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Atmospheric microplastic transport and deposition to urban and pristine tropical locations in Southeast Asia

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Abstract

Atmospheric microplastic transport is an important delivery pathway with the deposition of microplastics to ecologically important regions raising environmental concerns. Investigating atmospheric delivery pathways and their deposition rates in different ecosystems is necessary to understanding its global impact. In this study, atmospheric deposition was collected at three sites in Malaysia, two urban and one pristine, covering the Northeast and Southwest monsoons to quantify the role of this pathway in Southeast Asia. Air mass back trajectories showed long-range atmospheric transport of microplastics to all sites with atmospheric deposition varying from 114-689 MP/m^2/day. For the east coast of Peninsular Malaysia, monsoonal season influenced microplastic transport and deposition rate with peak microplastic deposition during

the Northeast monsoon due to higher wind speed. MP morphology combined with size fractionation and plastic type at the coastal sites indicated a role for long-range marine transport of MPs that subsequently provided a local marine source to the atmosphere at the coastal sites.

Keywords: Atmospheric microplastics, Transport, Deposition, Air pollution, Tropical coastal

Introduction

Microplastics (MPs; <5 mm in size) are ubiquitous in global ecosystems (Allen et al., 2019; Lwanga et al., 2023). This form of pollution is of concern due to their ability to absorb environmental pollutants and endogenous chemical additives (Wright and Kelly, 2017; Hee et al., 2022) as well as harming organisms by direct ingestion and transmission throughout the food web (Nelms et al., 2018). Primary MPs are manufactured as MPs with production of secondary MPs predominantly due to the poorly regulated disposal of plastic products (Kim et al., 2022). Airborne MPs are of increasing attention since the amount of MP inhaled may exceed those ingested via dietary consumption (Zhang et al., 2020). MPs are therefore an emerging air pollutant and threat to human health (Prata, 2018; Yao et al., 2022) particularly in Southeast (SE) Asia where air pollution is a major problem throughout much of the region (Chen et al., 2020a).

MP abundance is typically related to proximity of emission source (Loppi et al., 2021) with urban, industrial and domestic settings accounting for most environmental MPs (Dris et al., 2016; Allen et al., 2020). Urban MP deposition rates of up to ~1000 particles/m^2/day (Wright et al., 2020) result from local urban sources *e.g.* degradation of textiles, packaging materials and tyres due to wear. These MPs can be dispersed from their urban source by atmospheric and marine conveyance to remote aquatic and terrestrial regions involving multiple cycles of deposition,

transport, degradation and resuspension (Brahney et al., 2020; Allen et al., 2022). A recent review of atmospheric MPs by Allen et al. (2022) stated that there is limited global representation of atmospheric MP concentrations due to the limited number of studies and a lack of study intercomparability in atmospheric MPs. They highlighted a need to expand the information about atmospheric MP transportation and deposition at different environmental backgrounds in order to better assess the scale of atmospheric MP transport. Studies addressing atmospheric MP transportation are notably scarce for most SE Asian countries with no published studies in tropical remote coastal locations.

Atmospheric MP transport is influenced by atmospheric dynamics with horizontal transport primarily wind-driven with slower air mass velocities and intense rainfall allowing deposition (Brahney et al., 2020; Abbasi, 2021). SE Asian meteorological conditions are dominated by monsoonal seasons, *i.e.* the Northeast (NE, November-March) and Southwest (SW; May-September) monsoons, separated by two transitional inter-monsoon seasons (October and April). Previous studies reported that particulate air pollution in SE Asia shows long-range transport ≥100 km with monsoonal variability (Latif et al., 2018; Yin et al., 2019; Hassan et al., 2020). Long-range MP transportation in SE Asian is however understudied despite SE and East Asia being the leading global region for plastic production (Nkwachukwu et al., 2013; Geyer et al., 2017) and waste (Jambeck et al., 2015; Meijer et al., 2021).

To improve the understanding of MP transport and atmospheric deposition in a tropical region, this study aimed to quantify atmospheric MP deposition across monsoonal seasons at urban sites and a pristine site in Malaysia, and use MP characterisation and air mass back trajectories to examine their source and transport pathways.

Method

The quantification of atmospheric MP deposition across monsoonal seasons at urban sites and a pristine site was achieved via counting suspected MPs in total atmospheric deposition samples using the Nile Red method. MP characterisation was identified by μ-FTIR and air mass back trajectories using a Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to investigate their source and atmospheric transport pathway.

Study site and field sampling

Atmospheric MP deposition in Peninsular Malaysia was sampled from August 2020 to May 2021, covering the SW and NE monsoons. Sampling was at three stations (Fig. 1): at two urban sites located on the east coast (Kuala Nerus; 5°24′2″N, 103°5.124' E) and west coast (Bangi, 2° 55.47′N, 101°46.39′E) of Peninsular Malaysia and at a pristine beach on an island at Chagar Hutang (5°48.77' N and 103°0.50' E).

