

# Assessment of Indoor Air Pollution through Fine Particle Capturing Potential and Accumulation on Plant Foliage in Delhi, India

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## ABSTRACT

The dry deposition of PM on foliage of indoor plants in the households of Delhi has been reported in this study. It was observed that dustfall fluxes were higher at the industrial site (MH) as compared to the residential site (DH). Seasonal variations in dust deposition indicated that it was highest in the winter season and lowest in the monsoon season. Chemical profiling of the deposited dust marked that dust was less basic at MH as compared to DH and  $\text{Ca}^{2+}$  was ubiquitously the most abundant cation at both sites whereas  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  were the most abundant anions at DH and MH, respectively. Abundance of  $\text{K}^+$ ,  $\text{NO}_3^-$  and  $\text{NH}_4^+$  etc. indicated the influence of anthropogenic activities. The number of PM deposited on the foliar surfaces of indoor plants was also estimated and divided into  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  based on their size because particle count is more appropriate than particle mass for estimation of finer PM. PM accumulation on the foliar surfaces of selected plants for the present study followed the order,  $\text{PM}_{10} > \text{PM}_{2.5} > \text{PM}_{10}$  at both the sites. The foliar micromorphology of abaxial surfaces of the plants accounted for significant interspecies variability due to difference in presence of grooves and undulations, high stomatal density, epicuticular wax etc. Leaves with densely arranged grooves and ridges showed more PM accumulation. Investigation of plants with respect to dust deposition and selection of species which can perform the dual functions of improving air quality and providing aesthetic value are needed for understanding the role of vegetation in air pollution mitigation approaches in real life environment.

**Keywords:** Air Pollution, PM deposition, Foliar micromorphology, Dry deposition of dust

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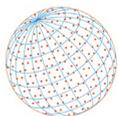
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## 1 INTRODUCTION

Dry deposition can be defined as “transport of particulate contaminants from the atmosphere onto surfaces in the absence of precipitation” (Davidson and Wu, 1990). It is the process by which atmospheric constituents are transferred by air motions to the natural surfaces like vegetation (Wesely and Hicks, 2000), which is significant especially, in the regions where dry weather conditions prevail. In India, dust derived from the soil is rich in  $\text{CaCO}_3$  due to which dust effectively scavenges atmospheric  $\text{SO}_2$  and forms  $\text{CaSO}_4$  which is also removed from the ambient air through dustfall (Kulshrestha et al., 2003; Kulshrestha, 2013). The occurrence of dust is influenced by many parameters such as wind velocity, moisture in soil, vegetation cover, rainfall etc. and apart from naturally originating dust in the atmosphere, anthropogenic sources which generate pollution such as fossil fuel and biomass burning, building construction, industrial activities, resuspension of dust, transportation, cooking, also contribute to overall dust abundance worldwide. The dust particles can be released directly as primary or formed through gas-to-particle conversion as secondary emissions in air. Mineral dust gets transported to distant places across the world through high speed winds after its generation in dry and arid regions (Asia and Africa) where it is considered as one of the key air pollutants (Tegen and Fung, 1995). Emissions may also occur from multiple internal sources such as consumer products, routine movement, smoking, cooking,

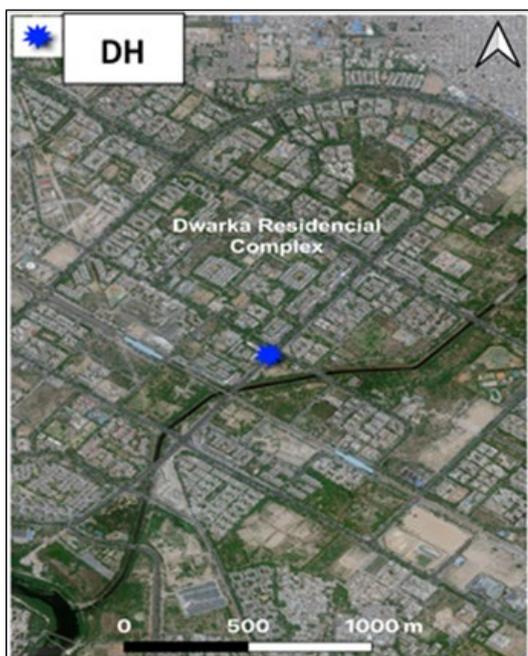
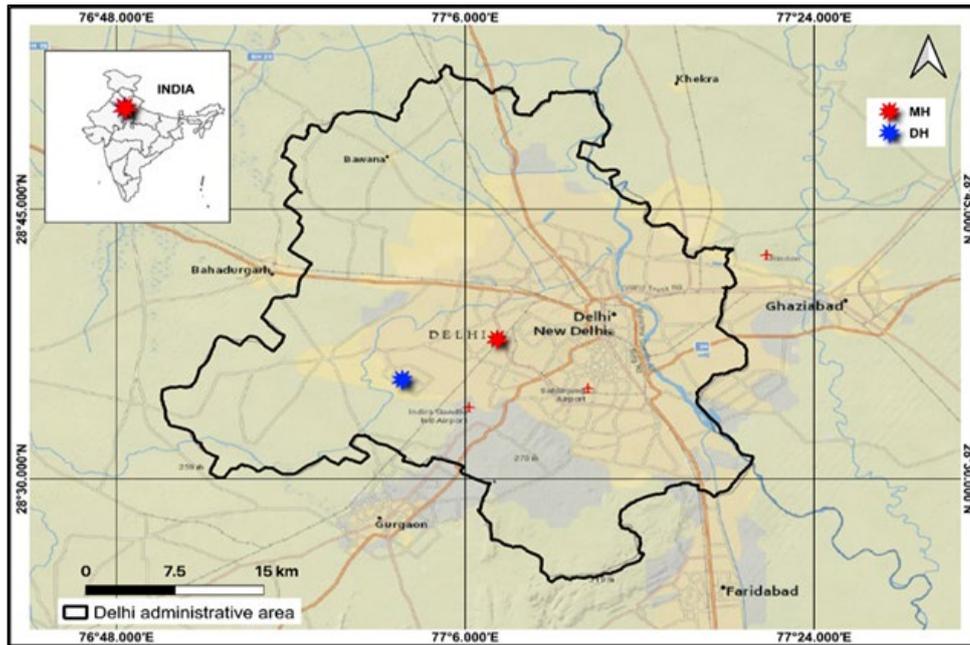
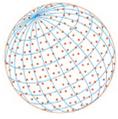


