  $PM_{2.5}$ -bound heavy metals which can be released during the recycling process causing environmental plastic contamination. According to a Scottish study team, the cutting, shredding, and washing of plastic in recycling facilities can result in the formation of microplastics, which are small, poisonous particles that can be present in our air along with particulate matter 2.5 and seriously endanger human health (9). Besides, industrial recycling activities, especially e-waste recycling, are significant sources of  $PM_{2.5}$  emissions, which often contain hazardous substances such as heavy metals. Waste-processing activities such as shredding, burning, smelting, and mechanical dismantling can generate fine particulate matter enriched with heavy metals (10). Studies in China have shown that  $PM_{2.5}$  concentrations near recycling facilities are higher than in surrounding areas, with elevated levels of heavy metals like lead (Pb), copper (Cu) and cadmium (Cd) released during the mechanical processing of electronic waste (10, 11). This type of process carried out at high temperature (200-300 °C) may also produce other toxic metals including copper and nickel which are considered as an endocrine disrupting chemical (EDCs) due to it can readily adsorb onto  $PM_{2.5}$  surfaces, allowing them to travel long distances and penetrate deep into the respiratory system (12, 13). When deposited in the lower airways, these metals can lead to acute and chronic toxicological effects in the lung including cancer risk and non-carcinogenic effects, especially for workers and nearby residents (11). Therefore, assessing  $PM_{2.5}$  alone is insufficient—its chemical composition, especially toxic metals such as Pb, Cd, Cu, and Ni, provides critical insight into potential human health risks.

Study in Guiyu, China, reported mean  $PM_{2.5}$  concentration was 49.9  $\mu\text{g}/\text{m}^3$  among e-waste dismantling community, which notably higher than the nearby reference area, 37.6  $\mu\text{g}/\text{m}^3$  while values of Pb (160  $\text{ng}/\text{m}^3$ ) and Cd (5.7  $\text{ng}/\text{m}^3$ ) are also significantly higher compared to the reference site (69  $\text{ng}/\text{m}^3$  and 3.4  $\text{ng}/\text{m}^3$ ) (11).  $PM_{2.5}$  exposure is related to worsened asthma, irregular heartbeat, nonfatal heart attacks, and early mortality from heart or lung illness while exposure to heavy metals

such as lead and cadmium is responsible for substantial neurological and hematological health consequences as well as kidney and bone damage (14). In addition, illegal recycling factories which apply improper ways of disposing of plastic waste such as illegal burning may cause negative impacts to the environment such as air pollution. In Jenjarom, Kuala Langat, Malaysia, residents living nearby the illegal recycling factories have reported several health symptoms that they have suffered since the factories operating which includes coughing, difficulties in breathing and skin rashes due to the air pollution from the burning of plastic waste by the factories (15).

Particulate matter ( $PM_{2.5}$ ) has been one of Malaysia's biggest air pollutants in the last ten years, especially in cities and industrial areas due to industrialization, high fuel combustion, and chemical processes (16). The Department of Environment (DOE) Malaysia often identifies  $PM_{2.5}$  as the primary pollutant causing air quality degradation in the National Air Quality Reports, with concentrations frequently elevated during industrial operations and haze events (17). Several local studies have reported  $PM_{2.5}$ -bound heavy metals, such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), and nickel (Ni), have been found in industrial and roadside settings, suggesting that nearby communities may be at risk for both non-carcinogenic and carcinogenic diseases. Study in Bangi, Selangor revealed that the average  $PM_{2.5}$  levels were ranged between 25 - 60  $\mu\text{g}/\text{m}^3$  and were frequently contained high levels of Pb, Cd, Ni and Cr which are 21.84, 0.54, 17.24 and 107.68  $\text{ng}/\text{m}^3$ , respectively (18).

Despite these monitoring efforts and localized studies, there remains a lack of targeted assessment on  $PM_{2.5}$  and associated heavy metals specifically surrounding imported waste processing industries, which have rapidly expanded following China's waste import ban. Most Malaysian studies focus on general industrial or urban sources as well as e-waste processing facility, overlooking the potential emissions from paper and plastic waste recycling facilities that process imported waste as well. These facilities may emit fine particles enriched with toxic metals through mechanical shredding, open burning, or inadequate air pollution control (10). Therefore, this study aims to bridge this knowledge gap by measuring the concentration of  $PM_{2.5}$  and associated heavy metals in the air near to imported waste processing facilities in Kuala Langat, Malaysia, and compare them with non-industrial control areas.

## MATERIALS AND METHODS

This study was conducted in Kuala Langat due to its dense clustering of imported waste processing facilities and increasing community complaints regarding environmental degradation and public health issues. The district of the Kuala Langat has 44.5 percent



target sites for a month (30 days) to measure the real-time concentration of  $PM_{2.5}$ . The Purple Air sensors collected  $PM_{2.5}$  data continuously at a 2-minute logging interval throughout the entire sampling period at each station. Data were later aggregated into hourly averages for analysis.

Additionally, a low-volume air sampler (BGI Omni FT- Ambient Air Sampler) was used for 24-hour measurements with 47-mm Advantec glass fiber filters to analyze the mass concentrations ( $\mu g$ ) of fine particulate matter and heavy metals ( $\mu g\ m^{-3}$ ). The air sampler operated for 3 to 5 days at each sampling location and a Kestrel 5500 was set up together to record the wind speed ( $m\ s^{-1}$ ), temperature ( $^{\circ}C$ ), and relative humidity (%) during the running time of the air sampler. The air sampler was run together with the Purple Air sensors but only for 3 to 5 days at each sampling locations (3 days at S4, 4 days at S1(B) and 5 days at S1(A), S2 and S3).

Field blanks were collected by handling unused filters in the same manner as sampled filters, without exposing them to ambient air, to detect contamination introduced during transport, handling, or laboratory processing. Laboratory blanks and procedural blanks were analysed alongside samples to monitor potential contamination during sample preparation and digestion. Recovery rates of the heavy metals analysis were maintained within 90 – 110%.