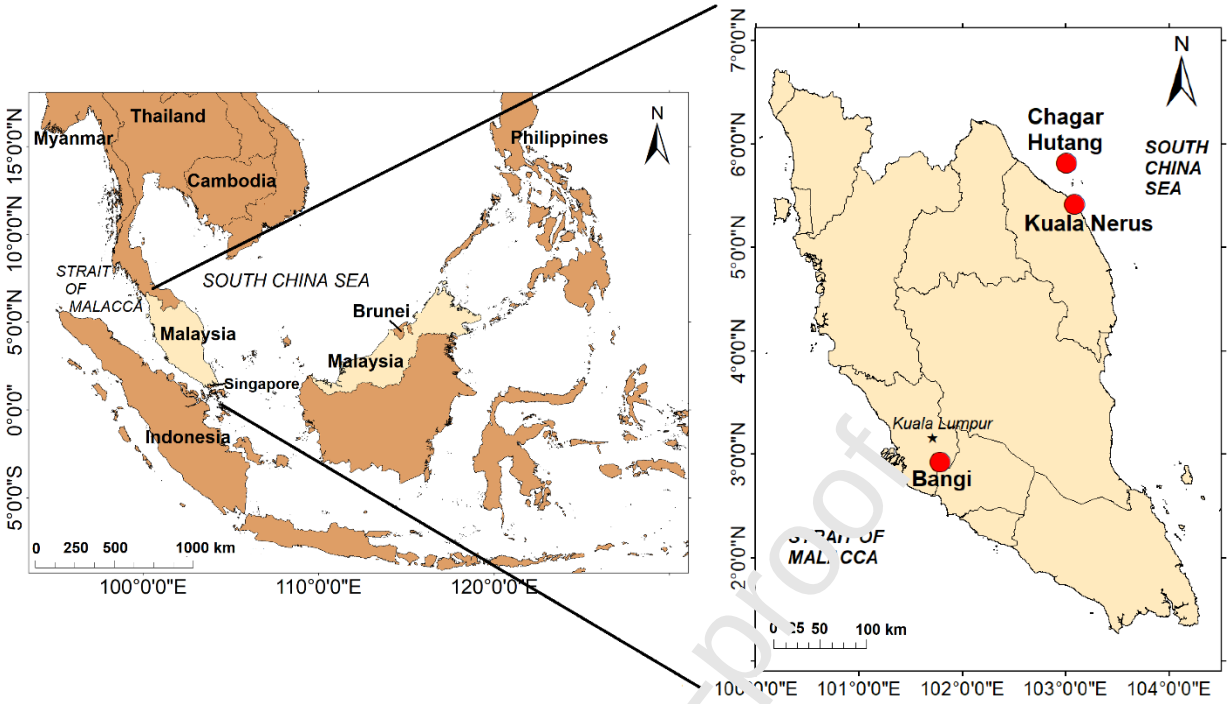

Fig. 1 Location of the sampling sites

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The Kuala Nerus sampling site is at a coastal location on the rooftop of Faculty of Science and Marine Environment at the Universiti Malaysia Terengganu, adjacent to the South China Sea. It is ~15 km away from the city of Kuala Terengganu with major land use including residential, industrial and agricultural areas (Asma et al., 2019). Together with Kuala Terengganu, the total population of Kuala Nerus and Kuala Terengganu is *ca.* 415,000 (SEPU, 2021). The Bangi sampling site is located on the rooftop of Faculty Science and Technology at the Universiti Kebangsaan Malaysia (UKM), ~25 km south of Malaysia's capital, Kuala Lumpur (1.77 million population; DOSM, 2022). Bangi is predominantly residential combined with small to medium industries (Hamid et al., 2019). Both Kuala Nerus and Bangi were developed as university towns and are undergoing rapid development and urbanisation. The Chagar Hutang station is located within a bay of a designated marine park at the northernmost part of Redang Island in

the South China Sea, ~55 km from the city of Kuala Terengganu. This beach is managed by the Sea Turtle Research Unit (SEATRU) of Universiti Malaysia Terengganu (UMT) due to its importance as a green turtles (*Chelonia mydas*) nesting beach in Malaysia (Nishizawa et al., 2021). Public access is strictly prohibited and enforced. Since this site is managed to minimise direct local anthropogenic impacts it is referred to hereafter as 'pristine'.

All sampling sites are influenced by monsoonal weather. The NE monsoon (wet season) has northerly to northeasterly prevailing winds at 10-30 knots and high rainfall (up to 330 mm/month) on the eastern coasts of Peninsular Malaysia (*i.e.* Kuala Nerus and Chagar Hutang) (Masseran and Razali, 2016). The SW monsoon is characterised by dry months (rainfall ~150 mm/month) with southeasterly to southerly wind at 15 knots and lowest rainfall in areas blocked by the island of Sumatra (Masseran and Razali, 2016). During inter-monsoonal periods, there is a short period with thunderstorms and relatively weak wind conditions with speeds not exceeding 10 knots and wind direction fluctuating (Masseran and Razali, 2016).

Passive sampling of total (dry and wet) atmospheric deposition, was carried out in this study in order to quantify atmospheric deposition across monsoonal seasons at all sampling sites, as in previous studies *e.g.* Cai et al., 2017; Allen et al., 2019; Amato-Lourenço et al., 2022. Total atmospheric deposition was continuously sampled for two weeks every month at all sites using a collector comprising a stainless funnels attached to a 2.5 L amber glass bottle. The bottle was placed in an aluminium cylinder to reduce evaporation. A funnel with a collecting area of 0.031 m^2 was used at Kuala Nerus and Bangi. A funnel with a smaller collecting area of 0.015 m^2 was used for sample collection at Chagar Hutang to avoid rainwater overflow due to its location preventing access during periods of higher rainfall with adverse weather preventing sampling in September and December at this site. One continuous sample was collected at Chagar Hutang throughout January to February and is represented as January. Five sets of the sampling

equipment were deployed at each site, with three for quantitative analysis and two for MP identification. An additional set of identical sampling equipment filled with 500 mL of ultrapure water (Milli-Q; Merck Millipore) was deployed to quantify evaporation. No correction for evaporation was necessary since sample volume changes did not exceed 10% (Schwartz et al., 2022). At the end of each sampling period, funnels were rinsed with 250 mL of ultrapure water into a glass bottle to recover any MPs on the funnel surface. Meteorological parameters (rainfall, wind speed and wind direction) during the sampling period from the nearest meteorological stations were obtained from the Malaysian Meteorology Department at Kuala Terengganu (KT) and Kuala Lumpur International Airport (KLIA) Sepang.