incense burning, pets, furniture and building materials as well as entry from outdoor environment through infiltration (Hsieh *et al.*, 2011; Saraga *et al.*, 2017; Turner and Simmonds, 2006). Due to increase in urbanization, a large number of individuals spend maximum daily time in the indoor environment which makes indoor airborne particulate matter (PM) a serious health concern for the population. Various hazardous air pollutants (including heavy metals) get accumulated in the indoor environment via their deposition in indoor dust and hence, dust is a major pathway of human exposure to toxic PM which is harmful to health. PM can be categorized based on aerodynamic size for classification: coarse PM/PM<sub>10</sub> (size  $\leq 10 \mu\text{m}$ ), fine PM/PM<sub>2.5</sub> (size  $\leq 2.5 \mu\text{m}$ ) and ultrafine PM/PM<sub>0.1</sub> (size  $\leq 0.1 \mu\text{m}$ ) (Chow *et al.*, 2006). The size of the PM bears a direct relation to the health impacts in humans due to their inhalation, deposition, and toxicity. Coarse PM can reach the thoracic part of the lower respiratory tract, following which they get deposited in bronchioles (Kelly and Fussell, 2012). Fine PM, also called as respirable PM, can reach further down in thinner spaces due to their finer size and enter the alveoli and terminal bronchioles. Ultrafine PM are most dangerous because they can enter systemic circulation by crossing air-blood barrier through the alveoli in respiratory system. Usually, PM of size  $> 10 \mu\text{m}$  with an ability to settle down from air via sedimentation process under gravitational force is considered as the main component of dustfall (Alahmr *et al.*, 2012; Espinosa *et al.*, 2001). These coarse PM are often associated with natural sources whereas the fine PM are emitted from anthropogenic activities (Espinosa *et al.*, 2001). Fine PM is generally formed by secondary processes inside the households depending on the emissions generated from indoor sources, the outdoor concentrations of PM, air exchange rate and depositional characteristics of the PM (Buczyńska *et al.*, 2014; Gemenetzi *et al.*, 2006). Urban PM is a cocktail of anthropogenic ions such as  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{SO}_4^{2-}$  and heavy metals which constitute 25%–50% of the total mass of PM (Gray *et al.*, 1986; Shrestha *et al.*, 2010). Mitigation approaches such as curtailing source emissions and setting up heavy pollutant sources at a considerable distance from existing pollution hotspots or inhabited localities were being considered to fight PM pollution across the world (Pugh *et al.*, 2012). Widespread greenery and tree plantations are key players in the improvement of air quality in urban settlements, as they absorb and metabolize various gases and PM (Woo and Je, 2006). Plants are known to function as a platform for dust capture and they act as a sink for air pollutants by absorbing and detoxifying the commonly abundant air pollutants (Ninave *et al.*, 2001). PM dry deposition was examined on different materials and it was observed that vegetation was better at capturing PM as compared to smoother building surfaces in this respect (Roupsard *et al.*, 2013). The fine PM ubiquitously found in dust gets deposited on various interior surfaces through diffusion and impaction (Gemenetzi *et al.*, 2006), including plant foliage which act as receptors for the depositions from ambient air (Barwise and Kumar, 2020; Gupta *et al.*, 2015a; Weerakkody, 2018). Hence, the dry deposition of fine and coarse PM on the foliar surfaces of indoor plants in this study is termed as dustfall. The average deposition fluxes of major cations and anions in the dustfall have been reported and the  $\Sigma^-/\Sigma^+$  ratios of the ions in the dustfall flux (DF) were calculated. The SEM micrographs of the particulate matter deposited on the foliar surfaces were analyzed for particle distribution of smaller PM (PM<sub>1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub>) using ImageJ software and to determine the variations in PM capture potential of the selected species of plants. Interactions between PM and plant surfaces determine the ability of leaves to capture and retain PM and these interactions are based on several factors including surface morphology of the leaf and its geometrical properties such as size, shape, and orientation, which vary among plants.

