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To cite this version:

Tran-Nguyen-Sang Truong, Emilie Strady, Thuy-Chung Kieu-Le, Quoc-Viet Tran, Thi-Minh-Tam Le, et al.. Microplastic in atmospheric fallouts of a developing Southeast Asian megacity under tropical climate. Chemosphere, 2021, 272, pp.129874. 10.1016/j.chemosphere.2021.129874 . hal-03141123

HAL Id: hal-03141123

https://hal.science/hal-03141123v1

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Microplastic in atmospheric fallouts of a developing Southeast Asian megacity under tropical climate

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highlights

- Deposition flux of microplastics varied between 71 and 917 items m^{-2} d^{-1}.
- The majority of deposited microplastics were fibers.
- Tropical monsoon climate does not influence the deposition fluxes of microplastics.
- Population density and space occupation influence deposition fluxes of microplastics.

articleinfo

Keywords:
Fragments
Fibers
Viet Nam
Ho chi minh city
Deposition fluxes

abstract

Microplastics in atmospheric fallouts from a developing megacity influenced by a tropical monsoon climate were investigated during a year. Three sites were selected according to the surrounding population density, the land use and occupation. The microplastic deposition fluxes varied between of 71–917 items m^{-2} d^{-1}, for an observation size range of 300–5000 μm. Fibers predominated while fragments were observed occasionally. Unexpectedly, contrary to available scientific literature, deposition fluxes did not vary temporally with rainfall and wind intensity or direction, showing no effect of the tropical climate. Variations were observed between sites and were attributed to their environmental characteristics: population density and occupation space. The median length of fibers also differed between sites and could be related to *in-situ* fragmentation processes due to occupation space (solid waste treatment facility). Those first results from tropical climate region are showing interesting insights and are opening new perspectives on the understanding of microplastics fate from atmospheric fallouts.

1. Introduction

Microplastics, i.e. the plastic items comprised between 1 μm and 5000 μm (Frias and Nash, 2019), are considered as emerging pollutants and have become a global concern. Microplastics are present in different types of environment worldwide like in marine and freshwater aquatic environments (Auta et al., 2017), in terrestrial environments (Guzzetti et al., 2018), in atmospheric fallouts (Huang et al., 2020) and in the biota (Li et al., 2018; Wong et al., 2020). Airborne microplastics enter the aquatic and terrestrial environments via dry and wet atmospheric fallouts (Huang et al., 2020). Because of their ubiquity in the air, relating to their light weight and very small size (Kaya et al., 2017) they can also be inhaled or ingested by human, causing potential health adverse effects (Prata et al., 2020). Since the evidence of the presence of microplastics in atmospheric fallouts (Dris et al., 2015), concerns and number of sites studied regarding airborne microplastics have increased. Studies are focusing on different types of environments from mountainous remote area (Allen et al., 2019), dense urban zone (Li et al., 2020), to oceanic environments (Wang et al., 2020). The fate of microplastics in the atmosphere is only partly understood. Microplastics were found in dry and wet atmospheric

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fallouts, and evidenced patterns with the amount of precipitation, as rainfall or as snowfall (Allen et al., 2019), and with the wind intensity and direction (Abbasi et al., 2019; Klein and Fischer, 2019). Therefore, they can be transported over a long distance (Li et al., 2020); (Allen et al., 2019). Parameters like population density, local environments and human activities have been highlighted to influence their deposition fluxes (Dris et al., 2016). In fact, the sources of microplastics in the atmosphere are multiple and were evidenced from indoor environments (Dris et al., 2017), road surface dust originating from tire wear (Sommer et al., 2018), degradation of macroplastics and of synthetic building material (Gasperi et al., 2018) and from waste incineration (Dris et al., 2016).

So far, most of the studies were conducted in developed countries, where plastic waste management is mostly effective, and under temperate climate, where precipitation can occur all year through. Viet Nam, a developing country with a high Gross Domestic Product, is characterised by a plastic waste mismanagement (Jambeck et al., 2015), leading to a large plastic pollution of its environment (Strady et al., 2020a). The plastic concentrations measured in the Saigon River, crossing the southern economic capital Ho Chi Minh City (HCMC), evidenced tremendous levels of macroplastics (van Emmerik et al, 2018, 2019), microplastics (Lahens et al., 2018) and synthetic fibers (Strady et al., 2020b). Southern Viet Nam is also subjected to tropical monsoon climate with two distinct seasons, a dry season and a rainy season, lasting 6 months each. Therefore, this paper aims to observe the temporal variation of microplastic deposition fluxes in atmospheric fallouts under a tropical monsoon climate and in a megacity characterized by plastic waste mismanagement. We hypothesized that the contrasted seasons may strongly influence the deposition fluxes annual pattern. More precisely, the objective of this study are (i) to monitor microplastic deposition fluxes in atmospheric fallouts in HCMC, (ii) to discuss the potential influence of anthropogenic activities on deposition fluxes and morphology of microplastics and (iii) to evaluate the effect of tropical monsoon climate on deposition fluxes and morphology of microplastics. To do so, we set a one-year survey of atmospheric fallouts, with subsampling for microplastics analysis twice a month, at three sites characterized by low and high population density and located close to waste treatment complex and construction site.