Quality assurance/quality control and procedural blanks

All sample collection and laboratory procedures followed quality assurance/quality controls to minimise MP contamination. In the laboratory, all procedures were carried out in a clean room with laminar flow. A 100% cotton laboratory coat was worn all times during equipment and sample preparation and analytical procedures. Before use, all funnels were cleaned with 5% diluted detergent (Decon 90) for 24 h, rinsed with ultrapure water, air dried in a laminar flow hood and covered with aluminium foil. Glassware was soaked in 5% diluted detergent (Decon 90) for 24 h, then acid-washed (10% hydrochloric acid), rinsed with ultrapure water and dried in an oven at 100 ºC except for measuring glassware that was air dried at room temperature in a laminar flow hood. Field blanks were evaluated for each monthly collection by rinsing an identical funnel and sampling amber bottle with 1 L of ultrapure water. As for the funnels used for sample collection, funnels used for field blank evaluation were covered with aluminium foil after drying and foil was removed during field blank collection to prevent cross-contamination. Procedural blanks were analysed using ultrapure water as for sample preparation. Blank values were subsequently subtracted from the field samples. Field blanks ranged from 11-26 (15±4

(mean ± SD)) MP particles and procedural blanks ranged from 6-18 (11±3) MP particles. Recovery tests were done by adding known quantities (n=30) of PP fibre, PES fibre, polystyrene (PS) fragment and HDPE fragment (with a diameter between 25-30 µm) separately into 1 L ultrapure water to provide spiked samples. Recovery rates were 98±2% for PP, 96±5% for PES, 93±7 for PS and 92±5% for HDPE.

Microplastic extraction

The preparation and analysis of MPs are described in Hee et al. (2022). Briefly, samples were filtered through a cellulose acetate membrane filter (0.45 µm pore size, Sartorius) after measuring the bulk volume of each sample. Retained samples then underwent organic matter removal by using 10% potassium hydroxide (KOH) followed by density separation of MPs using a 1.37 gcm^{-3} zinc chloride ($ZnCl_2$) solution. For MP quantification, samples were filtered onto a polycarbonate filter (2 µm pore size, Millipore) and stained with Nile Red solution; for MP identification, samples were filtered on silver membrane filters (0.45 µm pore size, Millipore). To prevent MP contamination the KOH and $ZnCl_2$ solutions were filtered through a GF/F filter (pore size 0.7 µm, Whatman) membrane filter and the Nile Red solution was filtered through a PTFE syringe filter (pore size 0.1 µm).

Microplastic quantification and identification

After staining, by using an approach first described according to Maes et al. (2017), all filters were imaged using a digital camera (Canon EOS 2000) coupled to a macro lens (Canon MP-E; 65 mm focal length) with an orange filter (HOYA orange (G)) for MP identification. Count, size and shape of MPs were undertaken on the captured images using the software ImageJ

following the method of Prata et al. (2019). Shape of MPs were categorised into either fibres, translated in a corresponding circularity of 0.0-0.3, or fragments (the remaining MPs with circularity of 0.3-1.0) according to Prata et al. (2019). In agreement with Prata et al. (2021) because some fibres did not display fluorescence under Nile Red staining, leading to a low number of fibres identified, fibres were also counted manually from captured images for 30% of total samples and then used to correct the estimated MPs and fibres counts for all samples. All non-fibre MPs were defined as 'fragment'.

The chemical composition of MPs was analysed by µ-FTIR using a Perkin-Elmer Spotlight 400 FTIR imaging system, operated with a total of 32 scans at a resolution of 4 cm^{-1} within a spectra range of 4000-750 cm^{-1}. µ-FTIR was widely used in previous studies to identify MPs (*e.g.* : Chen, 2020b; Wright et al., 2020; Szewc et al., 2021; Xiao et al., 2023) and analysis using µ-FTIR allowed identification of MPs down to 20 µm (Chen et al., 2020b; Wright et al., 2020). The resulting spectra were compared against library databases of Perkin Elmer, SIMPLE and KnowItAll, and evaluated individually by chemical and bond spectra peaks and matched with the reference spectra.

Air masses trajectory clustering

The open source modelling software Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Stein et al., 2015) was used to determine the origin of air masses and tracking before arrival at each sampling site. The HYSPLIT model is extensively used to identify sources of atmospheric MPs *e.g.:* Allen et al., 2019; Wang et al., 2020; Szewc et al., 2021; Ding et al., 2022. The model was run in backward mode for 168 hours simulations, 100 hours above surface level with 6-hour time intervals. The trajectories were calculated using meteorological

fields produced by WRF 2.5 deg 6P (>=1948 DA 220 Mb) NCAR/NCEP global reanalysis on pressure surfaces at 6 hour intervals (Allen et al., 2019).

Results

MP abundance was inversely related to particle size with ≤5-50 µm the most abundant (92.3%) size fraction (Fig. 2a). The remaining size fractions (*i.e*. 50-100, 100-1000 and 1000-5000 µm) comprised <10% of total MP number with the smaller size range (50-100 µm) together accounting for >50% of all MPs (Fig. 2a). MP shape was most commonly as fragments (54%), with the pristine site at Chagar Hutang having the highest proportion of fragments (63%) (Fig. 2b).

A total of 237 fragments/fibres were analysed for chemical composition with 136 identified as natural or synthetic fragment/fibre. Natural polymer (cellulose) was the dominant type (51%) with polyacrylamide the highest proportion of synthetic MP (40%), followed by high-density polyethylene (HDPE; 16%) and polyester (PES; 13%) (Fig. 2c and 2d). A minor proportion (7%) of analysed particles showed the presence of pigment.