## 2 METHODOLOGY

### 2.1 Site Description

For this study, two characteristically different households, MH (Mayapuri Household) and DH (Dwarka Household), were selected in the megacity Delhi (India). These urban households were situated in localities with significantly different land use pattern. DH was located in the Dwarka region which had residential characteristics whereas MH was situated in Mayapuri region bearing commercial and industrial characteristics. Fig. 1 shows the geographic representations of MH and DH sampling sites in Delhi (India). Both the households were naturally ventilated which implies that the outdoor environment directly influenced the indoor air. A more elaborate account of the

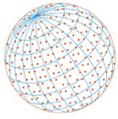


**Fig. 1.** Site map showing DH and MH sites in Delhi (India).

selected sites has been provided elsewhere (Katoch and Kulshrestha, 2020, 2021). Fully grown potted plants of *Ficus elastic* (FE), *Ficus lyrata* (FL) and *Schefflera arboricola* (SA) were placed in both households for experimental purpose. Similar conditions were ensured with respect to watering, natural ventilation through doors and windows, temperature, light and other routine influences by the inhabitants. During the exposure periods, plants were minimally disturbed in order to observe least disturbances with regard to particle deposition on leaf surfaces.

## 2.2 Sample Collection and Calculation of Dustfall Fluxes on Indoor Plants

The dustfall on the foliar surfaces was collected from July 2017 to June 2019 in all the seasons following an exposure of 10 days each time for the indoor plants viz. *Ficus elastica*, *Ficus lyrata*



and *Schefflera arboricola* in this study. Fully expanded and mature leaves, which were free from any defects, were selected, tagged, and properly washed to ensure cleaning with distilled-deionized water. After an exposure of 10 days, every time the leaves were collected and washed using surface washing method to obtain the extract of deposited dust (Davidson and Wu, 1990). The calculation of dustfall fluxes (DF) was done gravimetrically (Gupta *et al.*, 2015b). Collected leaves were gently immersed and intermittently shaken almost for 20 minutes in distilled deionized water in a preweighed petri dish ( $m_1$ ) to ensure leaching out of deposited dust from the leaf surfaces. The leaf specimen was carefully removed from the solution to prevent any kind of damage to the leaf tissue. Then, the petri dish was mounted on a hot plate where it was kept for about 25 minutes at 110°C until the water in the petridish evaporated. The petri dish was then allowed to cool down and weighed again ( $m_2$ ). Using the following equation the dustfall fluxes were estimated:

$$DF = (m_2 - m_1)/AD \quad (1)$$

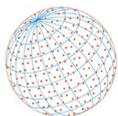
where, DF represents dustfall flux ( $\text{mg m}^{-2} \text{d}^{-1}$ ), petri dish initial weight is given by  $m_1$ , petri dish final weight is given by  $m_2$ , surface area of the leaf is given by A, and D is the number of days.

### 2.3 Ion Chromatography

Aqueous extract of the dustfall obtained from foliar surfaces were examined for their ionic composition using Ion Chromatography (Metrohm 883 Basic IC Plus). The aqueous extract of the dustfall was prepared by plucking the tagged leaves after 10 days and carefully washing with 50 mL distilled deionized water using the method given by Gupta *et al.* (2016). As control, the aqueous extracts of the clean leaves having no dust deposition were treated as blanks following the identical extraction procedure. Chemical analysis of the aqueous extracts of the blanks showed peak areas below detection limits for the anions and cations. Similarly, the blanks of petriplates used for the extraction process were also taken to ascertain the quality of sampling and analysis for extraction procedure following the method given elsewhere (Gupta *et al.*, 2016). The results showed peak areas below detection limit for the analyzed cations and anions which indicated negligible interference from tissue sap or the plates used in the experiment. For determination of major cations, a cation column (Metrosep A SUPP4, 250/4.0) and a solution containing 1.8 mmol L<sup>-1</sup> Na<sub>2</sub>CO<sub>3</sub> and 1.7 mmol L<sup>-1</sup> NaHCO<sub>3</sub> was used as eluent. On the other hand, anion column (Metrosep C4-100/4.0) was used to estimate anions with a solution of composition 0.7 mmol L<sup>-1</sup> dipicolinic acid and 1.7 mmol L<sup>-1</sup> nitric acid as eluent. MERCK certified standards of 1, 2, 5 and 10 ppm were used to obtain the standard calibration curve for cations and anions. Calibration equations with correlation coefficient values ( $r^2$ ) for major cations and anions were analyzed. At the time of fresh eluent preparation, the calibration curve was plotted again and quality of the analysis was ensured by repeating the examination of standard values frequently.

