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Dominance of local emission intensity over air-mass origin in PM_{10}-bound atmospheric microplastics: Insights from HYSPLIT analysis in Peninsular Malaysia

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Abstract: Atmospheric microplastics (AMPs) are emerging contaminants whose transport pathways and controlling factors remain poorly understood in tropical environments. This study investigated the relative roles of air-mass origin and local emission intensity in controlling PM_{10}-bound atmospheric microplastic concentrations across five locations in Peninsular Malaysia using HYSPLIT back-trajectory analysis. A total of 30 sampling events were analysed during the Northeast and Southwest monsoon periods. AMP concentrations exhibited significant spatial variability ($p < 0.001$), whereas no significant differences were observed between monsoon phases or trajectory clusters. Wind speed showed a significant negative association with AMP concentration ($\rho = -0.514$, $p = 0.004$), and multiple linear regression analysis ($R^2 = 0.416$) identified wind speed and PP proportion as important predictors. Overall, the findings indicate that local emission intensity and meteorological conditions exert greater influence on PM_{10}-bound AMP concentrations than broad-scale air-mass transport.

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1. Introduction

Microplastic (MP) pollution has emerged as one of the most pervasive environmental challenges of the twenty-first century, with plastic particles documented across marine sediments, freshwater systems, soils, biota, and, increasingly, the atmosphere [1-2]. Atmospheric microplastics (AMPs) are airborne plastic particles smaller than 5 mm that originate from a broad range of primary and secondary sources including textile abrasion, tyre wear, open burning of plastic waste, packaging fragmentation, and resuspension of surface-deposited particles [3-4]. Once airborne, AMPs can be transported over distances ranging from local to transoceanic scales, with implications for human inhalation exposure, ecosystem contamination, and the global plastic cycle [5-6].

Southeast Asia (SEA) represents a region of particular concern for AMP pollution, owing to rapid urbanisation, high population density, a large and growing manufacturing sector, and waste management systems under considerable strain. A recent scoping review identified elevated AMP concentrations in urban centres across Malaysia, Indonesia, and Thailand, attributing these patterns to vehicular emissions, textile production, industrial activity, and inadequate solid-waste management [7]. Within Malaysia, specifically in Kuala Lumpur and its surrounding metropolitan airshed, AMP burdens have been associated with markedly higher levels than in suburban and rural environments [8]. Despite these observations, the meteorological and source-region controls on PM_{10}-bound AMP concentrations across a climatically diverse, multi-site network in Peninsular Malaysia remain incompletely characterised.

Peninsular Malaysia experiences a tropical monsoon climate governed primarily by the Northeast (NE) monsoon (November–March), which brings onshore flow from the South China Sea, and the Southwest (SW) monsoon (May–September), which drives continental and maritime air masses from the Sumatra–Indian Ocean sector [9]. The alternation between these two regimes produces substantial seasonal variability in wind speed, atmospheric boundary layer dynamics, and the origin of advected air masses, all of which may influence AMP transport and near-surface accumulation. Back-trajectory modelling using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model has been widely employed as a source–receptor framework for atmospheric pollutants, including AMPs, enabling the classification of air-mass pathways into marine, continental, or mixed categories prior to their arrival at a receptor site [10-11]. However, HYSPLIT-based trajectory classification has not yet been systematically integrated with PM_{10}-bound AMP measurements across a geographically stratified Malaysian sampling network.

Despite increasing interest in atmospheric microplastics, previous studies have rarely integrated trajectory-based transport analysis with quantitative regression modelling to distinguish the relative contributions of local emission intensity and atmospheric transport in tropical environments.

This study addresses these gaps by integrating HYSPLIT back-trajectory classification with PM_{10}-bound AMP measurements collected across five contrasting sampling environments in Peninsular Malaysia during both monsoon seasons. The specific objectives were: (i) to quantify spatial variation in PM_{10}-bound AMP concentrations across urban, semi-urban, and rural locations; (ii) to evaluate whether monsoon phase or air-mass trajectory cluster significantly influences AMP concentration; and (iii) to quantify the relative influence of meteorological and compositional variables on AMP concentration using regression analysis.

2. Methodology

Backward trajectories were computed using the HYSPLIT model driven by GDAS meteorological data at 1° spatial resolution. Trajectories were generated for 72 h prior to each sampling event at an arrival height of 500 m above ground level, representing the lower boundary layer. The selected height reflects the typical mixing layer influencing PM_{10} transport in tropical environments. Uncertainty in trajectory pathways was considered in relation to meteorological input resolution and model assumptions, particularly for low-density particles such as microplastics.