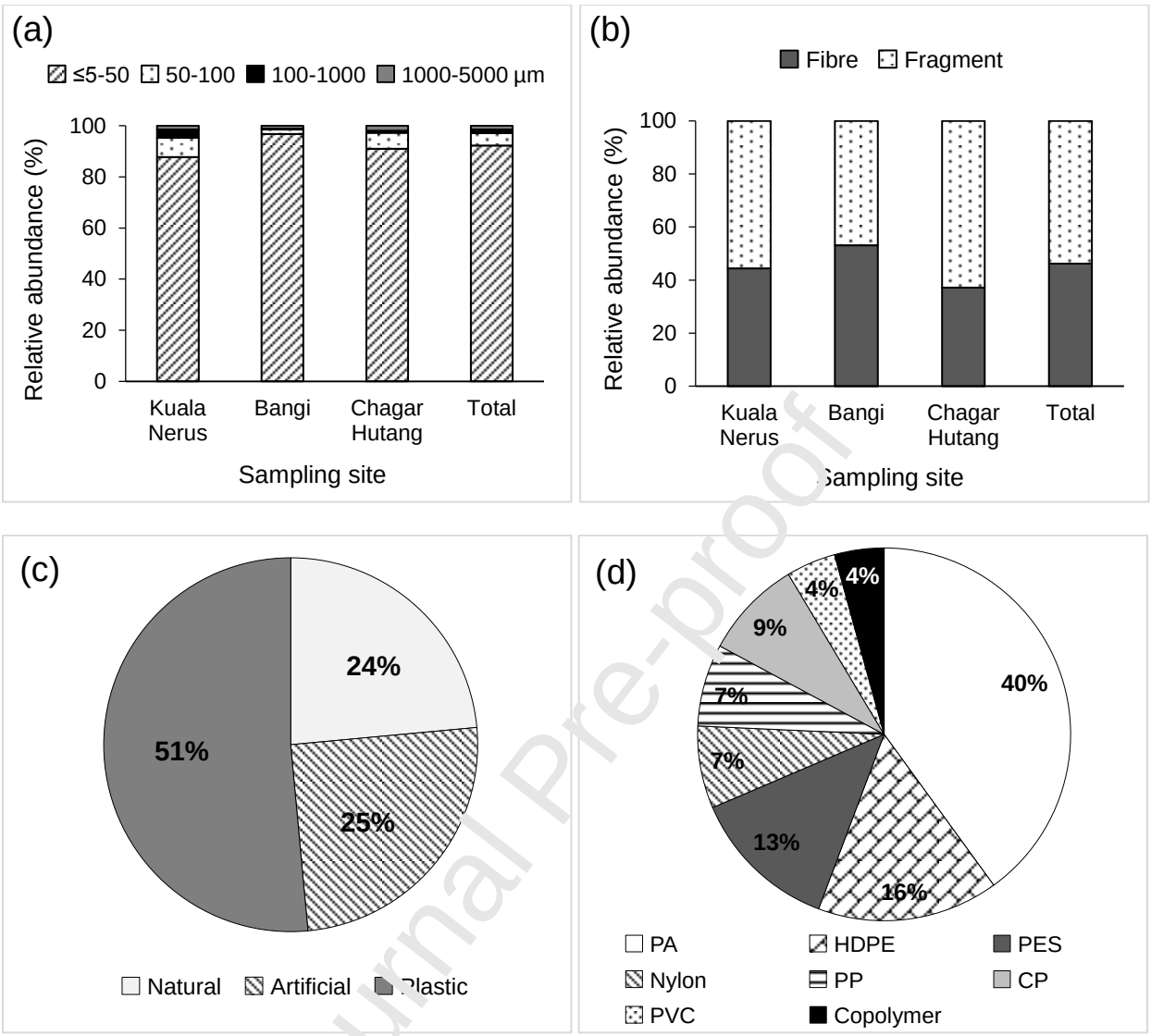

Fig. 2 Distribution of microplastic type in atmospheric deposition. (a) Polymer size, (b) distribution of fragments vs. fibres, (c) distribution of materials analysed and (d) summary of spectroscopic categorisation of polymer types. Note: Artificial polymer = transformed natural polymer; PA = polyacrylamide; HDPE = high-density polyethylene; PES = polyester; PP = polypropylene; CP = colour pigment; PVC = Polyvinylchloride

MP fibres and fragments were present in all samples (Fig. S1) with MP deposition fluxes in Kuala Nerus, Bangi and Chagar Hutang ranging from 114-689 (368±154), 280-394 (340±30)

and 172-476 (274±95) MP/m^2/day respectively (Fig. 3a; Table S1) without significant differences between stations (one-way ANOVA, $p>0.05$). Seasonal variation of atmospheric MP deposition in Kuala Nerus and Chagar Hutang was more pronounced than in Bangi with highest seasonal deposition in the NE monsoon (Fig. 3b-3d, Table S1; December for Kuala Nerus and February for Chagar Hutang). The NE monsoon at Kuala Nerus and Chagar Hutang typically showed higher wind speed and rainfall (Fig. 3b and 3d). MP deposition in Kuala Nerus and Chagar Hutang was more responsive to wind speed than rainfall (Fig. 3b and 3d) with the highest MP deposition during NE wind direction (Fig. 4d) and at peak wind speed (Fig. 3b and 3d). Overall, maximum wind speed was positively correlated with atmospheric MP deposition ($r=0.410$, $p<0.05$), while monthly rainfall showed no significant correlation with atmospheric MP deposition ($p>0.05$).