### 2.4 Foliar Surface Morphology Analysis

The leaf sections of 1.0 × 1.0 mm<sup>2</sup> in size were cut from the leaf blades of all the plant species. Three sections each of adaxial and abaxial leaf surfaces were prepared for every plant at both DH and MH sites. Leaf sections were studied using scanning electron microscope (Carl Zeiss EVO 40, Germany) at the Advance Instrumentation Research Facility (AIRF), JNU. The leaf sections were prepared to be studied by fixing them in 2.5% glutaraldehyde (prepared in phosphate buffer of pH 7.2). Successive dehydrations were carried out (two times) in 50, 70, 90 and 100% ethanol and the leaf sections were then placed in hexamethyldisilazane (HMDS) for 5 minutes. Every sample was mounted on aluminum stubs (held by carbon tape) and left for drying overnight in the presence of CO<sub>2</sub> in a critical point dryer. After drying, the samples were sputter-coated (Sputter coater-Polaron SC7640) and were ready to be observed. Subsequently, scanning electron micrographs of the adaxial and abaxial leaf surfaces were obtained. The number of PM belonging to different categories such as PM<sub>10</sub>, PM<sub>2.5</sub> and PM<sub>1</sub> were quantified using ImageJ analysis software (Ottelé *et al.*, 2010; Perini *et al.*, 2017; Weerakkody *et al.*, 2017). The surface morphology of foliar surfaces was studied at 250×, 500× and 1000× magnifications as appropriate. The micromorphological characteristics such as stomatal density, trichomes and hair were observed at 250× and 500× and the PM number fluxes were quantified at 500× and 1000× magnifications. The contrast and



brightness levels of micrographs were kept consistent as much as feasible to avoid any issues in defining the threshold for image analysis by using auto-threshold tool which helps to avoid user biased error. The fittest threshold was chosen for image analysis process from the montage having multiple micrographs which ensured that only the PM were filtered without the leaf surfaces. The average PM number flux (per 1 mm<sup>2</sup>) on adaxial and abaxial sides of every leaf was calculated using the micrographs. The overall PM number flux on the foliar surfaces per 1 mm<sup>2</sup> was calculated by combining the PM number fluxes obtained on adaxial and abaxial surfaces.

### 3 RESULTS AND DISCUSSION

The assessment of fine PM captured by *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* (using SEM technique) showed interesting outcomes which were associated with the complex micromorphology of the foliar surfaces of the investigated plants. The following sections describe the statistically significant variations in the indoor dustfall fluxes and the contributions of major ions in the dry deposition of dust in detail.

#### 3.1 Variations in Dustfall Fluxes

The average indoor dustfall fluxes on *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* foliar were compared. The results showed that the dustfall flux was significantly higher ( $p < 0.05$ ) at MH site than DH site for all three plant species. The dustfall flux at MH site was higher (Fig. 2) due to the contribution from various sources. Apart from indoor sources; resuspended road dust, industrial emissions, construction activities, vehicular emissions are quite prevalent in the outdoor surroundings of MH site. The Indo-Gangetic plain is known to have high loadings of atmospheric dust from natural sources such as earth's crust (Sharma and Kulshrestha, 2018). Dust enters the indoor spaces through ventilation and infiltration of outdoor air. The frequent movement of occupants into the household also brings in the outdoor dust (Gemenetzi et al., 2006; Zhong et al., 2014). The interspecies variation between the studied plant species for dustfall flux was statistically analyzed at the two sites which indicated that at DH site ( $F = 4.08$ ,  $p = 0.02$ ), the dustfall flux on *Ficus elastica* foliar surfaces was significantly higher than *Schefflera arboricola* foliar surfaces ( $p = 0.01$ ). Similarly, at MH site also ( $F = 3.52$ ,  $p = 0.04$ ), the dustfall flux between *Ficus elastica* and *Schefflera arboricola* was significantly different foliar surfaces ( $p = 0.04$ ). Table 1 presents the H<sup>+</sup> fluxes (mol m<sup>-2</sup> d<sup>-1</sup>) of the dustfall on all the plants which indicated that the deposited dust at MH site was slightly more acidic than DH site. Ca<sup>2+</sup> (mg m<sup>-2</sup> d<sup>-1</sup>), the most dominant ion in the dustfall flux deposited at both the sites, reflected the natural sources of dustfall. The dustfall flux of SO<sub>4</sub><sup>2-</sup> was different from other ions such that only SO<sub>4</sub><sup>2-</sup> was significantly higher ( $p < 0.05$ ) at MH site than DH site for all the plants. The equivalent dustfall fluxes of ions (meq m<sup>-2</sup> d<sup>-1</sup>) were calculated to assess the ionic contributions in dustfall. It was observed that