Preparations prior to sampling, the glass fibre filters were pre-baked at  $450^{\circ}C$  in an oven for 4 hours and desiccated for 24 hours before pre-weighing with analytical balances. The prepared glass fibre filter was installed in the low-volume sampler and operated for 24 hours to capture fine particulate matter at each location. The samples were then replaced and desiccated for another 24 hours to ensure no moisture retention while the low-volume sampler was run with a new filter paper for another 24-hour period. The desiccated filters were weighed again using gravimetric analysis to determine the mass concentration of fine particulate matter trapped on the filter. The US EPA Method IO-3.1 was used to extract all used filter papers before heavy metal analysis using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in the lab. Each filter was transferred to a beaker, treated with 10 mL of ultrapure  $HNO_3$ , and heated inside a fume hood to dissolve metal-bound particulates. After cooling, 10 mL of reagent water was added, and the solution was transferred to a 20 mL volumetric flask and diluted. Samples were stored in acid-washed 15 mL centrifuge tubes before analysis. The extracted samples were transferred into 15 mL centrifuge tubes to be sent to the lab for heavy metal analysis ( $\mu g\ m^{-3}$ ) including Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), and Lead (Pb). All data analyses were entered and performed using SPSS software version 27.0. Assumptions of normality and variance homogeneity for all data were tested using Shapiro Wilk Normality

Test before applying the parametric tests. Independent T-tests for normally distributed data or Mann-Whitney U tests for non-normally distributed data were used to compare heavy metal and  $PM_{2.5}$  concentrations at each site with the control area. Results are presented with the corresponding test statistic (t for Independent T-Test and Z for Mann-Whitney U Test) and p-value ( $p < 0.05$  considered statistically significant). Although multiple pairwise comparisons were conducted, no multiple comparison correction was applied, given that the study objectives focused on specific a priori comparisons between industrial sites and the control site, where this is acknowledged as a limitation. Due to the comparisons were limited and predetermined, the likelihood of inflating Type I error was minimized. The analysis focused on direct pairwise comparisons to examine differences between industrial and control locations. Therefore, other statistical analysis including ANOVA or multivariable regression modelling was not applied in this study due to the limited sample size and the objective of conducting site-specific comparisons rather than modelling predictive relationships. Moreover, correlation analysis between daily concentrations of heavy metals and  $PM_{2.5}$  concentrations with the meteorological variables was performed using Pearson correlation coefficient (r) for normally distributed data and Spearman's rank correlation ( $\rho$ ) for non-normal data to identify environmental drivers of dispersion or accumulation.

## RESULTS

### Meteorological Data

The air temperature throughout the sampling period for all sampling locations varied from  $32.92^{\circ}C$  to  $36.02^{\circ}C$ . The mean relative humidity throughout the sampling period is between 50.0 % to 57.49 % with S1(A) recorded the highest humidity but lowest temperature. The wind speed data, which varied between 0.8 and  $0.9\ m\ s^{-1}$ , showed that the wind speed was nearly constant across all sampling locations. Furthermore, the mean rainfall data derived from the meteorological data ranged from 2.1 mm to 4.1 mm, with site S2 having the highest mean rainfall, indicating that some days experience more rainfall than others.

### Daily Real Time Concentration of $PM_{2.5}$

The mean concentration of  $PM_{2.5}$  at all sampling locations were found to be higher than the daily limit from World Health Organization (WHO) 2021 Guideline ( $15\ \mu g\ m^{-3}$ ) and Malaysian Ambient Air Quality Standards (MAAQS) ( $35\ \mu g\ m^{-3}$ ) as shown in a boxplot in **Figure 2**. To further support the daily variation shown in **Figure 2**, **Table I** summarizes the statistical comparisons across sites. The comparison reported that  $PM_{2.5}$  concentration was statistically higher at plastic and e-waste recycling factory (S3 and S2) than at the paper waste recycling factory (S1A and B) and control site (S4) (**Table I**).  $PM_{2.5}$  concentrations at the paper waste recycling factory

sites showed significant variation between stations. The  $PM_{2.5}$  concentrations at S1(A) ( $t(65) = -4.249$ ,  $p < 0.001$ ,  $d = -1.039$ ) was significantly lower than S1(B). These differences may indicated potential variations in pollution dispersion or meteorological influences at this location, including wind speed and direction.

### Diurnal Trend of $PM_{2.5}$

The hourly trend of  $PM_{2.5}$  concentrations across all sampling locations showing elevated levels during the early morning (00:00 – 05:00), ranging from 33.94 to 53.78  $\mu g m^{-3}$ , and late evening (18:00 – 23:00), ranging from 37.00 to 46.14  $\mu g m^{-3}$  (Figure 3). These patterns were further supported through statistical comparisons in Table II. The highest  $PM_{2.5}$  concentration during early morning (00:00 – 05:00) was observed at plastic waste recycling factory (S2) ( $53.78 \pm 2.54 \mu g m^{-3}$ ), which was significantly elevated relative to the control site, S4 ( $t(10)$

$= 5.049$ ,  $p < 0.001$ ,  $d = 2.915$ ). In contrast, the morning peak (06:00 – 11:00) showed fluctuations across all sites, likely influenced by daily human activities and atmospheric conditions while the subsequent afternoon (12:00–17:00) decline likely reflects improved dispersion conditions or reduced emission sources with higher afternoon wind speeds and increased mixing due to daytime convective heating. Despite the decline during the afternoon period, comparisons between industrial areas with the control site (S4) indicated significantly greater concentrations at paper waste recycling factory, S1(B) ( $t(10) = 2.971$ ,  $p = 0.014$ ,  $d = 1.715$ ) and plastic and e-waste recycling facility, S3 ( $t(10) = 3.078$ ,  $p = 0.012$ ,  $d = 1.777$ ). Additionally, the late evening peak (18:00 – 23:00) was also reported as most pronounced at the plastic and e-waste recycling factory (S3) ( $46.14 \pm 5.28 \mu g m^{-3}$ ). While the exact sources cannot be confirmed due to lack of industrial operational data,

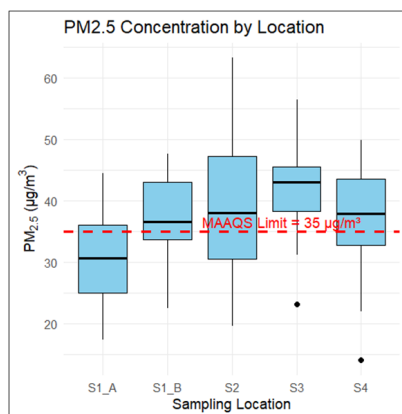


Fig. 2: Boxplot for  $PM_{2.5}$  mean concentration at all sampling locations. S1(A) and S1(B) represent a paper waste recycling factory, S2 represent plastic waste recycling factory and S3 represent a plastic & e-waste recycling factory while S4 represent control site.