2. Materials and methods

2.1. Study area

Ho Chi Minh City is located in the South of Vietnam and is considered as the economic capital of Viet Nam (Fig. 1). It has a population of 8,598,700 inhabitants (GSO, 2018) with a population density of 4171 inhabitants km^{-2}(GSO, 2018). HCMC has an area of 2095 km^2 divided by 24 districts: 5 rural districts (1601 km^2) gathering 1.8 million inhabitants and 19 urban districts (494 km^2) gathering 7.1 million inhabitants. Its economy is structured on service sector (i.e. 51.1%), on industry and construction (i.e. 47.7%) and a few on forestry, agriculture and aquaculture (i.e 1.2%). Past studies evidenced high concentrations of microplastics in the aquatic system of HCMC which was related to the high density of population, the poor wastewater treatment plants facilities and the presence of industrial zones in HCMC and Binh Duong Province including textile, apparel, plastic and packaging production industries (Lahens et al., 2018; Strady et al., 2020b). HCMC is under a tropical climate with an average temperature ranging annually from 27 °C to 34 °C (2018–2019) and with two distinct seasons: a dry season generally lasting from December to April and a rainy season from May to November. In 2018–2019, the dry season was shorter and lasted from January 2018 to March 2018 (Fig. 2a-b-c), with important rainfall (more than 350 mm accumulation per month) recorded in November 2018 (i.e. Usagi storm) and in June 2019 ((Southern Institute of Hydrology, Meteorological and Climate Change, personal communication). In HCMC, during the period considered, the wind speed fluctuated between 1 and 12 m s^{-1} with a median of 6.4 m s^{-1} (Hersbach et al., 2019), and the dominant wind directions were N-NNE-NE and S-SSW-SW (Fig. 2d–e).

Three sites in HCMC were selected to collect dry and wet atmospheric fallout samples (Fig. 1): in rural area of Cu Chi (i.e. CC), in dense urban area of District 10 (i.e.D10) and near the landfill of Phuoc Hiep (i.e. PH). The site D10 is 28.5 km far from the site CC and 32.5 km far from the site PH, while the distance between the two sites PH and CC is only 7.0 km. More precisely, the site CC (10°58^{0}31.6^{00}N; 106°29^{0}58.0^{00}E) is located in the rural district of Cu Chi (930 inhabitant km^{-2}; GSO 2018) in a household area. The sampling site is in a courtyard at 2 m above the ground and less than 50 m far from a road with intense traffic. The site D10 (10° 46^{0}28.4^{00}N 106°39^{0}40.7^{00}E) is located in a dense urban area of district 10 (41,000 inhabitants km^{-2}; GSO 2018) on the rooftop of our laboratory's building (e.g. 10 m height) in the University's campus. The sampling sites is 50 m away from a main road characterized by intense motorbike traffic and 200 m far from an important construction's site (a 38-level tower complex of 800 units). The site PH (10°57^{0}36.9^{00}N 106°25^{0}49.9^{00}E) is also located in the rural district of Cu Chi, far from households, at the entrance of the Phuoc Hiep waste treatment complex, at 1 m above the ground and close to a road. This complex was until 2015 the main landfill of HCMC processing 8000 tons of waste per day on an area of 6.9 km^2. Since its partial closure due to pollution of the surrounding environment, the majority of the waste was transferred to Da Phuoc landfill located in the South of HCMC, and a municipal solid facility capturing methane emissions was set up at Phuoc Hiep. The project launched in 2013 and still in progress, reduce methane emissions by sorting the waste and then establishing and operating composting facilities to treat organic matter collected from municipal waste. The total designed capacity is of 432,000 tons of solid waste per year with daily waste reception of 1200 tons and the proposed product of organic compost is as 53,568 tons annually (Vietstar, 2020).

2.2. Sampling

Dry and wet atmospheric fallout samples were taken twice a week during twelve months from June 15th, 2018 to May 25th, 2019, with a sampling duration of 3 days (Monday to Wednesday) or 4 days (Thursday to Sunday) (Fig. 2). The collection of samples was carried out on the same day at all sites. Among those samples, a total of 72 sub-samples, equivalent to two samples per month and per site (Table 1), was collected to study the presence of microplastics. The sampling device, inspired by the device described by Cai et al.(2017) and Dris et al.(2015), consisted of a 250 mm diameter glass funnel placed on a 10-L glass bottle to collect rain water and air dust falling into the funnel area (surface of 491 cm^2) and then into the bottle. It was installed at the three sampling sites.

Dry atmospheric fallout samples (collected during dry days, i.e., absence of rain) were collected by rinsing the funnel with filtered milli-Q water in order to collect all dry dust settled in the 10 L glass bottle. The funnel and the bottle were actually rinsed three times with filtered milli-Q water and then total water was poured into the 500 mL glass bottles in order to recover all microplastics that might be adhering into its walls. Then, the bottles were brought back to the laboratory and stored at 4 °C until analysis.

Wet atmospheric fallout samples (i.e., rainy days) were collected in two steps. Firstly, the volume of rain water was recorded for