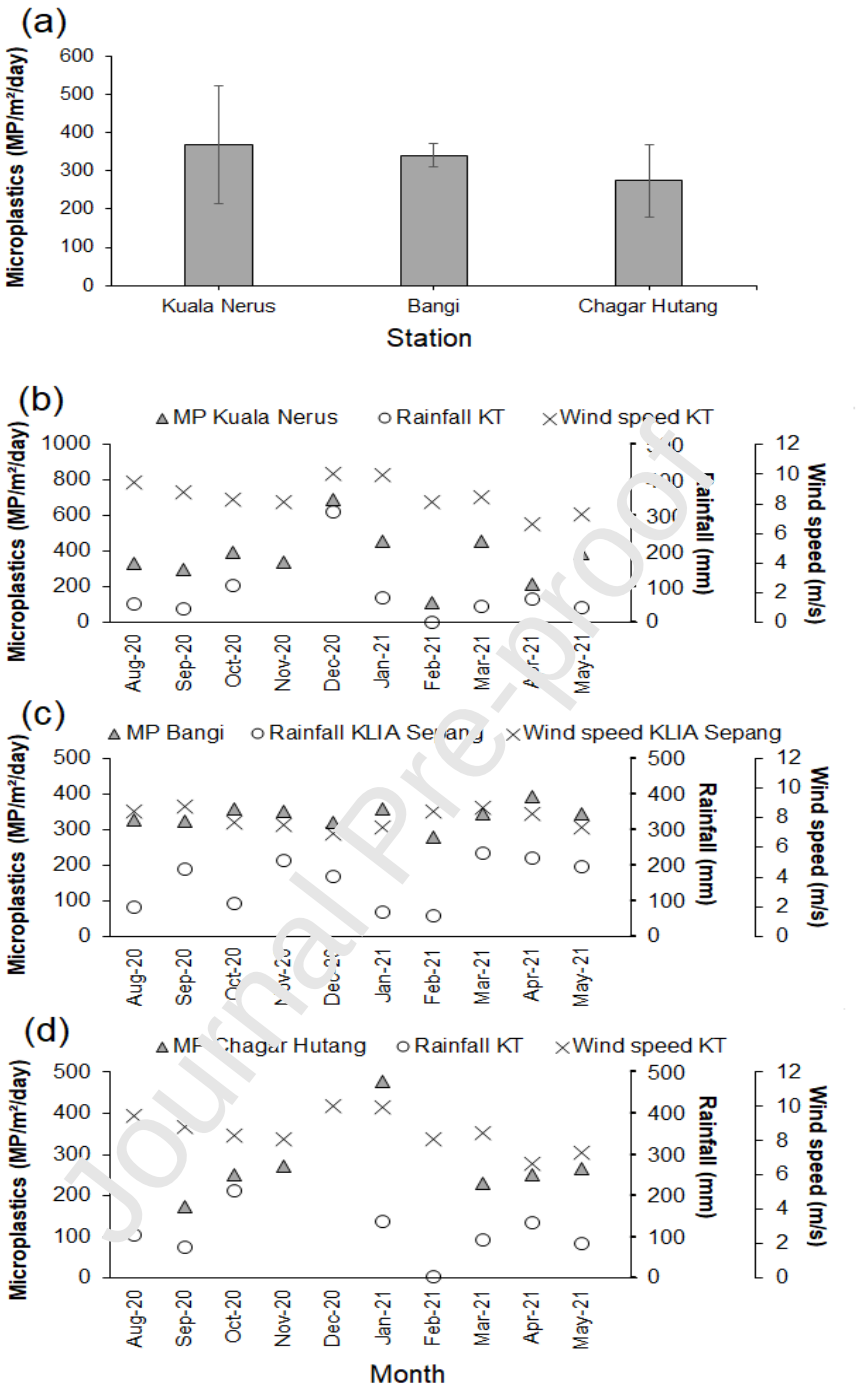

Fig. 3 (a) Mean atmospheric deposition rate of microplastics and monthly atmospheric deposition rate of microplastics at (b) Kuala Nerus, (c) Bangi and (d) Chagar Hutang and monthly cumulative rainfall and mean maximum wind speed from (b and d) Kuala Terengganu (KT) and (c) Kuala Lumpur International Airport (KLIA) Sepang meteorological stations. Error bars in (a) represent SD.