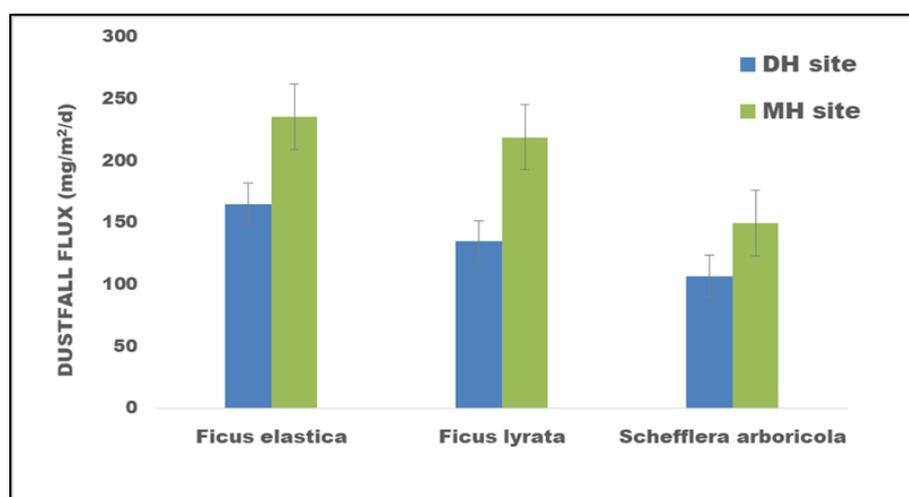
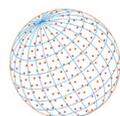


Fig. 2. Average indoor dustfall fluxes on the plants at DH and MH sites.



**Table 1.** Average fluxes of the indoor dustfall ( $\text{mg m}^{-2} \text{d}^{-1}$ ),  $\text{H}^+$  ( $\text{mol m}^{-2} \text{d}^{-1}$ ) and the major ions ( $\text{mg m}^{-2} \text{d}^{-1}$ ) on *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* foliar surfaces at DH and MH sites.

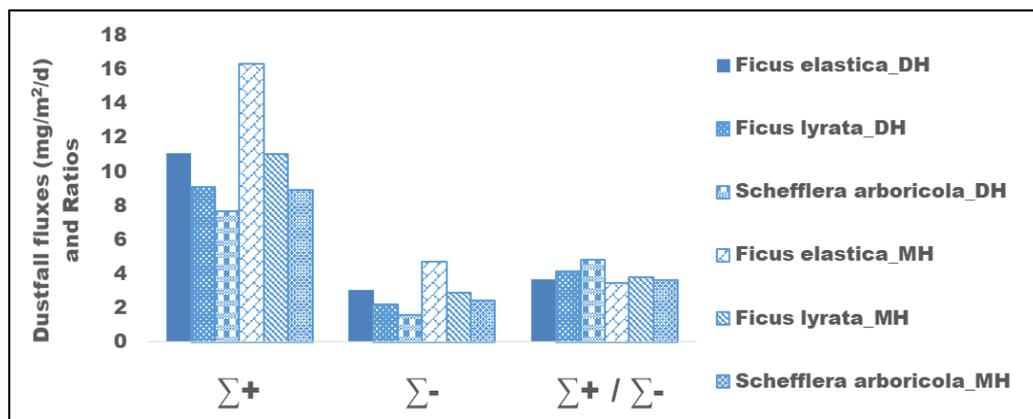
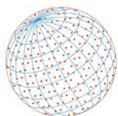
Parameters	DH SITE			MH SITE		
	<i>Ficus lyrata</i>	<i>Ficus elastica</i>	<i>Schefflera arboricola</i>	<i>Ficus lyrata</i>	<i>Ficus elastica</i>	<i>Schefflera arboricola</i>
Dustfall	134.7 ± 34	165.5 ± 37.8	106.6 ± 31.8	218.9 ± 39.2	235.5 ± 41.4	149.6 ± 36.2
$\text{H}^+$	$5.2 \times 10^{-8}$	$1.8 \times 10^{-8}$	$1.7 \times 10^{-7}$	$8.5 \times 10^{-8}$	$2.6 \times 10^{-8}$	$2.7 \times 10^{-7}$
$\text{Na}^+$	1.11 ± 0.36	1.19 ± 0.54	1.04 ± 0.41	1.54 ± 0.31	1.60 ± 0.26	1.30 ± 0.43
$\text{NH}_4^+$	0.22 ± 0.10	0.34 ± 0.12	0.09 ± 0.03	0.25 ± 0.08	0.42 ± 0.11	0.12 ± 0.04
$\text{K}^+$	1.51 ± 0.96	3.2 ± 0.62	0.68 ± 0.24	1.92 ± 0.64	3.59 ± 0.61	0.89 ± 0.25
$\text{Ca}^{2+}$	5.72 ± 2.61	7.09 ± 2.62	5.49 ± 2.63	6.6 ± 2.13	9.08 ± 2.56	6.26 ± 2.16
$\text{Mg}^{2+}$	0.54 ± 0.27	1.44 ± 0.52	0.33 ± 0.14	0.69 ± 0.15	1.63 ± 0.54	0.37 ± 0.11
$\text{F}^-$	0.21 ± 0.08	0.32 ± 0.11	0.22 ± 0.10	0.22 ± 0.09	0.35 ± 0.17	0.23 ± 0.12
$\text{Cl}^-$	1.00 ± 0.47	1.44 ± 0.54	0.58 ± 0.11	0.83 ± 0.30	0.99 ± 0.23	0.51 ± 0.08
$\text{NO}_3^-$	0.36 ± 0.14	0.44 ± 0.21	0.26 ± 0.13	0.51 ± 0.23	0.60 ± 0.28	0.33 ± 0.18
$\text{SO}_4^{2-}$	0.60 ± 0.22	0.84 ± 0.19	0.50 ± 0.19	1.35 ± 0.84*	2.78 ± 0.75*	1.36 ± 0.89*