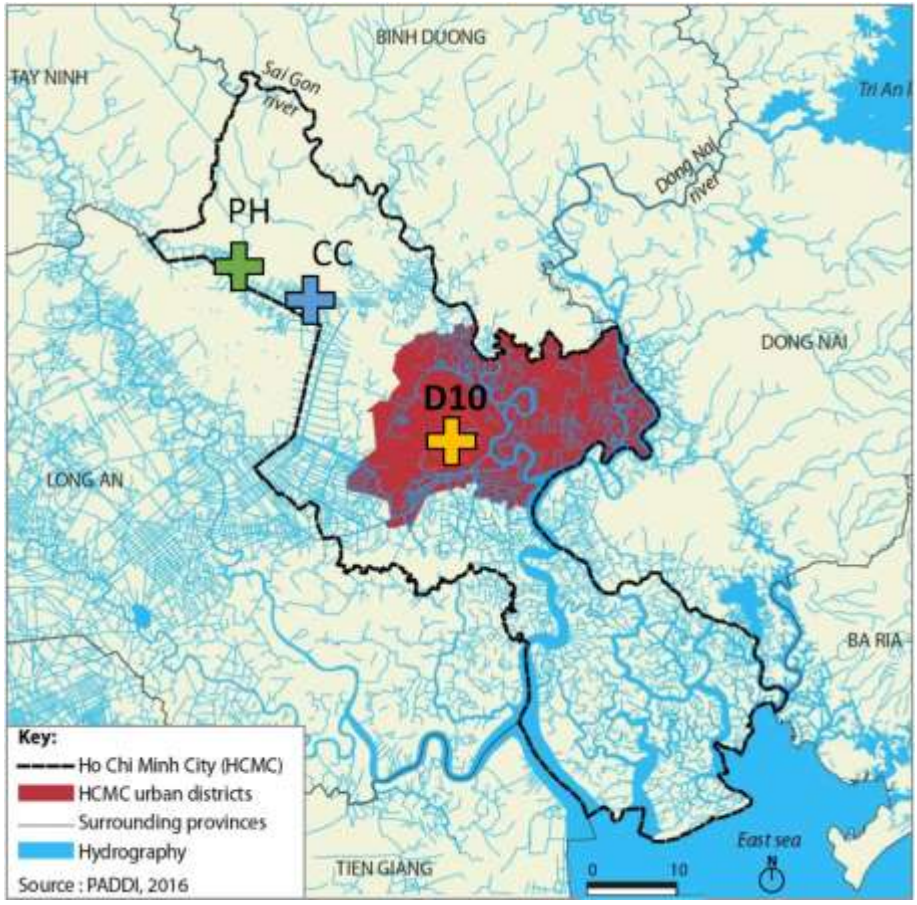

Fig. 1. Study area map with sampling sites.

determining the rainfall by pouring the sample into a pre-weight 500 mL glass bottle and by weighing it back in the laboratory. Then, in a second step, the funnel and the bottle were rinsed three times with filtered milli-Q water, the water was poured into the 500 mL glass bottles and the bottles were brought back to the laboratory and stored at 4 °C until analysis.

2.3. Analyses

The sample treatment's protocol was adapted from Strady et al.(2020a) for surface waters and is described as followed. At first, the samples were sieved through a 1-mm sieve using filtered milli-Q water to remove pieces of organic particles, fibers or fragments bigger than 1 mm size. If any, the two items later were kept separately for observation by stereomicroscope afterward. After the sieving step, samples with water volume less than 350 mL were directly stored in a glass bottle, and samples with water volume exceeded 350 mL were put 24 h in the fridge for particles settlement, and the exceeding 350 mL supernatant, which may retain low density plastic, was filtrated in GF/A filters while the 350 mL remained in the glass bottle. In the second step, a density separation using sodium chloride solution (1.18 ± 0.02 g cm^{-3}) was performed in the separatory funnel in a volume ratio 1:1. After 30 min of separation, the dense bottom layer was discarded while the supernatant was stored in a glass bottle for the next step. In the third step, 1 g SDS (Sodium Dodecyl Sulphate, Merck; ratio: 1 g for 350 mL sample) was added into the sample and the bottle was kept in the laboratory oven at 50 °C for 24 h. Then, in the fourth step, 1 mL of bioenzym SE (protease and amylase, Spinnrad® ratio: 1 mL for 350 mL sample) and 1 mL of bioenzym F (lipase, Spinnrad®; ratio: 1 mL for 350 mL sample) were added into the sample and the bottles were kept in the laboratory oven at 40 °C for 48 h. We note that preliminary tests evidenced clearer filter for observation with the addition of bioenzyms. In the fifth step, 15 mL of H_2O_2 (Hydrogen Peroxide, Merck®; ratio: 15 mL for 350 mL sample) was added into the sample and the bottles then were kept in the laboratory oven at 40 °C for 48 h. Finally, the pre-treated samples were filtrated on GF/A filters (1.6 ㎛ porosity, Whatman®), using a glass filtration unit, and the filters were kept in petri dishes for observation step by stereomicroscope. We note that (i) all glassware was previously rinsed with filtered water and kept closed until sample collection and analysis, (ii) technicians were wearing gloves and cotton lab-clothes, (iii) fans in the laboratory were shut down and room temperature was maintained using air conditioning.

2.4. Stereomicroscope and FTIR analyses

The filters were observed using the stereomicroscope Leica S6D® with HD camera. Morphology of fibers, i.e, length and diameter, and fragments i.e, area, were measured, using the LAS software® and their color were recorded. The minimum length size of observation was set up at 300 ㎛, as recommended by GESAMP (2019) when the determination of the nature of plastic is not done automatically on all items, and the maximum was at 5 mm. We defined fibers as elongated fibers being equally thick, not tapered towards the ends, having a three-dimensional bending. We defined fragments as irregular shaped hard particles having appearance of being broken down from a larger piece of litter, or flat flexible