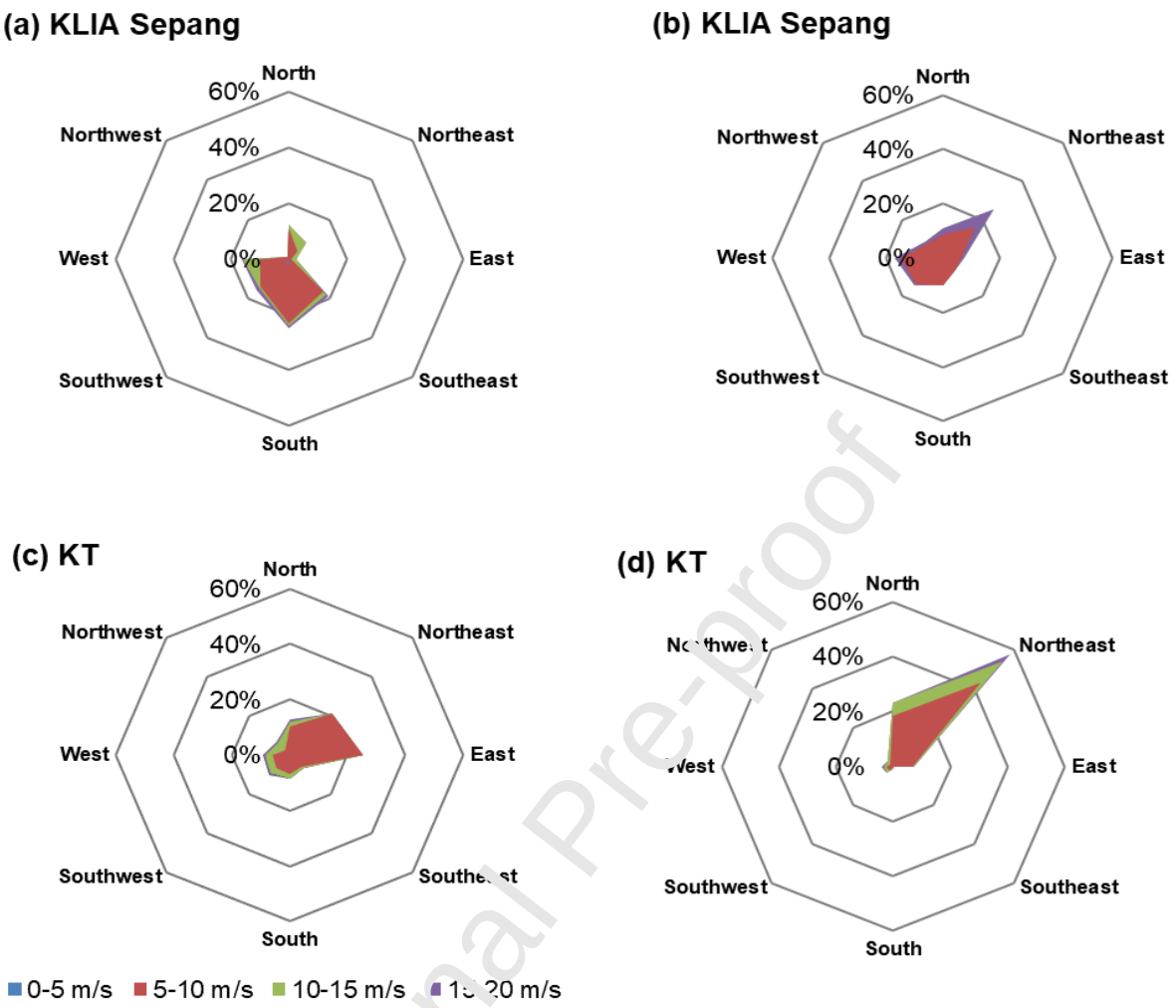

Fig. 4 Dominant wind direction at Kuala Lumpur International Airport (KLIA) Sepang and Kuala Terengganu (KT) during Southwest (a and c) and Northeast (b and d) monsoons

(to be printed in colour)

Cluster analysis for the month with highest atmospheric MP deposition showed that the dominant air mass originated from the northeast for Kuala Nerus (Fig. 5a) with predominantly marine cluster trajectories originating from the East China Sea and Mongolia then travelling across the South China Sea (SCS) and Indochina. Air masses to Bangi (Fig. 5b) were mainly

from inland Peninsular Malaysia and the dominant air masses for Chagar Hutang (Fig. 5c) originated from eastern China via Taiwan and SCS.

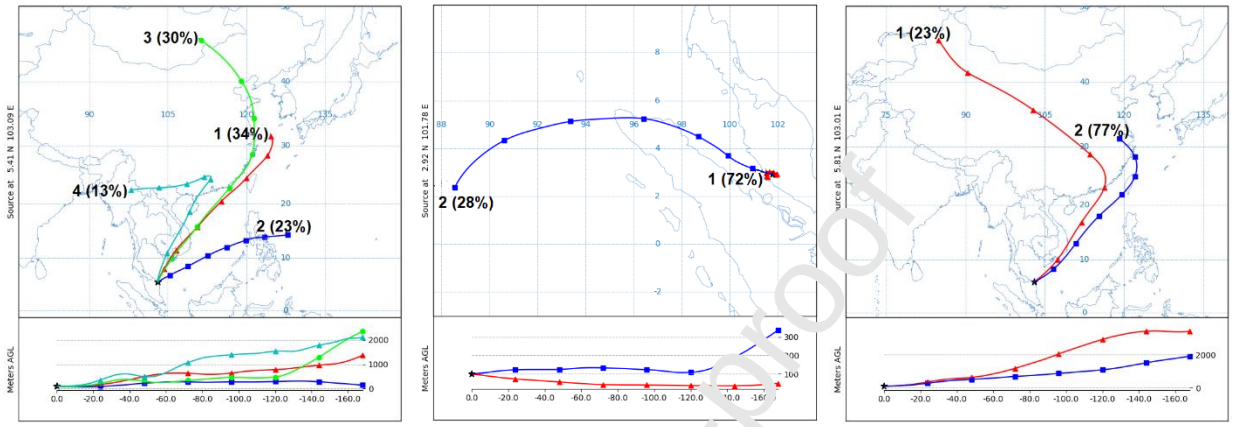

Fig. 5 Backward cluster trajectory of air mass at (a) Kuala Nerus during December 2020, (b) Bangi during April 2021 and (c) Chagar Hutang during January 2021

(to be printed in colour)

Discussion

Microplastic characterisation and morphology

Cellulose is one of the most common fibres used in the textile industry accounting for 36% of global textiles (Textile Exchange, 2021) and formed the dominant MP fraction of all analysed samples (Fig. 2c) in agreement with most previous atmospheric MP studies (Finnegan et al., 2022). For synthetic MPs, polyacrylamide was the most abundant polymer (Fig. 2d) and, although the third most abundant MP types in aquatic environments (Burns and Boxall, 2018), it is uncommon in atmospheric samples (Dris et al., 2016; Wang et al., 2020; Wright et al., 2020).

HDPE, the second most abundant MP in this study, is used in the manufacture of plastic bottles, bags and food containers and PES, also known as PET, is the predominant synthetic textiles and is used in most single-use drink bottles and food containers. Although HDPE and PET can be recycled, there are local and regional sources since five SE Asian countries, *i.e.* Malaysia, Indonesia, Philippines, Vietnam and Thailand, are in the top ten countries globally for mismanaged plastic waste (Jambeck et al., 2015). This mismanagement results in MPs and their source materials entering the environment. Long-term exposure to solar UV radiation and ambient temperature fluctuations causes plastic container and textile breakdown resulting in secondary MP release to the atmosphere (Liu et al., 2019) and marine environment (Issac and Kandasubramanian, 2021).