\* At  $p < 0.05$ .

**Table 2.** Comparison of dustfall fluxes on the foliar surfaces of plants at different sites.

References	Type of Locality	Foliar Surfaces	Dustfall flux ( $\text{mg m}^{-2} \text{d}^{-1}$ )	Country
(Prusty et al., 2005)	Urban	<i>P. pinnata</i> <i>T. divaricota</i> <i>I. carnaea</i>	100 220 180	India
(Wang and Li, 2006)	Urban	<i>E. japonicus</i>	774	China
(Prajapati and Tripathi, 2008)	Urban	<i>D. sissoo</i> <i>M. indica</i> <i>F. benghalensis</i> <i>F. religiosa</i>	100–500	India
(Gupta et al., 2015b, 2015a)	Urban	<i>M. alba</i> <i>T. arjuna</i>	108–271 95–229	India
(Sarma et al., 2017)	Urban	<i>C. tora</i> <i>C. sofera</i>	143–214 115–179	India
Present study	Urban (Indoor)	<i>F. elastica</i> <i>F. lyrata</i> <i>S. arboricola</i>	165–236 135–219 107–150	India

the cationic species exerted more influence than the anionic species. The percentage contribution of major ions in the average equivalent dustfall flux also corroborated the significant variation in  $\text{SO}_4^{2-}$  flux at the two sites.  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  contributed more than 80% of the major ions in the average dustfall flux on the foliar surfaces at the MH and DH sites. *Ficus elastica* and *Ficus lyrata* have leathery leaves that are alternately arranged on the stem with small petioles that favor dust deposition whereas, in the palmately compound leaves of *Schefflera arboricola*, the leaflets have long petioles. However, the micromorphology of the foliar surfaces plays a distinct role in size specific PM accumulation which has been discussed in the later sections. Table 2 shows the comparison of dustfall fluxes on foliar surfaces at different sites that have been reported in other studies. It was observed that the dustfall fluxes on indoor plants in the present study were obtained in a similar range as these studies which were usually conducted on outdoor vegetation. Therefore, it could be concluded that the dustfall flux was greatly influenced by ambient outdoor conditions near the households that are quite dusty. However, there are significant differences in the outdoor and indoor conditions per se which affect the deposition of PM on the foliage. Wind speed is one such factor which specifically influences PM deposition in the outdoor atmosphere. It has been reported that deposition of coarse PM is more at high wind speed whereas, deposition of fine PM is low (Janhäll, 2015). Similarly, precipitation can wash off the deposited coarse PM



**Fig. 3.** Dustfall fluxes ( $\text{mg m}^{-2} \text{d}^{-1}$ ) and ratios of  $(\text{Na}^+ + \text{NH}_4^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})/(\text{F}^- + \text{Cl}^- + \text{SO}_4^{2-} + \text{NO}_3^-)$  taking  $\text{mg m}^{-2} \text{d}^{-1}$  fluxes on the foliar surfaces of *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* at DH and MH sites.

on the foliar surfaces more readily. When PM is embedded in the leaf wax, its resuspension by wind or rain is comparatively less which is relevant in the case of indoor plants in the present study (Dzierzanowski *et al.*, 2011).

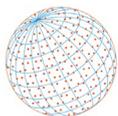
In order to find the balance between the cationic and anionic components in the average dustfall flux deposited on the plant foliar surfaces,  $\Sigma^+ / \Sigma^-$  ratios  $(\text{Na} + \text{NH}_4^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})/(\text{F}^- + \text{Cl}^- + \text{SO}_4^{2-} + \text{NO}_3^-)$  were calculated at DH and MH sites (Fig. 3). The  $\Sigma^+ / \Sigma^-$  ratios were slightly lesser at MH site as compared to DH site which indicated presence of more anionic species in the dustfall flux at MH site. The dustfall deposited on the foliar surfaces at DH site had lesser flux of anionic species which corroborates the average pH values of the aqueous extract of dustfall (Table 1) that were recorded as  $\text{pH} > 7$  for all the plants and were higher than the corresponding values at MH site. Higher dustfall flux of anions at MH site led to a lower pH value of the deposited dustfall which could pose a risk to plant health due to its relatively more acidic nature.