Trajectories were classified into marine, continental, and mixed pathways according to dominant transport direction and source region. The dataset consisted of 30 sampling events collected from Senawang, Kuantan, Pudu, Batu Pahat, and Gua Musang, with three events representing the Northeast (NE) monsoon and three events representing the Southwest (SW) monsoon at each location. Variables considered in this study included AMP concentration (MP m^{-3}), air-mass cluster, fibre percentage, PP percentage, wind speed, and relative humidity. Marine trajectories were mainly associated with the South China Sea, continental trajectories originated primarily from Sumatra/Indonesia, whereas mixed trajectories represented transition pathways and local recirculation influenced by the Sumatra–Straits of Malacca and Indian Ocean regions.

Descriptive statistics were calculated according to location, monsoon period, and trajectory cluster. Since sample sizes were relatively small and normality assumptions were not met, nonparametric tests were employed. Kruskal–Wallis tests were used to assess differences among locations and trajectory clusters, whereas the Mann–Whitney U test was applied to compare the NE and SW monsoon periods. Spearman's correlation analysis was performed to evaluate associations between AMP concentration and meteorological or compositional variables. In addition, multiple linear regression (MLR) analysis was conducted to quantify the relative influence of meteorological and compositional factors on AMP concentration. Predictor variables included wind speed, relative humidity, PP proportion, and air-mass cluster, while model performance was evaluated using R^2 and regression coefficients.

3. Results and Discussion

AMP concentrations ranged from 0.0025 to 0.0246 MP m^{-3}, with Pudu recording the highest mean concentration (0.0189 ± 0.0030 MP m^{-3}), followed by Senawang and Batu Pahat, whereas Kuantan and Gua Musang exhibited comparatively lower concentrations (Table 1).

Table 1. Descriptive statistics of AMP concentration by sampling location.

Location	Mean	SD	Median	Min	Max
Batu Pahat	0.0122	0.0040	0.0120	0.0057	0.0177
Gua Musang	0.0056	0.0017	0.0057	0.0032	0.0076
Kuantan	0.0061	0.0021	0.0066	0.0025	0.0082
Pudu	0.0189	0.0030	0.0180	0.0164	0.0246
Senawang	0.0127	0.0035	0.0120	0.0088	0.0183

Figure 1 further illustrates the spatial variability of PM_{10}-bound AMP concentrations across the five sampling locations under both monsoon conditions. Spatial differences were statistically significant (Kruskal–Wallis H = 21.88, $p < 0.001$), indicating that local emission intensity and surrounding land-use characteristics strongly influence AMP abundance. Similar spatial variability has been reported in other urban environments, where higher population density and anthropogenic activities contribute to elevated atmospheric levels of microplastics [12-14]. Pudu, representing a densely urbanised commercial area, recorded AMP concentrations approximately three times higher than those observed at Gua Musang, suggesting a substantial influence of local anthropogenic activities and emission intensity on atmospheric microplastic abundance.

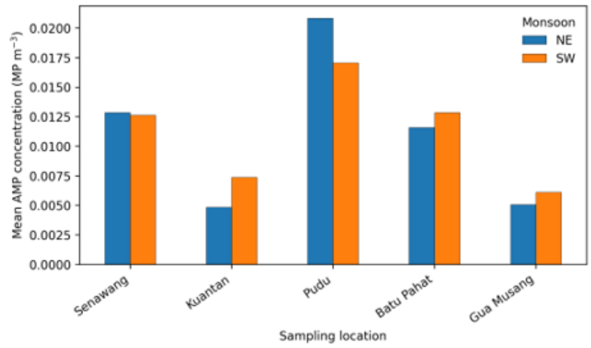

Figure 1. Mean PM_{10}-bound AMP concentrations across the sampling locations under NE and SW monsoon conditions.

Mean AMP concentrations were comparable between the NE and SW monsoon periods (0.0110 and 0.0112 MP m^{-3}, respectively), and no significant differences were observed between monsoon phases or trajectory clusters ($p > 0.05$). Although HYSPLIT trajectories indicated contrasting transport pathways between seasons, representative trajectories (Figure 2) suggest that local emissions and atmospheric stagnation exert stronger control on AMP concentrations than broad-scale air-mass origin. Similar findings have been reported in previous atmospheric microplastic studies, in which local sources dominated over long-range transport [8,12].