In agreement with previous studies (*e.g.:* Allen et al., 2021; Liao et al., 2021; Wang et al., 2021) the dominant fraction of atmospheric MPs was composed of the smaller size fractions. This was expected result from larger atmospheric MPs tending to settling more rapidly and being deposited in closer proximity to their source with smaller MPs remaining suspended in the atmosphere (Wang et al., 2021). Fibres are typically the dominant morphology of atmospheric MPs since their greater surface area-to-volume ratios increase drag forces and reduce settling velocity facilitating atmospheric conveyance (Wang et al., 2020; Liu et al., 2019). Fragments were however dominant at all sites suggesting an important role for other transport pathways.

Microplastic deposition rate and monsoonal influence

This study demonstrated the scale of atmospheric MP deposition in tropical urban areas and for the first time to a 'pristine' tropical beach on an island in the South China Sea with similar rates to other urban (*e.g.*: Dris et al., 2016; Cai et al., 2017; Wright et al., 2020) and pristine locations (Allen et al., 2019). Higher average MP deposition was at urban sites *i.e.* Kuala Nerus and

Bangi, with the latter located in the greater urban area associated with Kuala Lumpur, Malaysia's most populous city (1.77 million population; DOSM (2022)). In comparison to previous studies, the average MP deposition of 334±110 MP/m^2/day was similar to other urban areas, ranging from 64 MP/m^2/day in Shiraz, Iran to 712 MP/m^2/day in London, UK (Table 1). These results support urban areas being a major source of MPs due to urban and industrial production, inadequate disposal of plastic waste and tyre wear resulting in MP production (Dehghani et al., 2017; Dris et al., 2018; Wright et al., 2020).

Table 1 Summary of previous studies measuring atmospheric microplastic deposition rates at sites including urban locations

Location	Microplastic deposition (MP/m²/day)	Mean microplastic deposition (MP/m²/day)	Environment	Reference
Paris, France	2-355	110	Urban deposition	Dris et al., 2016
Gongguan, China	175-313	2[illegible]8	Urban deposition	Cai et al., 2017
Yantai, China	0-602	NA	Urban deposition	Zhou et al., 2017
Hamburg, Germany	25-800	215 (urban)	Urban, rural & forest deposition	Klein and Fischer, 2019
London, UK	575-1008	712 (fibres)	Urban deposition	Wright et al., 2020
Shiraz, Iran	27-116	64	Urban deposition	Abbasi and Turner, 2021
Guangzhou, China	51-178	114	Urban deposition	Huang et al., 2021
Ho Chi Minh City, Vietnam	71-917	374 (urban)	Urban deposition	Troung et al., 2021
San Paulo, Brazil	57-220	123	Urban deposition	Amato-Lourenço et al., 2022
Pyrenees Mountains, France	204-599	365	Remote mountain deposition	Allen et al., 2019
Muskoka-Haliburton region, Canada	32-73	57	Remote lake deposition	Welsh et al., 2022

Monsoonal season exerts a regionally important role on meteorology in SE Asia. The Kuala Nerus and Chagar Hutang sites experienced intense rainfall and higher wind speed in November-December and December-January respectively due to the NE monsoon (Suhaila et al., 2011; Hee et al., 2020). The west coast of Peninsular Malaysia showed a bimodal annual cycle with higher rainfall (November and March-April) and wind speed (September and March) during the inter-monsoon seasons (Suhaila et al., 2011), with a less pronounced peak of rainfall and wind speed compared to the east coast sites. Despite meteorological conditions previously having been shown to have an influence on atmospheric pollutant distribution (Mohtar et al., 2018), there was no significant correlation of MP deposition with rainfall in this study. This may be due to rain events washing out MPs from the atmosphere prior to reaching the sampling sites reducing atmospheric load available for later deposition (Abbassi, 2021).

Previous studies have shown the effect of wind direction and speed on atmospheric transport to be key factors in long-range MP transport (Allen et al., 2019; Liu et al., 2019; Wang et al., 2020; Wang et al., 2021) with MPs transported 95 km to the French Pyrenees (Allen et al., 2019) and 85-350 km to Ontario, Canada (Welsh et al., 2022). The significant positive correlation of wind speed with MP abundance shows a role for wind speed in controlling MP transport and deposition. The elevated MP deposition at Kuala Nerus and Chagar Hutang in December and January during the strong NE wind and easterly offshore winds showed that long-range atmospheric MP transport contributed to urban-levels of deposition at the pristine site.

Air masses reaching the east coast of Peninsular Malaysia in the NE monsoon mainly originated from the SCS, continental regions of China and Taiwan (Fig. 5a and 5c) and shared similar emission sources for MPs as previously shown for other air pollutants (Mohyeddin et al., 2020;

Rahim et al., 2021). The high deposition rate from April-May in Bangi during the inter-monsoon season (Fig. 5b) showed that regional sources mainly from inland Peninsular Malaysia dominate when a change of monsoon wind direction occurs. During this inter-monsoonal period, atmospheric particulate matter may have predominantly originated from the local sources due to air stagnation (Yap and Hashim, 2013) with the local urban sources of MPs in Bangi dominating in this season. Overall, the air masses arriving at all sites received inputs from mixed sources of pollution and from local and far field sources with seasonal meteorological conditions influencing MP sources. With climate change predicted to alter the characteristics of the monsoonal season, such as weakening monsoon flow and reduced precipitation (Lou et al., 2015; Liang et al., 2022), changes in the future pattern of atmospheric MP deposition can be also expected.

Marine microplastic as a source to atmospheric deposition

Atmospheric MP deposition rate at the pristine site of Chagar Hutang was not significantly different from the urban sites despite strictly controlled access and the absence of local pollution sources from urban and industrial activities. This suggests that long-range MP sources were dominant since direct local MP sources due to these activities were prevented. A wind-driven atmospheric transport pathway for MPs to the pristine site was shown by back trajectory air masses with continental origin providing a source for MPs.