### 3.2 Assessment of PM Capture Potential of Indoor Plants Using SEM Technique

The PM capturing potential of selected indoor household plants such as *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* in the urban households of Delhi (India) has compared and discussed in this section. PM accumulation ( $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ) on the foliar surfaces was quantified to determine the particle size distribution using Scanning Electron Microscope (SEM) and ImageJ software as similar procedures have been followed earlier (Ottel  *et al.*, 2010; Perini *et al.*, 2017; Weerakkody *et al.*, 2018a). Plant species with complex foliar micromorphology such as the presence of hair, trichomes, epicuticular wax, high proportion of grooves, stomatal density etc. on the surface are reported to be more efficient at capturing PM in urban areas (Liang *et al.*, 2016; Weerakkody *et al.*, 2018a). In case of dry deposition of PM, the process usually occurs via sedimentation under the effect of gravity and diffusion. However, weak electrostatic forces between PM and vegetation surfaces may also exist (Ha *et al.*, 2021). In fact, the electrostatic forces affect the particle adhesion and detachment on available surfaces. The electrostatic forces between heavy metal ions in PM and leaf blade have been described in literature (Gawrońska and Bakera, 2015). The airborne PM is weakly charged due to thermal fluctuations of electrostatic energy. Hair-like objects on the leaf could serve as a sharp pin where the electric charge is concentrated at the very top of the pin. The plants in this study lacked hair like structures but these type of intermolecular forces arising between the structure of the leaf and the deposited material could be of tremendous interest in future.

### 3.3 Interspecies Variability in PM Accumulation

The SEM micrographs were used to estimate the number of PM deposited on the foliar surfaces of the plants which were divided into three categories based on their size such as  $\text{PM}_{10}$ ,

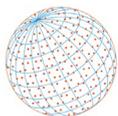


PM<sub>2.5</sub> and PM<sub>10</sub>. The number of PM deposited on per unit area of the foliar surfaces and the micromorphological characteristics such as stomatal density, grooves, epidermal hair, trichomes etc. were ascertained using the surface images of the plant leaves. It has been reported that particle count is more appropriate than particle mass (such as the gravimetric method used earlier) for reporting the smaller PM (Sager and Castranova, 2009; Weerakkody et al., 2017) and hence, PM number flux (number of PM present on 1 mm<sup>2</sup> of the foliar surfaces) has been used to calculate PM accumulation on the foliar surfaces of indoor plants for this part of the present study. Table 3 shows the mean PM number flux on the foliar surfaces of the selected plant species at MH and DH sites and the interspecies variation in PM accumulation. It has been established in previous studies that the relationship between indoor and outdoor airborne PM concentrations significantly influences their accumulation in the indoor environment (Chithra and Shiva Nagendra, 2012; He et al., 2004; Morawska et al., 2001). Secondary PM may drift from outdoor surroundings or it may also be formed as a result of chemical conversions occurring from indoor precursors (Katoch and Kulshrestha, 2021; Zhang et al., 2021). Apart from natural and anthropogenic outdoor sources, the increase in indoor PM has been specifically attributed to indoor activities such as smoking, candle burning, grilling, frying and stove use (He et al., 2004). The deposition rate of PM in the indoor environment is influenced by friction velocity, air exchange rate and gravitational settling (Liu et al., 2018). The order of the accumulation of the PMs on the leaf surface is related with their relative concentrations in the indoor, and possibly, in the outdoor air. The mean PM accumulation followed the order, PM<sub>1</sub> > PM<sub>2.5</sub> > PM<sub>10</sub> for the plants at both the sites. PM number flux was higher at MH site as compared to DH site for PM<sub>1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> but this increase was observed to be statistically insignificant ( $p > 0.05$ ) for all the plants. *Ficus elastica* apparently showed higher PM accumulation as compared to *Ficus lyrata* and *Schefflera arboricola* at both the sites. The indoor PM is influenced by complex physical mechanisms near the surface during deposition (Nazaroff, 2004). For example the resuspended PM in indoor air is known to be influenced by electrostatic forces induced by human body voltage during walking (Malekian et al., 2018). In case of plants also, the electrostatic forces between PM and leaf have been reported (Gawrońska and Bakera, 2015). In indoor deposition, advection transports the PM from core air to the boundary layer which is in close proximity to the surface. Transfer of particle from boundary layer to the surface regulates deposition of PM. For fine PM, Brownian diffusion serves as the major deposition mechanism on the foliar surfaces whereas impaction and gravitational settling are applicable for coarse PM. The PM could have experienced more friction during transportation and diffusion on the *Ficus elastica* foliar surfaces which augmented PM deposition as compared to other plants. Statistical analysis was employed to observe significant differences between the plant species, if present, for PM number flux. The assessment of interspecies variability between the plants showed significant difference in PM<sub>1</sub> accumulation for the plant species. There was statistically significant difference between *Ficus elastica* and *Ficus lyrata* ( $p = 0.032$  and  $p = 0.030$  at MH and DH sites, respectively) and between *Ficus elastica* and *Schefflera arboricola* ( $p = 0.041$  and  $p = 0.045$  at MH and DH sites, respectively), such that *Ficus elastica* showed higher PM<sub>1</sub> accumulation per mm<sup>2</sup> on its foliar surfaces as compared to *Ficus lyrata* and *Schefflera arboricola*. Variation in PM<sub>2.5</sub> number flux was evident for the plants as the PM<sub>2.5</sub> accumulation per mm<sup>2</sup> on *Ficus elastica* foliar surfaces was significantly higher than *Ficus lyrata* ( $p = 0.030$  and  $p = 0.048$  at MH and DH sites, respectively). However, similar statistically important inter-species difference was not observed for PM<sub>10</sub> capture ( $p > 0.05$ ) the plants at the two sites.