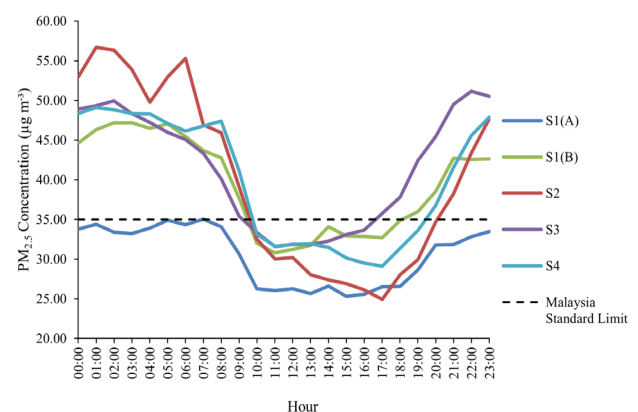


Fig. 3: Hourly average of  $PM_{2.5}$  concentration ( $\mu g m^{-3}$ ) at all sampling locations. S1(A) and S1(B) represent a paper waste recycling factory, S2 represent plastic waste recycling factory and S3 represent a plastic & e-waste recycling factory while S4 represent control site.

Table I: The comparison of daily  $PM_{2.5}$  ( $\mu g m^{-3}$ ) Concentration Between Sampling Locations.

| Comparison between Industrial Areas |                              |                    |                              |                     |         |
|-------------------------------------|------------------------------|--------------------|------------------------------|---------------------|---------|
| Sampling Locations                  | Mean (SD) ( $\mu g m^{-3}$ ) | Sampling Locations | Mean (SD) ( $\mu g m^{-3}$ ) | Statistical test, t | p-value |
| S1(A)                               | 30.56 (7.23)                 | S1(B)              | 37.52 (6.18)                 | -4.249              | <0.001* |
| S1(A)                               | 30.56 (7.23)                 | S2                 | 39.95 (11.70)                | -3.677              | <0.001* |
| S1(A)                               | 30.56 (7.23)                 | S3                 | 41.41 (6.37)                 | -6.579              | <0.001* |
| S1(B)                               | 37.52 (6.18)                 | S2                 | 39.95 (11.70)                | -0.994              | 0.327   |
| S1(B)                               | 37.52 (6.18)                 | S3                 | 41.41 (6.37)                 | -2.609              | 0.011*  |
| S2                                  | 39.95 (11.70)                | S3                 | 41.41 (6.37)                 | -0.594              | 0.556   |
| Comparison with control site (S4)   |                              |                    |                              |                     |         |
| Sampling Locations                  | Mean (SD) ( $\mu g m^{-3}$ ) | Sampling Locations | Mean (SD) ( $\mu g m^{-3}$ ) | Statistical test, t | p-value |
| S1(A)                               | 30.56 (7.23)                 | S4                 | 36.96 (8.19)                 | -3.377              | <0.001* |
| S1(B)                               | 37.52 (6.18)                 | S4                 | 36.96 (8.19)                 | 0.325               | 0.746   |
| S2                                  | 39.95 (11.70)                | S4                 | 36.96 (8.19)                 | 1.148               | 0.257   |
| S3                                  | 41.41 (6.37)                 | S4                 | 36.96 (8.19)                 | 2.560               | 0.013*  |

\*Significant value <0.05, Independent Sample T-Test

(Note: S1(A) and S1(B) – paper waste recycling factory, S2 – plastic waste recycling factory, S3 – plastic & e-waste recycling factory, S4 – control site)