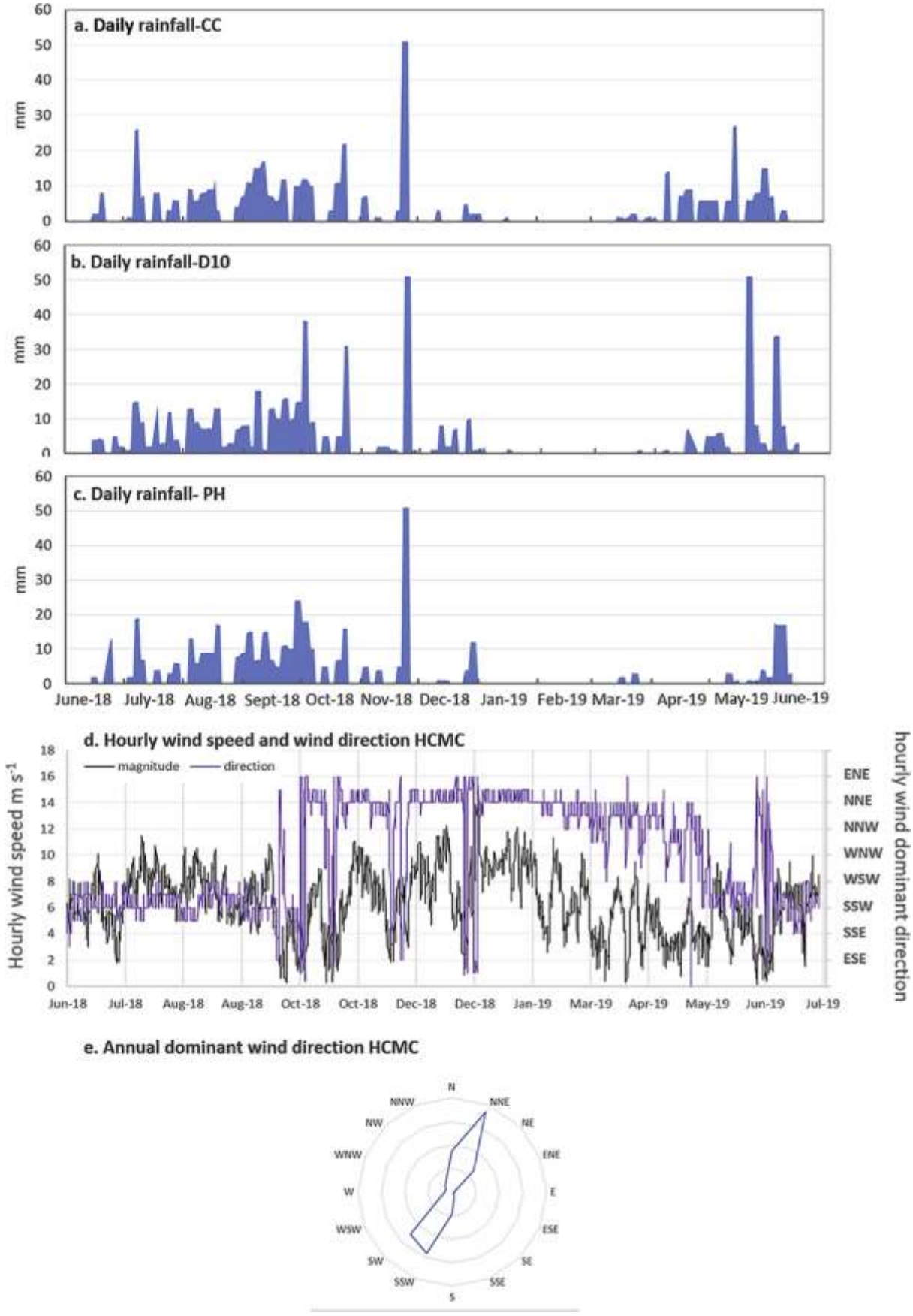

Fig. 2. a-b-c Cumulative daily rainfall in mm (from Mondays to Wednesdays and frim Thursdays to Sundays) at the three sampling sites CC,D10 and PH; d: modeled hourly wind speed and wind direction at HCMCity (Hersbach et al., 2019); e: dominant wind direction over the year of survey.

particle with smooth or angular edges, or near spherical or granular particle which deforms readily under pressure and can be partly elastic. All must have an absence of visible cellular or organic structures and being homogeneously colored (red, blue, green, grey, black). Despite particles from tires are a major source of microplastic to the environment (Sommer et al., 2018), we excluded them from our observation, due to the difficulty to recognize them from visual observation only. FTIR microscopy (FTIR-ATR iS50 Thermo Fisher Scientific®) was performed on selected microplastic particles to improve the identification and classification of particles that were tricky to classify as microplastics based on visual observation only. In our knowledge, μFTIR, or even μRaman, are not available in Vietnam, making systematic identification of plastic polymer difficult and inefficient. Within 35 microplastics analyzed (e.g. 33 fragments and fibers), 30 were identified as PP, 2 as PE, 2 as PVC and 1 as silica.

2.5. Control quality

The control quality and prevention of contamination were assured based on the recommendations of Dehaut et al. (2019): operators were always using cotton lab clothes and gloves, the water and NaCl solution were filtered before use on GF/A filters (porosity 1.6 μm) and kept in glass bottles, all glassware were rinsed with filtered water before being used, and fan was prohibited and air conditioning was used to maintain cool temperature in the room and avoid dust settling. Specific control samples were established: (i) sieving atmospheric control (SAC) consisting on a filter places on the benchmarked and exposed to airborne contamination during digestion and sieving steps, (ii) observation atmospheric control (OAC) consisting on a filter places on the benchmark and exposed to airborne contamination during stereomicroscope observation, (iii) positive extraction control (PEC) consisting on spiked PE grinded beached yellow fish box (CRT 171, Carat GmbH) in the original sample. The quality control evidenced a SAC ¼ 0 items (n ¼ 24 filters), OAC ¼ 11 fibers (n ¼ 24 filters) and PEC ¼ 95% (n ¼ 240 spiked microplastics).

2.6. Statistical analysis

The Pearson correlation coefficient matrix, the Kruskall-Wallis test followed by Conover-Iman test and the Mann-Whitney test at probability level $p < 0.05$ were performed using XLSTAT statistical and data analysis solution.

3. Results and discussion

3.1. Microplastic's deposition fluxes

In HCMC, the atmospheric deposition flux of microplastics, varied between 71 and 606 items m^{-2} d^{-1} at CC, 156–917 items m^{-2} d^{-1} at D10 and 71–785 items m^{-2} d^{-1} at PH (Truong et al., 2020; Fig. 3; Table 1).

3.1.1. Comparison to other study sites

The measured deposition fluxes in HCMC are in the higher ranges, and even up to the deposition fluxes estimated in Paris megacity France (29–280 items m^{-2} d^{-1}; Dris et al., 2015), in Dongguan China (175–313 items m^{-2} d^{-1}; Cai et al., 2017), in Yantai China (130–624 items m^{-2} d^{-1}; Zhou et al., 2017) in Hamburg city Germany (136–512 items m^{-2} d^{-1}; Klein and Fischer, 2019) and in Pyrenees Mountains France (365 ± 29 items m^{-2} d^{-1}; Allen et al., 2019). The size range of observation in the present study (i.e. 300-5000 μm) has smaller spectra than the size range of observa- tion from Paris megacity, Dongguan, Yantai, Hamburg or in the Pyrennes (i.e 50-5000 μm in (Allen et al., 2019; Dris et al., 2016; Klein and Fischer, 2019; Zhou et al., 2017); 100-5000 μm in Dris et al.(2015) and 200-5000 μm in Cai et al.(2017-). In the Pyrenees, 100% of fragments, 48% of fibers and 96% of films were comprised within 50–300 μm size range (Allen et al., 2019), and the same tendency was observed in Hamburg, Germany, (Klein and Fischer, 2019), while in Paris, France, the proportion of synthetic fibers was of 20% in the 50–400 μm range (Dris et al., 2016) and the 100–300 μm range represents 31% of the microplastics observed in Yantai, China (Zhou et al., 2017). Accordingly, even if the comparison between studies are inadequate because of the difference inobservation's size range, we can highlight that a non-negligible proportion of microplastics smaller than 300 μm is not observed and so are omitted in our measurement, leading to a large underestimation of the deposition fluxes. We note that fibers and fragments smaller than 300 μm and looking like microplastics were observed, but with the absence of a μFTIR and/or μRaman, we could not identify their nature and consider them robustly as microplastics.