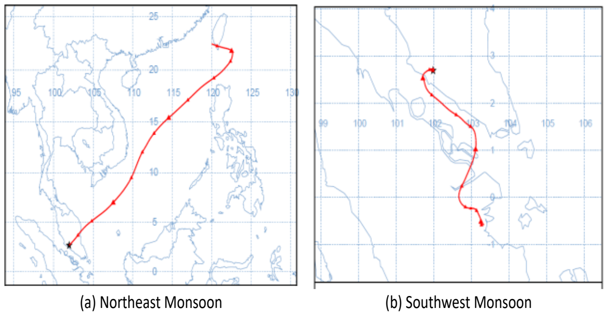

Figure 2. Representative HYSPLIT backward trajectories at Senawang during the NE and SW monsoons.

Spearman correlation analysis showed a significant negative relationship between AMP concentration and wind speed ($\rho = -0.514$, $p = 0.004$), indicating enhanced AMP accumulation under stagnant atmospheric conditions. In contrast, PP proportion exhibited a significant positive correlation with AMP concentration ($\rho = 0.442$, $p = 0.015$), whereas relative humidity and fibre proportion showed no significant associations (Table 2).

Table 2. Spearman correlations between AMP concentration and selected explanatory variables

Variable Spearman	ρ	p-value
Wind_Speed (m/s)	-0.514	0.004
Relative Humidity (%)	-0.115	0.547
Fiber_%	-0.177	0.350
PP_%	0.442	0.015

Multiple linear regression analysis further demonstrated that wind speed remained a significant negative predictor, while PP proportion positively influenced AMP concentration (Figure 3), indicating that meteorological dispersion and local plastic-related sources are important factors controlling PM_{10}-bound AMP concentrations. The significant influence of wind speed suggests that low-wind conditions favour the accumulation of atmospheric microplastics by reducing atmospheric dispersion and increasing particle residence time, consistent with previous studies [18–21].

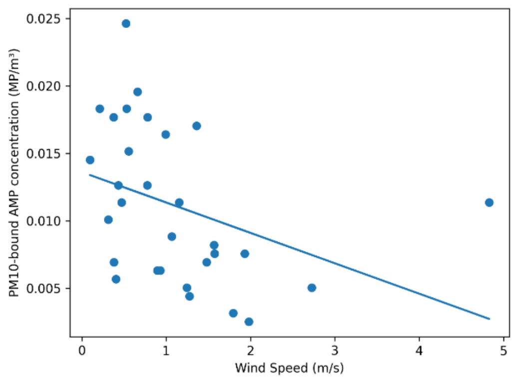

Figure 3. Relationship between PM_{10}-bound AMP concentration and wind speed.

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No significant differences in AMP concentration were observed among the trajectory clusters (Kruskal–Wallis H = 0.46, p = 0.795), indicating that broad-scale air-mass origin had a limited influence on PM_{10}-bound AMP concentrations. In contrast, significant spatial variability was observed among the sampling locations, with Pudu recording the highest AMP concentration. These results indicate that local factors exert greater influence on AMP concentrations than trajectory-cluster effects. Elevated concentrations at Pudu are likely associated with intensive vehicular traffic, commercial activities, and plastic-related emissions. In addition, the positive association between polypropylene and AMP concentration indicates the contribution of packaging materials and urban waste sources, consistent with previous studies conducted in Southeast Asia [7,20,21]. This study was limited by the relatively small sample size and broad trajectory classification, which may have reduced the ability to detect subtle transport-related effects. Future studies involving larger datasets and finer trajectory clustering are required to improve source attribution and better understand atmospheric microplastic transport in tropical environments.

4. Conclusion

This study demonstrated significant spatial variability in PM_{10}-bound atmospheric microplastic concentrations across Peninsular Malaysia, with the highest levels observed at the urban Pudu site. No significant differences were found between monsoon periods or trajectory clusters, suggesting that local emission intensity and meteorological conditions exert greater influence on AMP concentrations than broad-scale air-mass transport. Wind speed was identified as an important factor affecting AMP variability. These findings provide new insights into atmospheric microplastic dynamics in tropical environments and may support future source attribution and mitigation efforts.

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