**Table II: Comparison of PM<sub>2.5</sub> Real Time Concentration Based on Classified Time.**

| Comparison between Industrial Areas |              |                   |              |                               |                   |              |                   |              |                               |
|-------------------------------------|--------------|-------------------|--------------|-------------------------------|-------------------|--------------|-------------------|--------------|-------------------------------|
| Early Morning                       |              |                   |              |                               | Morning           |              |                   |              |                               |
| Sampling location                   | Mean (SD)    | Sampling location | Mean (SD)    | Test statistic, t/z (p-value) | Sampling location | Mean (SD)    | Sampling location | Mean (SD)    | Test statistic, t/z (p-value) |
| S1(A)                               | 33.94 (0.62) | S1(B)             | 46.47 (0.99) | -26.297 (<0.001)*             | S1(A)             | 31.07 (4.11) | S1(B)             | 38.74 (6.24) | -2.513 (0.031)*               |
| S1(A)                               | 33.94 (0.62) | S2                | 53.78 (2.54) | -18.554 (<0.001)*             | S1(A)             | 31.07 (4.11) | S2                | 41.65 (9.57) | -2.486 (0.043)*               |
| S1(A)                               | 33.94 (0.62) | S3                | 48.29 (1.46) | -22.128 (<0.001)*             | S1(A)             | 31.07 (4.11) | S3                | 38.14 (5.52) | -2.514 (0.031)*               |
| S1(B)                               | 46.47 (0.99) | S2                | 53.78 (2.54) | -6.560 (<0.001)*              | S1(B)             | 38.74 (6.24) | S2                | 41.65 (9.57) | -0.623 (0.547)                |
| S1(B)                               | 46.47 (0.99) | S3                | 48.29 (1.46) | -2.525 (0.030)*               | S1(B)             | 38.74 (6.24) | S3                | 38.14 (5.52) | 0.178 (0.862)                 |
| S2                                  | 53.78 (2.54) | S3                | 48.29 (1.46) | 4.584 (0.001)*                | S2                | 41.65 (9.57) | S3                | 38.14 (5.52) | 0.778 (0.454)                 |
| Comparison with Control Site (S4)   |              |                   |              |                               |                   |              |                   |              |                               |
| S1(A)                               | 33.94 (0.62) | S4                | 48.34 (0.70) | -37.702 (<0.001)*             | S1(A)             | 31.07 (4.11) | S4                | 41.04 (7.08) | -2.983 (0.014)*               |
| S1(B)                               | 46.47 (0.99) | S4                | 48.34 (0.70) | -3.793 (0.004)*               | S1(B)             | 38.74 (6.24) | S4                | 41.04 (7.08) | -0.598 (0.563)                |
| S2                                  | 53.78 (2.54) | S4                | 48.34 (0.70) | 5.049 (<0.001)*               | S2                | 41.65 (9.57) | S4                | 41.04 (7.08) | 0.124 (0.904)                 |
| S3                                  | 48.29 (1.46) | S4                | 48.34 (0.70) | -0.081 (0.937)                | S3                | 38.14 (5.52) | S4                | 41.04 (7.08) | -0.793 (0.446)                |
| Afternoon                           |              |                   |              |                               | Late Evening      |              |                   |              |                               |
| Comparison between Industrial Areas |              |                   |              |                               |                   |              |                   |              |                               |
| S1(A)                               | 25.99 (0.55) | S1(B)             | 32.59 (1.00) | -14.215 (<0.001)*             | S1(A)             | 30.86 (2.67) | S1(B)             | 39.55 (3.59) | -4.752 (<0.001)*              |
| S1(A)                               | 25.99 (0.55) | S2                | 27.26 (1.80) | -1.659 (0.149)                | S1(A)             | 30.86 (2.67) | S2                | 37.00 (7.66) | -1.854 (0.112)                |
| S1(A)                               | 25.99 (0.55) | S3                | 33.09 (1.48) | -10.986 (<0.001)*             | S1(A)             | 30.86 (2.67) | S3                | 46.14 (5.28) | -6.328 (<0.001)               |
| S1(B)                               | 32.59 (1.00) | S2                | 27.26 (1.80) | 6.350 (<0.001)*               | S1(B)             | 39.55 (3.59) | S2                | 37.00 (7.66) | 0.738 (0.477)                 |
| S1(B)                               | 32.59 (1.00) | S3                | 33.09 (1.48) | -0.687 (0.507)                | S1(B)             | 39.55 (3.59) | S3                | 46.14 (5.28) | -2.530 (0.030)*               |
| S2                                  | 27.26 (1.80) | S3                | 33.09 (1.48) | -6.124 (<0.001)*              | S2                | 37.00 (7.66) | S3                | 46.14 (5.28) | -2.408 (0.037)*               |
| Comparison with Control Site (S4)   |              |                   |              |                               |                   |              |                   |              |                               |
| S1(A)                               | 25.99 (0.55) | S4                | 30.66 (1.24) | -8.425 (<0.001)*              | S1(A)             | 30.86 (2.67) | S4                | 39.47 (6.63) | -2.951 (0.023)*               |
| S1(B)                               | 32.59 (1.00) | S4                | 30.66 (1.24) | 2.971 (0.014)*                | S1(B)             | 39.55 (3.59) | S4                | 39.47 (6.63) | 0.024 (0.981)                 |
| S2                                  | 27.26 (1.80) | S4                | 30.66 (1.24) | -3.809 (0.003)*               | S2                | 37.00 (7.66) | S4                | 39.47 (6.63) | -0.599 (0.563)                |
| S3                                  | 33.09 (1.48) | S4                | 30.66 (1.24) | 3.078 (0.012)*                | S3                | 46.14 (5.28) | S4                | 39.47 (6.63) | 1.926 (0.083)                 |

\*Significant value &lt;0.05, Independent Sample T-Test

Note: Early Morning (12AM - 5AM), Morning (6AM - 11AM), Afternoon (12PM - 5PM), Late Evening (6PM - 11PM)

S1(A) and S1(B) – paper waste recycling factory, S2 – plastic waste recycling factory, S3 – plastic &amp; e-waste recycling factory, S4 – control site

these peaks are consistent with patterns reported in industrial regions where stable nighttime meteorological conditions accumulates overnight pollutant and reduces atmospheric dispersion. The timing of these peaks also reflects operational trends reported for similar recycling facilities in the region.

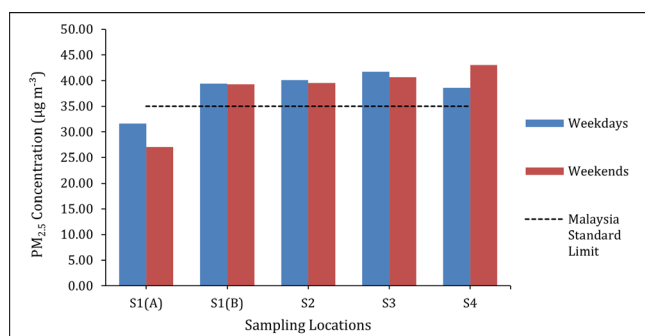
### Weekday and Weekend Trend of PM<sub>2.5</sub>

The mean concentrations of PM<sub>2.5</sub> during weekdays at all sampling locations S1(A), S1(B), S2 and S3 are higher compared to during weekends, ranging from 31.59 to 41.72 µg m<sup>-3</sup> (**Figure 4**). The PM<sub>2.5</sub> concentrations on

weekdays and weekends at all sites were exceeding the PM<sub>2.5</sub> MAAQS daily limit of 35 µg m<sup>-3</sup> except for S1(A). A non-parametric Mann-Whitney U Test shows that the mean weekend concentrations of PM<sub>2.5</sub> at S1(A) (27.08 ± 2.31 µg m<sup>-3</sup>) was 14.3% lower than weekdays concentrations (31.59 ± 4.34 µg m<sup>-3</sup>), (Z = -3.010, p = 0.003, r = -0.43).