MP characterisations may also provide potential source origin information. Atmospheric MPs sampled at remote areas *e.g.* lake basin of Tibetan Plateau (Dong et al., 2021), West Pacific Ocean (Liu et al., 2019) and northwestern Pacific Ocean (Ding et al., 2022), typically have fibres as the dominant shape due to their greater surface area-to-volume ratios facilitating atmospheric conveyance (Brahney et al., 2020). The presence of the highest relative fraction of fragments (63%) at the pristine Chagar Hutang site however suggests an alternative source for

MPs which was likely to be of marine origin since fragments form a large portion (34-50%) of marine MPs in contrast to atmospheric samples in the SE Asian region (Curren et al., 2021).

Deposition via long-range atmospheric transport to remote areas also shows the dominance of the smaller size MPs (Allen et al., 2019; Wang et al., 2020). In contrast MPs from aqueous environments are typically relatively larger (Nasseri and Azizi, 2022). The lower proportion of smallest size range MPs at the pristine site relative to the urban Bangi site therefore supports a marine MP source having a role in MP atmospheric deposition locally. Chemical composition can also be used to aid source discrimination (Forster et al., 2023; Liu, et al., 2023; Parashar and Hait, 2023; Zhang et al., 2023). Polyacrylamide is atypical of atmospheric MPs (Dris et al., 2016; Wang et al., 2020; Wright, et al., 2020; Huang et al., 2021) but represented the highest proportion of synthetic MP in the samples at Kuala Nerus and Chagar Hutang supporting a marine MP source. Additionally, the HDPE, PET, PP, colour pigment and cellulose acetate MP fragments deposited at the Chagar Hutang (Fig. S2) suggest possible sources associated with marine transport since they are produced by marine vessels and their paint and also plastic pollution associated with riverine and coastal plastic input to the marine environment *e.g.* degraded plastic bags, food containers and cigarette filters (Cai et al., 2017; Sanjay et al., 2020; Hee et al., 2022;).

The ocean and marine environment is generally been considered as microplastic sink, however recent studies suggested that these marine MPs are potentially being entrained and transported via ocean currents with particles in the sea surface layer acting as a local secondary source to the atmosphere via bubble bursting (Allen et al., 2020; Trainic et al., 2020). Although the methods used in this study do not allow the quantification of far field MP transport by marine versus atmosphere pathways, the combination of MP morphology, size and chemical composition indicates a key role for marine MP as a source for coastal MP deposition via the

atmosphere. This marine source represents an important route for contamination of all coastal sites globally since there are an estimated 170 trillion plastic pieces in the marine environment (Eriksen, 2023). This marine store of MPs means this pathway may become relatively more important for the future management of MP contamination at coastal sites if future environmental MP production and input is effectively controlled.

Conclusion

The magnitude of MP transport and deposition in a tropical region of SE Asia to a remote tropical island is shown to be at similar rates to urban areas with atmospheric transport acting as a major delivery pathway. Composition and morphology of the deposited MPs indicated a role for marine pathways to tropical coastal sites by providing a local input of MPs into the atmosphere. This transfer pathway of MPs from the sea surface to atmosphere and its subsequent deposition in combination with long-range atmospheric transport and deposition makes it is unlikely that there are any 'pristine' coastal ecosystems globally with respect to MP contamination.

Author contributions

Y.Y.H: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Visualization, Writing-Original Draft; **N.M.H.:** Methodology, Investigation, Resources, Funding acquisition, Writing-Review & Editing; **K.W.:** Methodology, Supervision, Writing-Review & Editing; **M.T.L.:** Resources, Writing-Review & Editing; **S.S.:** Resources, Supervision, Project administration, Funding acquisition; **M.U.R.:** Methodology, Writing-Review & Editing; **A.G.M.:** Methodology, Resources, Project administration, Funding acquisition, Writing-Review & Editing.

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Ethics declarations

The authors declare no competing interests.

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CRediT author statement

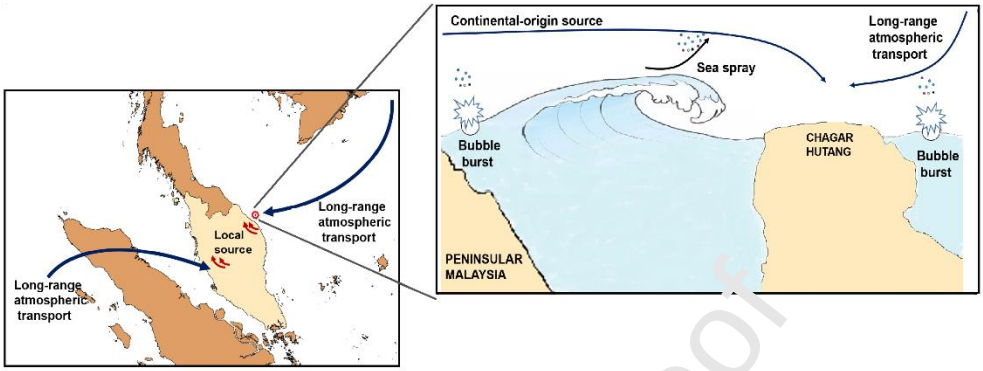
Y.Y.H: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Visualization, Writing-Original Draft; **N.M.H.:** Methodology, Investigation, Resources, Funding acquisition, Writing-Review & Editing; **K.W.:** Methodology, Supervision, Writing-Review & Editing; **M.T.L.:** Resources, Writing-Review & Editing; **S.S.:** Resources, Supervision, Project administration, Funding acquisition; **M.U.R.:** Methodology, Writing-Review & Editing; **A.G.M.:** Methodology, Resources, Project administration, Funding acquisition, Writing-Review & Editing.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Highlights

- Atmospheric MP deposition to a pristine tropical site was similar to urban sites
- Long-range atmospheric transport of MPs occurred at all sites
- Higher Northeast monsoon wind speed enhanced atmospheric MP transport and deposition
- MP composition and morphology indicated a role for a marine source of MPs to the atmosphere