3.1.2. Deposition fluxes variation

The deposition fluxes of microplastics varied between the three sampling sites (Figs. 3 and 4, Table 1). The Kruskall-Wallis test followed by Conover-Iman test evidenced that sites PH and D10 are significantly different from each other but not from CC (p ¼ 0.008; PH ¼ a, CC ¼ ab, D10 ¼ b). The median values of the deposition fluxes of microplastics through the year of survey were higher at D10 (i.e. 296 items m^{-2} d^{-1}) than at CC (i.e. 231 items m^{-2} d^{-1}) and PH (i.e. 172 items m^{-2} d^{-1}) (Fig. 4a). The deposition fluxes of fibers present the same patterns than microplastics: PH (i.e. 163 items m^{-2} d^{-1}) and D10 (i.e. 293 items m^{-2} d^{-1}) sites are significantly different from each other but not from CC (i.e. 230 items m^{-2} d^{-1}) (p ¼ 0.002; PH ¼ a, CC ¼ ab, D10 ¼ b) (Fig. 4b). The deposition fluxes of fragments do not vary between sites (Fig. 4c, Kruskall-Wallis test followed by Conover-Iman test, $p > 0.05$). In fact, fragments were not systematically observed and varied between 5 and 14 items m^{-2} d^{-1} (n ¼ 7 samples) at CC, 5–20 items m^{-2} d^{-1} (n ¼ 12 samples) at D10 and between 5 and 27 items m^{-2} d^{-1} (n ¼ 8 samples) at PH (Table 1).

3.1.3. Variation of morphology

Regarding the morphology of fibers, their length distributions in respect to their occurrences per sample presented for each site (Fig. 5) show close distribution in patterns through time within a site and also between sites. More precisely, the median length of fibers through the sampling period were of 840 μm at CC, 730 μm at D10, 667 μm at PH, with a minimum-maximum length observed of 301 μm and 4872 μm (Fig. 6a; Table 1). The Kruskall-Wallis test followed by Conover-Iman test on length evidenced that sites PH and D10 are not significantly different but are both significantly different from CC site (p ¼ 0.003; CC ¼ c, D10 ¼ b, PH ¼ a; Fig. 6a). Regarding the morphology of fragments, the median area of fragments in the sampling period per site were of 121,811 μm^2 at CC site, 115,642 μm^2 at D10 and 82,850 μm^2 at PH (Fig. 6b). The Kruskall-Wallis test followed by Conover-Iman test on area evidenced that the three sites PH and D10 are not significantly different (p ¼ 0.702; CC ¼ D10 ¼ PH ¼ a; Fig. 6b).

The temporal and spatial variations of microplastic's deposition fluxes and morphologies evidenced a higher deposition flux of microplastics and fibers at D10 characterized by a smallest median length and a lower deposition flux of microplastics and fibers at PH characterized by a longer median length. We assume that these spatial differences could be related to factors such as the population density, the space occupation and/or weather conditions such as rainfall and wind.

Table 1
Data of measured rainfall and deposition fluxes (items m^{-2} d^{-1}) of microplastic (MiP), fiber only and fragment only at the three sites per sampling time and of yearly median and average deposition fluxes (items m^{-2} d^{-1}) of microplastic (MiP), fiber only and fragment only.

	CC				D10				PH			
Sampling	rainfall	MiP	fiber	fragment	rainfall	MiP	fiber	fragment	rainfall	MiP	fiber	fragment
Date	mm	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$	mm	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$	mm	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$	items $m^{-2}d^{-1}$
June 14, 2018	20	82	82	0		e	e	e		e	e	e
June 25, 2018	0	95	88	7		e	e	e	0	82	82	0
July 12, 2018	36	331	331	0	8	290	280	10	10	82	82	0
July 26, 2018	0	245	197	48	35	414	394	20	43	265	265	0
August 13, 2018	50	296	290	5	22	280	280	0	0	138	122	15
August 23, 2018	48	95	95	0	12	489	489	0	58	129	115	14
September 14, 2018	0	494	494	0	4	255	255	0	42	92	87	5
September 24, 2018	65	380	380	0	62	285	285	0	20	170	170	0
October 15, 2018	0	183	178	5	20	260	250	10	48	143	143	0
October 25, 2018	0	258	245	14	93	346	326	20	15	333	306	27
November 19, 2018	9	148	148	0	6	163	153	10	0	107	107	0
November 29, 2018	0	143	143	0	2	156	149	7	4	258	258	0
December 13, 2018	0	285	280	5	24	301	296	5	0	413	413	0
December 24, 2018	0	217	217	0	0	564	557	7	0	645	645	0
January 14, 2019	0	336	331	5	0	601	586	15	0	173	168	5
January 24, 2019	0	122	122	0	0	238	238	0	0	115	109	7
February 14, 2019	0	204	194	10	0	561	550	10	0	71	71	0
February 25, 2019	8	163	163	0	0	815	815	0	0	129	129	0
March 14, 2019	0	255	250	5	0	917	917	0	13	148	148	0
March 25, 2019	0	367	367	0	2	183	170	14	0	285	285	0
April 15, 2019	28	606	606	0	2	377	367	10	0	183	178	5
April 25, 2019	0	421	421	0	0	380	380	0	2	238	238	0
May 13, 2019	0	163	163	0	0	194	189	5	3	785	785	0
May 24, 2019	0	245	245	0	24	211	211	0	8	367	367	0
June 14, 2019		e	e	e	7	290	290	0	0	173	163	10
June 25, 2019		e	e	e	0	401	401	0		e	e	e
yearly median		245	231	0		296	293	5		172	166	0
yearly average		256	251	4		374	368	6		230	226	4