### Meteorological Influence

A correlation analysis in this study shows the PM<sub>2.5</sub> concentrations at paper waste recycling factory, S1(A) were moderately negatively correlated with relative



**Fig. 4:** Average concentration for PM<sub>2.5</sub> (µg m<sup>-3</sup>) at all sampling sites by weekdays and weekends. S1(A) and S1(B) represent a paper waste recycling factory, S2 represent plastic waste recycling factory and S3 represent a plastic & e-waste recycling factory while S4 represent control site.

humidity ( $r = -0.489$ ,  $p = 0.005$ ), wind speed ( $p = -0.369$ ,  $p = 0.038$ ) and rainfall ( $p = -0.427$ ,  $p = 0.015$ ) and moderately positively correlated with temperature ( $p = 0.484$ ,  $p = 0.005$ ). This indicates that higher PM<sub>2.5</sub> concentrations were observed during periods of lower wind speed, lower rainfall, and lower relative humidity, while higher temperatures were associated with increased PM<sub>2.5</sub> levels. However, there are no significant correlation ( $p > 0.05$ ) was found between PM<sub>2.5</sub> and all meteorological parameters at other sites. This suggests limited or site-specific influence of meteorological variables, although unmeasured factors such as industrial emissions may also contribute. The correlation between concentrations of PM<sub>2.5</sub> at plastic recycling factory, S2 and the temperature was moderately positive ( $p = 0.385$ ,  $p = 0.043$ ), while correlation between PM<sub>2.5</sub> at S2 with relative humidity and rainfall was strong negative ( $r = -0.587$ ,  $p = 0.001$  and  $p = -0.574$ ,  $p = 0.001$ , respectively), indicating that higher PM<sub>2.5</sub> levels were observed during periods of elevated temperatures, lower relative humidity, and lower rainfall.

### Concentrations of Heavy Metals

The results of PM<sub>2.5</sub>-bound heavy metals collected using the low volume sampler was reported in **Table III**. Copper (Cu) ( $10.08 \pm 11.47$  µg m<sup>-3</sup>) was found to be the highest at the paper waste processing facility (S1A) followed by chromium (Cr) ( $0.16 \pm 0.11$  µg m<sup>-3</sup>) and nickel (Ni) ( $0.11 \pm 0.09$  µg m<sup>-3</sup>). However, a comparison of copper (Cu) concentrations at all industrial areas with control site (S4) shows no significant difference ( $p > 0.05$ ), while comparison of chromium (Cr) concentrations revealed statistically higher concentration at S1(A) ( $t(5.2) = 2.611$ ,  $p = 0.046$ ) and S2 ( $Z = -2.066$ ,  $p = 0.039$ ). Additionally, greater concentrations of Nickel (Ni) ( $t(7) = 2.418$ ,  $p = 0.046$ ) and lead (Pb) ( $Z = -2.324$ ,  $p = 0.020$ ) were reported at plastic waste processing facility (S2) than S4. Similarly, lead (Pb) concentrations at plastic waste recycling facility (S2) ( $1.03 \pm 1.48$  µg m<sup>-3</sup>) were substantially elevated, ranging from 5-fold to 23-fold higher than the other sites and significantly higher ( $Z = -2.324$ ,  $p = 0.020$ ) than S4. Specifically, the lead (Pb) concentrations at S2 were 14.4-fold higher than S1(A), 8.9-fold higher than S1(B), 5.3-fold higher than S3, and

23.3-fold higher than S4 and was also exceeded the standard limit by WHO (0.5 µg m<sup>-3</sup>) by approximately 105%.

Despite the cadmium (Cd) concentrations across all sites were ranging from 0.002 to 0.005 µg m<sup>-3</sup>, comparison across all industrial areas revealed a significantly elevated concentrations at paper waste processing facility, S1(B) ( $t(5) = 2.941$ ,  $p = 0.032$ ), plastic and e-waste processing facility, S3 ( $t(6) = 4.069$ ,  $p = 0.007$ ), and plastic waste processing facility, S2 ( $Z = -2.324$ ,  $p = 0.020$ ) as shown in **Table III**. However, no enrichment factor analysis was performed; thus, future work should characterize anthropogenic contribution. Lastly, a Spearman Correlation test conducted shows significantly moderate positive correlation between the Cd ( $p = 0.417$ ,  $p = 0.043$ ) and Pb ( $p = 0.608$ ,  $p = 0.002$ ).

## DISCUSSION

### Daily Real Time Concentration of PM<sub>2.5</sub>

The higher PM<sub>2.5</sub> concentrations near plastic waste, S2 (39.95 µg m<sup>-3</sup>) and e-waste processing facilities, S3 (41.41 µg m<sup>-3</sup>) than paper waste, S1(B) (37.52 µg m<sup>-3</sup>), may potentially be associated with manual dismantling, mechanical grinding, mechanical agitation, and waste separation and movement during the waste recycling process which are the contributors to the airborne particulate matter (19). Although both S1(A) and S1(B) are located near to the paper waste processing facility, a significant lower PM<sub>2.5</sub> concentration was reported at S1(B) which is 750 m radius from the facility compared to S1(A) which is 500 m radius from the facility ( $t = -4.249$ ,  $p < 0.001$ ). This variation may reflect site-specific environmental exposure where terrain shielding, and emission plume alignment can influence PM<sub>2.5</sub> variability through local dispersion patterns, though detailed plume modelling was not performed in this study (20). Furthermore, the meteorological factors such as wind speed and temperature may further influence how emission disperse in the atmosphere (20). Since S1(B) is directly align with the emission stack, it is likely that the direction of the primary wind and the plume behaviour enhanced the pollutant transport towards that location (21). In contrast, S1(A) may have been located in a plume shadow, where the emitted plume does not descend to ground level, despite its closer proximity to the paper waste processing facility (22).

### Diurnal Trend of PM<sub>2.5</sub>

The diurnal trend shows higher PM<sub>2.5</sub> concentrations across all sampling locations during the early morning (00:00 – 05:00) and late evening (18:00 – 23:00) ranging from 33.94 to 53.78 µg m<sup>-3</sup>, and 37.00 to 46.14 µg m<sup>-3</sup>, respectively, with the most pronounced observed at plastic processing facility (S2) ( $53.78 \pm 2.54$  µg m<sup>-3</sup>). These peaks may be associated with combination of local anthropogenic emissions and atmospheric dispersion conditions where the late evening peak may

Table III: Comparison of heavy metals concentrations between sampling locations.