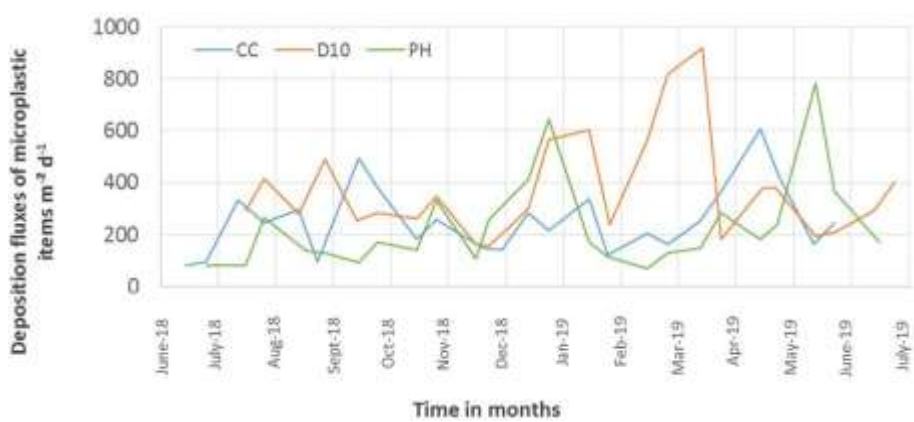

Fig. 3. Measured monthly deposition fluxes of microplastic (items m^{-2} d^{-1}) from June 2018 until July 2019 at the three sites CC, D10, PH.

3.2. *Potential influence of industrial context, population density and space occupation on deposition fluxes of microplastics*

a. Industrial context

The elevated deposition fluxes of microplastics observed in HCMC developing megacity compared to other worldwide studied cities (Paris, Donguan, Hamburg, Shanghai) (Cai et al., 2017; Dris et al, 2015, 2016; Klein and Fischer, 2019; Liu et al., 2019), could be related to the industrial context of HCMC and its high population density (i.e. 4292 inhabitants km^{-2}). Viet Nam produced in 2018 a volume of 2,825,000 tons of all kinds of textile fibers, involving 7000 enterprises in the industry and providing jobs for 3 million workers (Statistic 2020). A large majority of the textile, apparel and garment industry (e.g. 70%) is located in the South of Viet Nam, in HCMC and its surroundings provinces Binh Duong, Dong Nai and Tay Ninh. In addition to poor wastewater treatment before being discharged in the river, this industry is playing an important role in

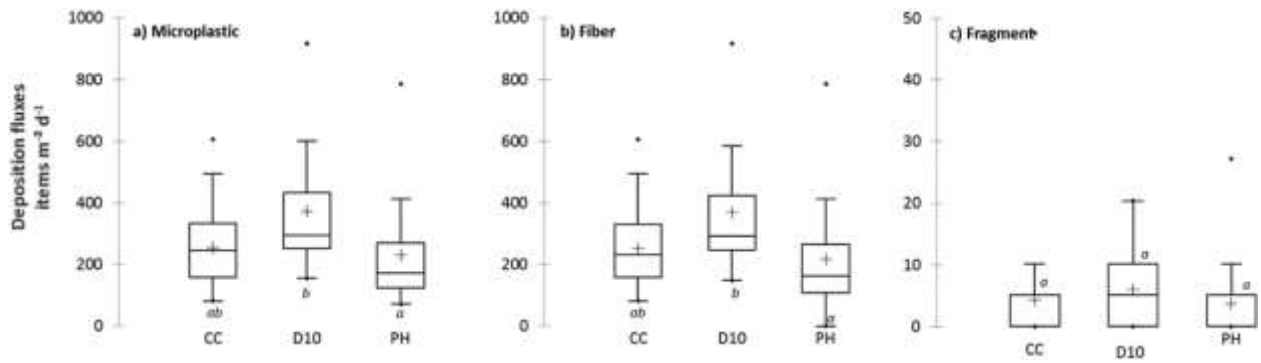

Fig. 4. Boxplot of deposition fluxes (items $m^{-2} d^{-1}$) of a) microplastic, b) fiber only and c) fragment only at the three sites CC,D10 and PH. The letters a, b,c represent the results of the Kruskall-Wallis test followed by Conover-Iman test.

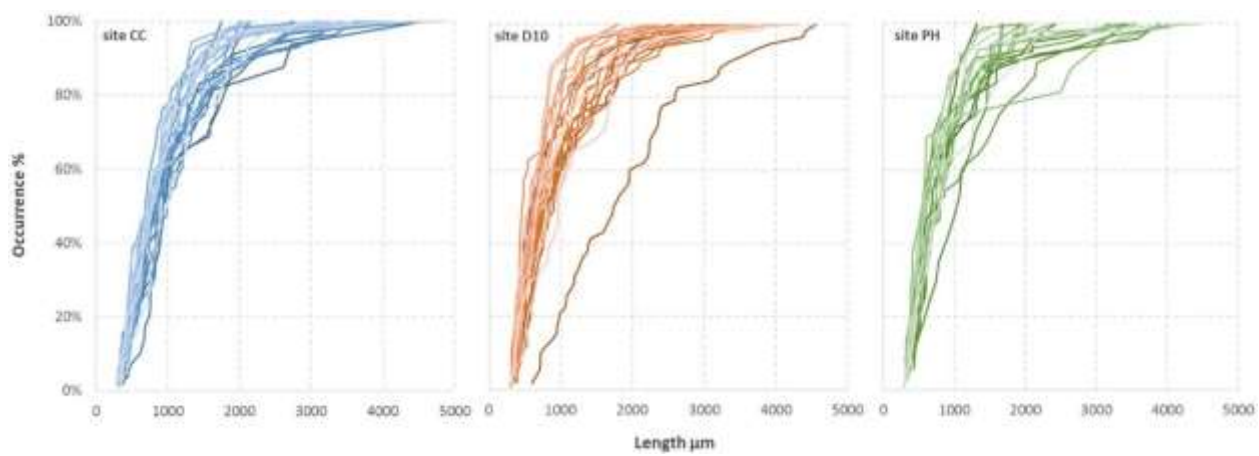

Fig. 5. Length distribution of fibers in respect to their occurrences per sample for each site over the whole sampling period.