| Cadmium (Cd)                                               |                    |                               |                   | Chromium (Cr)      |                               |                   |                    | Copper (Cu)       |                    |                               |                   | Nickel (Ni)        |                               |                   |                    | Lead (Pb)                     |                   |                    |                               |
|------------------------------------------------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|
| Mean (SD) - Site 1                                         | Mean (SD) - Site 2 | Test statistic, t/z (p-value) | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Test statistic, t/z (p-value) | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Test statistic, t/z (p-value) | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Test statistic, t/z (p-value) | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Test statistic, t/z (p-value) | Mean (SD) -Site 1 | Mean (SD) - Site 2 | Test statistic, t/z (p-value) |
| Comparison between Industrial Areas (S1(A), S1(B), S2, S3) |                    |                               |                   |                    |                               |                   |                    |                   |                    |                               |                   |                    |                               |                   |                    |                               |                   |                    |                               |
| S1(A)                                                      | 0.002 (0.001)      | -2.717 <sup>a</sup> (0.026)*  | 0.156 (0.108)     | 0.078 (0.027)      | 1.685 <sup>a</sup> (0.144)    | 10.080 (11.473)   | 0.402 (0.258)      | 0.114 (0.086)     | 0.036 (0.012)      | -1.706 <sup>b</sup> (0.088)   | 0.071 (0.033)     | 0.115 (0.053)      | 2.218 <sup>a</sup> (0.05)     | 0.071 (0.033)     | 0.115 (0.053)      | -1.617 <sup>a</sup> (0.144)   |                   |                    |                               |
| S1(A) – S2                                                 | 0.002 (0.001)      | -1.601 <sup>b</sup> (0.109)   | 0.156 (0.108)     | 0.092 (0.053)      | -1.281 <sup>b</sup> (0.200)   | 10.080 (11.473)   | 3.322 (5.230)      | 0.114 (0.086)     | 0.042 (0.016)      | -1.281 <sup>b</sup> (0.200)   | 0.071 (0.033)     | 1.025 (1.480)      | 2.019 <sup>a</sup> (0.06)     | 0.071 (0.033)     | 1.025 (1.480)      | -2.242 <sup>b</sup> (0.025)*  |                   |                    |                               |
| S1(A) – S3                                                 | 0.002 (0.001)      | -2.447 <sup>a</sup> (0.037)*  | 0.156 (0.108)     | 0.066 (0.025)      | 1.982 <sup>a</sup> (0.098)    | 10.080 (11.473)   | 0.407 (0.207)      | 0.114 (0.086)     | 0.035 (0.013)      | 2.065 <sup>a</sup> (0.094)    | 0.071 (0.033)     | 0.194 (0.173)      | 2.225 <sup>a</sup> (0.074)    | 0.071 (0.033)     | 0.194 (0.173)      | -1.722 <sup>a</sup> (0.119)   |                   |                    |                               |
| S1(B) – S2                                                 | 0.005 (0.002)      | -0.853 <sup>b</sup> (0.394)   | 0.078 (0.027)     | 0.092 (0.053)      | 0.000 <sup>b</sup> (1.000)    | 0.402 (0.258)     | 3.322 (5.249)      | 0.036 (0.012)     | 0.042 (0.016)      | -1.492 <sup>b</sup> (0.136)   | 0.115 (0.053)     | 1.025 (1.480)      | -0.731 <sup>a</sup> (0.486)   | 0.115 (0.053)     | 1.025 (1.480)      | -1.066 <sup>b</sup> (0.286)   |                   |                    |                               |
| S1(B) – S3                                                 | 0.005 (0.002)      | 1.082 <sup>a</sup> (0.315)    | 0.078 (0.027)     | 0.066 (0.025)      | 0.711 <sup>a</sup> (0.500)    | 0.402 (0.258)     | 0.407 (0.207)      | 0.036 (0.012)     | 0.035 (0.013)      | -0.490 <sup>b</sup> (0.624)   | 0.115 (0.053)     | 0.194 (0.173)      | 0.037 <sup>a</sup> (0.972)    | 0.115 (0.053)     | 0.194 (0.173)      | -0.874 <sup>a</sup> (0.411)   |                   |                    |                               |
| S2 – S3                                                    | 0.005 (0.004)      | -0.640 <sup>b</sup> (0.522)   | 0.092 (0.053)     | 0.066 (0.025)      | -0.913 <sup>b</sup> (0.361)   | 3.322 (5.230)     | 0.407 (0.207)      | 0.042 (0.016)     | 0.035 (0.013)      | -1.643 <sup>b</sup> (0.100)   | 1.025 (1.480)     | 0.194 (0.173)      | 0.794 <sup>a</sup> (0.448)    | 1.025 (1.480)     | 0.194 (0.173)      | -1.095 <sup>b</sup> (0.273)   |                   |                    |                               |
| Comparison with Control Site (S4)                          |                    |                               |                   |                    |                               |                   |                    |                   |                    |                               |                   |                    |                               |                   |                    |                               |                   |                    |                               |
| S1(A) – S4                                                 | 0.002 (0.001)      | 0.893 <sup>a</sup> (0.402)    | 0.156 (0.108)     | 0.040 (0.011)      | 2.611 <sup>a</sup> (0.046)*   | 10.080 (11.473)   | 0.287 (0.191)      | 0.114 (0.086)     | 0.021 (0.007)      | 1.428 <sup>a</sup> (0.196)    | 0.071 (0.033)     | 0.044 (0.003)      | 1.909 <sup>a</sup> (0.098)    | 0.071 (0.033)     | 0.044 (0.003)      | 1.990 <sup>a</sup> (0.101)    |                   |                    |                               |
| S1(B) – S4                                                 | 0.005 (0.002)      | 2.941 <sup>a</sup> (0.032)*   | 0.078 (0.027)     | 0.040 (0.011)      | 2.546 <sup>a</sup> (0.061)    | 0.402 (0.258)     | 0.287 (0.191)      | 0.036 (0.012)     | 0.021 (0.007)      | -1.061 <sup>b</sup> (0.289)   | 0.115 (0.053)     | 0.044 (0.003)      | 2.020 <sup>a</sup> (0.099)    | 0.115 (0.053)     | 0.044 (0.003)      | 2.247 <sup>a</sup> (0.075)    |                   |                    |                               |
| S2 – S4                                                    | 0.005 (0.004)      | -2.324 <sup>b</sup> (0.020)*  | 0.092 (0.053)     | 0.040 (0.011)      | -2.066 <sup>b</sup> (0.039)*  | 3.322 (5.230)     | 0.287 (0.191)      | 0.042 (0.016)     | 0.021 (0.007)      | -1.549 <sup>b</sup> (0.121)   | 1.025 (1.480)     | 0.044 (0.003)      | 2.418 <sup>a</sup> (0.046)*   | 1.025 (1.480)     | 0.044 (0.003)      | -2.324 <sup>b</sup> (0.020)*  |                   |                    |                               |
| S3 – S4                                                    | 0.004 (0.001)      | 4.069 <sup>a</sup> (0.007)*   | 0.066 (0.025)     | 0.040 (0.011)      | 1.644 <sup>a</sup> (0.151)    | 0.407 (0.207)     | 0.287 (0.191)      | 0.035 (0.013)     | 0.021 (0.007)      | 0.818 <sup>a</sup> (0.445)    | 0.194 (0.173)     | 0.044 (0.003)      | 1.938 <sup>a</sup> (0.101)    | 0.194 (0.173)     | 0.044 (0.003)      | 1.456 <sup>a</sup> (0.196)    |                   |                    |                               |

\*Significant value &lt;0.05

Notes: (a) – Independent T-Test; (b) – Mann-Whitney U Test

(S1(A) and S1(B) – paper waste recycling factory, S2 – plastic waste recycling factory, S3 – plastic &amp; e-waste recycling factory, S4 – control site

potentially be influenced by industrial operations while the morning peak fluctuations are likely influenced by daily human activities and atmospheric conditions (23). Additionally, comparisons with the control site showed plastic waste processing facility (S2) recorded significantly higher levels of  $PM_{2.5}$  during early morning ( $t(10) = 5.049$ ,  $p < 0.001$ ,  $d = 2.915$ ). This suggests possible overnight or early-shift emissions from the facility, combined with stable boundary layer conditions that trap pollutants near the surface (24). However, due to limited information on the industrial operating hours, these observed patterns are more plausibly attributed to meteorological conditions under stable nighttime. A shallow and stable atmospheric boundary layer during the early morning may trap pollutants near the surface, leading to higher  $PM_{2.5}$  levels (25).

The subsequent afternoon decline across all sampling locations likely reflects reduced emission sources or improved dispersion conditions coincided with higher wind speeds and due to atmospheric boundary layer gradually deepens, consistent with previous findings that observed patterns of diurnal variations, showing the peak during the night and reaching the minimum in the afternoon, indicating minimum surface  $PM_{2.5}$  concentrations present in the afternoon (26). In addition, paper waste (S1(B)) and e-waste processing facilities (S3) reported significantly higher concentrations during afternoon compared to control site ( $t = 2.971$ ,  $p = 0.014$  and  $t = 3.078$ ,  $p = 0.012$ , respectively) which may reflect increased operational intensity at these facilities during daytime working hours, coupled with plume behavior (12, 16-17). The e-waste processing sites, S3 appear to have more pronounced emission impacts during afternoon periods, whereas the paper waste facility, particularly S1(A), shows lower impact possibly reflect to fewer emissions or may benefit from more effective dispersion conditions (27, 28). Additionally, high concentration of  $PM_{2.5}$  during late evening at e-waste recycling factory (S3) may potentially associated with an increase of human activities during the late evening rush hour which contributes to the increased of  $PM_{2.5}$  concentrations (29).

### Comparison Between Weekdays and Weekends

Comparison between weekdays and weekends  $PM_{2.5}$  concentrations shows that the concentrations of  $PM_{2.5}$  during weekdays, ranging from 31.59 to 41.72  $\mu g m^{-3}$ , at all sampling locations are reported to be higher compared to weekends. This aligns with the presumption that greater industrial operations and human activity during weekdays contribute to higher  $PM_{2.5}$  concentrations in the ambient air (30). Importantly, the concentrations of  $PM_{2.5}$  at all sites exceeded the Malaysian Ambient Air Quality Standard (MAAQS) daily limit (35  $\mu g m^{-3}$ ) during both weekdays and weekends, suggesting that it may be reflected by a broader regional air quality issue including long-range atmospheric transport of particulates (23). These elevated  $PM_{2.5}$  concentration observed

pose potential health risks to nearby communities, including respiratory and cardiovascular effects (31). Nevertheless, statistically significant difference was reported between weekdays ( $31.59 \pm 4.34 \mu g m^{-3}$ ) and weekends concentration ( $27.08 \pm 2.31 \mu g m^{-3}$ ) of  $PM_{2.5}$  at paper waste processing facility (S1(A)) ( $Z = -3.010$ ,  $p = 0.003$ ,  $r = -0.43$ ), indicating the contribution of human weekday activities including nearby traffic and school sessions (32). These findings underscore the importance of local regulatory oversight by DOE Malaysia, including monitoring of waste processing facilities and enforcement of emission standards.

### Meteorological Influence

Significant correlation of  $PM_{2.5}$  concentrations at the paper waste processing facility (S1(A)) shows moderately negative correlation with relative humidity ( $r = -0.489$ ), rainfall ( $\rho = -0.427$ ) and wind speed ( $\rho = -0.369$ ). This indicates that higher relative humidity and rainfall can promote the removal of  $PM_{2.5}$  through condensation and wet deposition where water droplets from the rain fall effectively absorbed the pollutants and removes it from the atmosphere, reducing the concentrations of  $PM_{2.5}$  while higher wind speed conditions enhance dispersion of the pollutants to another area, reducing pollutant accumulation at the specific area (33, 34). Furthermore, the moderate positive correlation with temperature ( $\rho = 0.484$ ), suggesting that higher temperatures may promote secondary particle formation and possibly associated with local emission patterns as well as the decreased of wind speed, enhancing the pollutant accumulation (35). Additionally, analysis correlation of meteorological factors with  $PM_{2.5}$  concentrations at Jakarta has a similar outcome where the correlation analysis shows that the temperature has a unidirectional relationship ( $\rho = 0.55$ ) with  $PM_{2.5}$  while relative humidity and rainfall have inverse relationship with  $PM_{2.5}$  ( $\rho = -0.55$  and  $\rho = -0.43$ , respectively) (36). This also supported the result from this study where concentrations of  $PM_{2.5}$  at plastic waste processing facility (S2) also showed a positive moderate correlation with temperature and strong negative correlation with relative humidity and rainfall, indicating that increased of temperature and decreased rainfall and relative humidity highly correlated with the increased of  $PM_{2.5}$  concentrations at the site. These patterns suggest that rainfall and humid conditions likely reduced  $PM_{2.5}$  through enhanced wet scavenging, a process in which raindrops capture suspended particles, while elevated temperatures may coincide with enhanced pollutant accumulation (35). However, no significant correlation found between  $PM_{2.5}$  at e-waste processing facility and control site with meteorological parameters suggesting that the  $PM_{2.5}$  concentration at the locations has limited influence observed with meteorological factors yet can be affected by other factors such as industrial activity nearby.