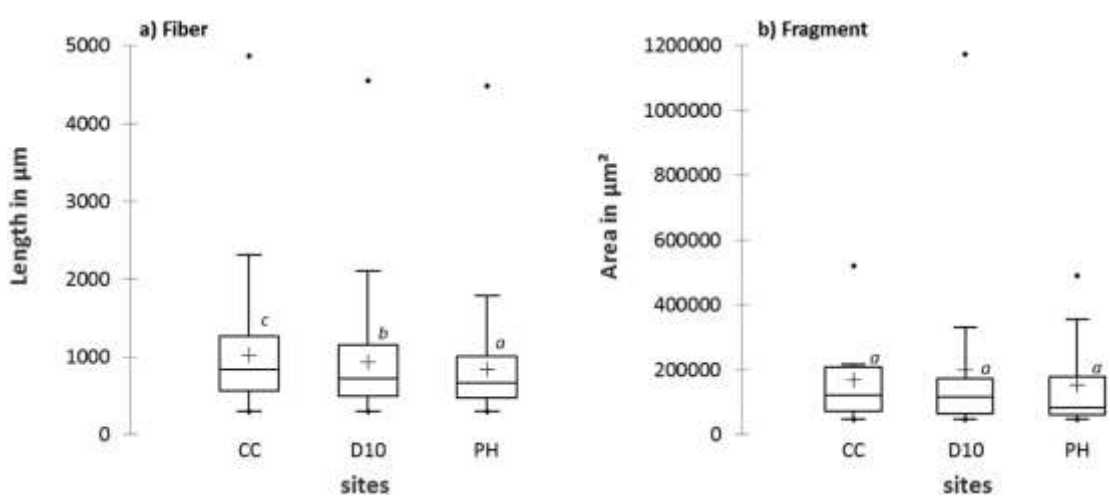

Fig. 6. Boxplot of microplastic morphology: a) length of fibers (in mm) and b) area of fragments (in mm^2) at the three sites. The letters a, b,c represent the results of the Kruskall-Wallis test followed by Conovar-Iman test.

the tremendous anthropogenic fiber-concentrations measured in the Saigon River, the river crossing HCMC and bordering those three provinces (22–251 fibers L^{-1};Strady et al., 2020b). The manufacturing processes during the textile, apparel and garment production emit anthropogenic fibers in the air, including microplastic's fibers. The overall percentage of fibers in the dry and wet fallouts represented 89%–100% of microplastics (e.g. 45 over 72 samples evidenced fibers only; Table 1), which is in agreement with the high proportion of fibers measured in the urban canals and the river crossing HCMC (Lahens et al., 2018; Strady et al., 2020b). Thus the local textile, apparel and garment industrial context may induce high levels of microplastic's deposition fluxes in HCMC.

b. Population density

In HCMC, the population density differs drastically between District 10 (i.e. 41,000 inhabitants km^{-2}; site D10) and Cu Chi district (930 inhabitants km^{-2}; sites CC and PH). A higher deposition flux measured in the denser sampling site supports the hypothesis that synthetic fibers from clothing wears or drying clothes, from indoor environment of houses and degradation of macroplastics are the main sources of microplastics to the air (Dris et al., 2016; Gasperi et al., 2018; Liu et al., 2019). In Shanghai, inhabitants's habits are to dry their clothes, bed sheets, pillows, and blankets on balconies or lines (Liu et al., 2019). With the sunlight exposure, UV irradiation can easily enhance the breakdown and degradation of the synthetic textiles into microfibers (Song et al., 2017). Same habits can be observed in Viet Nam and the high UV index recorded in tropical zone can participate and even enhance the degradation of synthetic textiles into microplastics. Population density is thus an important factor to consider when monitoring microplastic's deposition fluxes in dry and wet atmospheric fallouts.

c. Occupation space

The differences of deposition fluxes of microplastic and morphologies of fibers between CC and PH (Figs. 4a and 6a), might be linked to the space occupation and activities surrounding the sampling sites. As observed, the site CC located in a household zone presented slightly higher deposition fluxes of microplastics and longest fiber's length than at PH, located at the entrance of a waste's sorting and compost complex, a few km far from household (Figs. 4a and 6a). We can hypothesize that the activities at the waste's sorting and compost complex contribute to the emission (i) of the same quantity of fibers as the one found in a rural household area with a low density of inhabitants (i.e. 930 inhabitants km^{-2}) and (ii) of fibers which have been more fragmented, resulting in shorter fibers's length, probably due to the additional anthropogenic activities of sorting, compacting, and composting of plastic items, conducted in this area. In the dense urban area of D10, the construction's site located nearby the sampling site could also be responsible of additional emission of fibers and enhanced fiber's fragmentation, leading to shorter fiber's length compared to the rural household zone. Thus, the impact of anthropogenic activities such as landfills and construction's site is rather seen on the morphology of the fibers than on their deposition fluxes, evidencing enhanced fragmentation processes during those activities.