### Concentrations of Heavy Metals

In addition to  $PM_{2.5}$  concentrations, the analysis of  $PM_{2.5}$ -bound heavy metals was conducted to understand the potential source contributions. Copper (Cu) ( $10.08 \pm 11.47 \mu\text{g m}^{-3}$ ) was the highest at the paper waste processing facility (S1A) followed by chromium (Cr) ( $0.16 \pm 0.11 \mu\text{g m}^{-3}$ ) and nickel (Ni) ( $0.11 \pm 0.09 \mu\text{g m}^{-3}$ ). These metals are widely used in metallic pigments and printing inks on printed wastepaper which may contribute to elevated levels of heavy metal content including Cu, Cr and Ni during the paper recycling process (37).

Besides, Cr concentrations in this study were found to be higher at locations near paper, S1(A) ( $t = 2.611$ ,  $p = 0.046$ ) and plastic waste processing facility, S2 ( $Z = -2.066$ ,  $p = 0.039$ ) when compared to control site. This is possibly because Cr are commonly used in pigments, inks or dyes for printed plastic and paper packaging (38). A study also reported that heavy metals contents such as Cr in the plastic waste products are found to be higher than the standard limit (39), suggesting that the high concentration of Cr at the plastic waste recycling facility may resulted from the heavy metals in the plastic waste itself. This aligns with a study which detected Cr as the highest heavy metals concentration in artificial sweat representing worker exposure during sorting of recycled plastics operation (40).

Additionally, Ni concentrations were also reported to be significantly higher at locations near plastic waste processing facility, S2 ( $t = 2.418$ ,  $p = 0.046$ ). Previous study on an overview of chemical additives presents in plastics also indicates that the plastic processing operations especially older electrical plastic casings may release transition metals through dust and thermal emissions (41). Thus, the elevated concentrations of Ni and subsequently Pb at plastic waste processing facility are also likely contributed by the combustion, heating or mechanical treatment of plastics (42).

This is also aligned with the result from this study where Pb ( $1.03 \pm 1.48 \mu\text{g m}^{-3}$ ) was mainly high at plastic waste recycling facility (S2) exceeded the ambient standard limit by WHO ( $0.5 \mu\text{g m}^{-3}$ ) and significantly higher ( $Z = -2.324$ ,  $p = 0.020$ ) compared to control site (S4). The high concentration of Pb was likely reflects the use of Pb-based inorganic pigment colorants in colored plastic as well (43). A study reported that plastic waste is the highly significant main material carrier of around 17% total of Pb; thus, material disposal and recycling involve waste with metal may result in the contamination of Pb in fly ash and bottom ash (44).

Moreover, the elevated Cd concentrations reported at locations near paper (S1(B)), plastic (S2) and e-waste processing facility (S3) compared to control site (S4) may likely reflect the presence of Cd as a common metal in plastic stabilizers, coatings, batteries and

e-waste components as well as one of the heavy metals that are significantly presented in recycled papers (45). The presence of Cd at all waste processing facility may reflect emissions from the locally process of recycling paper, plastic, and electronic waste as well as waste incineration (46). A study also reported Cd's widespread presence in mixed waste facilities especially municipal plastic and e-waste recycling facilities (47). Overall, this study provides the first comparative evidence across three waste-processing facility types in Malaysia, showing distinct  $PM_{2.5}$  and metal fingerprints associated with each operation.

### CONCLUSION

To conclude, this study provides one of the first empirical assessments of  $PM_{2.5}$  concentrations and associated heavy metals near imported waste processing facilities in Malaysia, addressing a critical research gap in understanding local air quality impacts from different types of waste recycling industries. This study identifies higher  $PM_{2.5}$  and heavy metal concentrations near waste processing facilities but it does not prove that these facilities are the main contributors of the pollution.  $PM_{2.5}$  concentrations at most sampling sites, exceeded the Malaysian Ambient Air Quality Standards ( $35 \mu\text{g m}^{-3}$ ) daily limit by 5 – 20% and exceeded WHO standard limit ( $15 \mu\text{g m}^{-3}$ ) by 103 – 180%. Plastic and e-waste facilities recorded higher  $PM_{2.5}$  levels, particularly during early morning and evening hours, while meteorological parameters showed moderate correlations with  $PM_{2.5}$  such as temperature ( $\rho = 0.484$ ), humidity ( $r = -0.489$ ), rainfall ( $\rho = -0.427$ ) and wind speed ( $\rho = -0.369$ ), significantly influenced dispersion patterns. Weekday levels of  $PM_{2.5}$  were significantly higher than weekend levels at certain sites ( $p < 0.05$ ), reflecting anthropogenic activity trends. Notably, Cd was elevated at all sites, and Ni, Pb, and Cr were present in site-specific patterns consistent with the types of processing activities and known material used such as Cd as stabilizers, Pb in pigments, and Cr and Ni in printed paper and plastic materials.

The elevated  $PM_{2.5}$  and metal concentrations near recycling facilities suggest a need for improved emission control systems and stricter regulatory monitoring of imported waste processing industries in Malaysia, including installation of filtration systems. These findings raise concerns for community exposure and underscore the need for improving careful consideration of facility placement to protect public health, especially in proximity to schools and residential areas, given the proximity of several facilities to residential areas are within 500 – 800 m.

The relatively short sampling duration and the limited number of sampling sites, which may not fully capture seasonal variations or broader spatial trends that could influence  $PM_{2.5}$  patterns, representing key limitations

of this study. While the elevated levels of PM<sub>2.5</sub> and heavy metals observed near waste processing facilities raise environmental health concerns, this study does not conclusively show these waste processing facilities as the sole sources of pollution. Therefore, future study should consider long-term PM<sub>2.5</sub> monitoring, plume dispersion modelling, and wind direction to accurately identify pollutant origins.

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