3.3. Influence of the tropical monsoon climate on the deposition fluxes of microplastics

In atmospheric fallouts from both urban and remote areas and from temperate region, rainfall and wind were highlighted to play a role on the microplastic deposition fluxes (Allen et al., 2019; Dris et al., 2015; Klein and Fischer, 2019; Liu et al., 2019). In Paris and Hamburg megacity, an absence of significant correlation between the levels of fibers in atmospheric fallout and the mean daily rainfall and between total fibers and cumulative rainfall were observed (Dris et al., 2016; Klein and Fischer, 2019). In Paris (Dris et al., 2016), concluded that the absence of rainfall strength may limit microplastics in atmospheric fallout but that rainfall height is a significant factor to understand microplastic fallout variability. The south of Viet Nam including HCMC is under tropical monsoon climate with two distinct seasons, dry and rainy, and two wind direction regime, NNE and SSW. Therefore, the influence of rainfall, by considering the dry and wet fallouts separately, on microplastic's deposition fluxes was investigated. The deposition fluxes of microplastics did not differ between the dry and the rainy seasons (Fig. 7), when all sites are considered together (Mann-Whitney test, $p = 0.852$), at CC site (Mann-Whitney test, $p = 0.893$) and at PH site (Mann-Whitney test, $p = 0.510$). Only at D10 site higher deposition fluxes of microplastics were measured during the dry season (Mann-Whitney test, $p = 0.014$).

The influence of wind on microplastic deposition fluxes was observed in Hamburg city, especially the dominant wind direction, the wind speed and storm events (Klein and Fischer, 2019). The influence of wind regime considering both the dominant wind direction and the mean wind speed was thus investigated in this study. At first, the deposition fluxes of microplastic were considered according to the two main wind directions observed in HCMC during the survey: NNE and SSW. The deposition fluxes of microplastics did not differ between the two wind directions (Fig. 7b), when all sites are considered together (Mann-Whitney test, $p = 0.34$) or even at each site (Mann-Whitney test, $p = 0.355$, $p = 0.549$, $p = 0.564$ for CC, D10 and PH). The mean wind speed was also not correlated to the deposition fluxes estimated at the three sites, for a wind duration equivalent to the sampling period (i.e. 3 or 4 days) or for a duration of seven days prior to the sampling (Pearson correlation, $p > 0.1$ for all).

Thus, the tropical wind and rainfall regime and their intensity do not seem to influence the deposition fluxes of microplastics in atmospheric fallouts. The scavenging of microplastics during precipitation event is not a major process controlling the deposition fluxes of microplastics in this tropical area. However, we point out

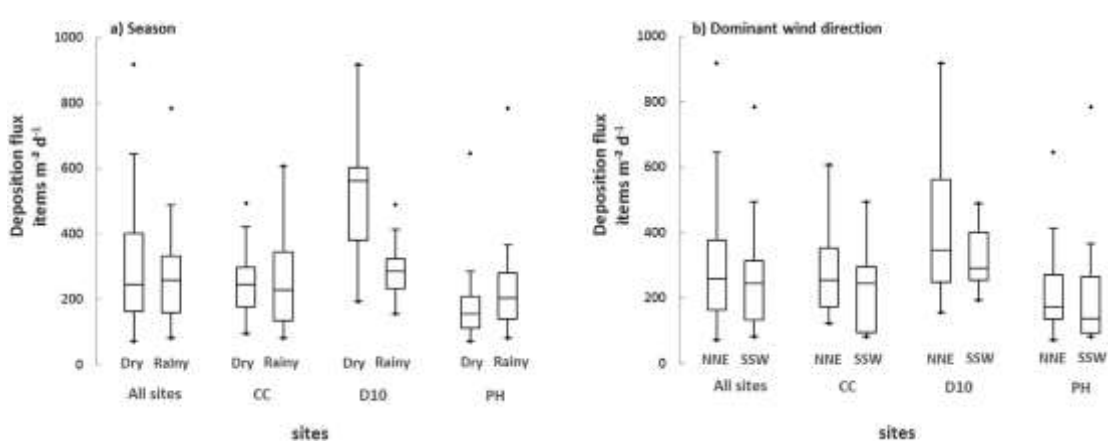

Fig. 7. Boxplot of microplastic deposition fluxes a) between dry and wet seasons and b) between NNE and SSW dominant wind conditions at all sites, CC site, D10 site and PH site.

that all the studies which evidenced positive effect of wind and rainfall on deposition fluxes have considered a lower size limit of observation of 50 mm and not of 300 mm. We thus hypothesize that the scavenging effect of microplastics by precipitation and the influences of wind and precipitation could be size dependent. In all studied sites, the median length of fibers were significantly longer during SSW dominant wind compared to during NNE dominant wind direction (Mann-Whitney test, $p = 0.096$ at CC, $p = 0.021$ at D10 and $p = 0.064$ at PH). We recommend thus in further investigation to consider the wind, and rainfall, on the microplastic deposition fluxes by class sizes.

4. Conclusions

Microplastics in atmospheric fallouts from developing Southeast Asian megacity under tropical environment present higher deposition fluxes than atmospheric fallouts from temperate and developed countries, despite a narrower size range of observation, especially on the lower size where they are the most abundant. The annual deposition fluxes pattern was different than expected and neither rainfall nor wind intensity and direction influence the deposition fluxes. The deposition flux appeared more related to population density and space occupation. A parameter poorly exploited so far, the morphology of plastics, showed interesting variation among sites and might evidence *in-situ* fragmentation processes or meteorological processes; this observation should be further investigated in future studies.

Credit author statement

Tran-Nguyen-Sang Truong: Investigation; Writing - Original Draft; Writing - Review & Editing. Emilie Strady: Conceptualization; Supervision; Writing - Original Draft; Writing - Review & Editing. Thuy-Chung Kieu-Le: Conceptualization; Supervision; Writing - Review & Editing. Quoc-Viet Tran: Investigation; Writing - Review & Editing. Thi-Minh-Tam Le: Investigation; Writing - Review & Editing. Quoc-Thinh Thuong: Investigation; Writing - Review & Editing.

Declaration of competing interest

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.

Acknowledgements

This study has been conducted under the framework of CARE-RESCIF initiative and under the JEAI PLASTIC research team funded by IRD. This study was funded by Ho Chi Minh City University of Technology - VNU-HCM under grant number Tc-ĐCDK-2018-01.

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