**Table 3.** Average PM number flux (mm<sup>-2</sup>) on the foliar surfaces of the plant species.

PM category	MH site			DH site		
	<i>Ficus elastica</i>	<i>Ficus lyrata</i>	<i>Schefflera arboricola</i>	<i>Ficus elastica</i>	<i>Ficus lyrata</i>	<i>Schefflera arboricola</i>
PM <sub>1</sub> number flux × 10 <sup>3</sup> (mm <sup>-2</sup> )	86.8 <sup>a</sup> ± 24	47.8 <sup>bc</sup> ± 9.5	50.9 <sup>bc</sup> ± 12.3	68.9 <sup>ab</sup> ± 17.4	29.9 <sup>c</sup> ± 11.4	30.3 <sup>c</sup> ± 5.9
PM <sub>2.5</sub> number flux × 10 <sup>2</sup> (mm <sup>-2</sup> )	43.5 <sup>a</sup> ± 12.8	21.1 <sup>bc</sup> ± 7.6	27.1 <sup>ab</sup> ± 5.9	27.4 <sup>ab</sup> ± 8.8	14.7 <sup>c</sup> ± 6.8	17.3 <sup>bc</sup> ± 3.2
PM <sub>10</sub> number flux × 10 <sup>2</sup> (mm <sup>-2</sup> )	31 <sup>a</sup> ± 9.3	14.7 <sup>a</sup> ± 5.1	15.8 <sup>a</sup> ± 3.8	14.4 <sup>a</sup> ± 5.2	8.5 <sup>a</sup> ± 2.5	8.8 <sup>a</sup> ± 1.9

For PM number flux (mm<sup>-2</sup>) on foliar surfaces of the plants, a, b and c are superscripts to denote the values which are statistically different from each other. However, values assigned with the same alphabets in each PM category are not statistically different from others in their respective PM category (Tukey's HSD post hoc test,  $p > 0.05$ ).



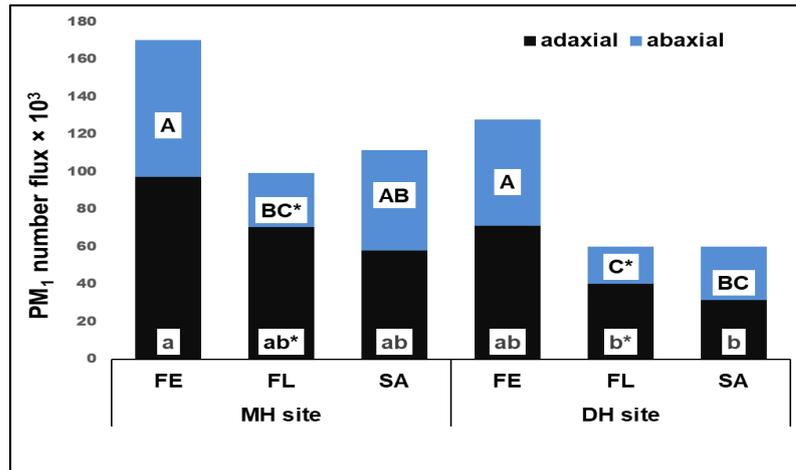
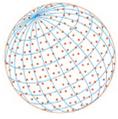
The adaxial and abaxial foliar surfaces of the plants were analyzed separately for more information on PM deposition. Fig. 4 shows the average PM number flux on the adaxial and abaxial foliar surfaces of each plant species at DH and MH sites. For PM<sub>1</sub> number flux, it can be noted in Fig. 4(a) that the adaxial foliar surfaces did not show any statistical significant inter-species variability at both DH and MH sites. However, the abaxial surface examination showed statistical significant inter-species variation for PM<sub>1</sub> capture between *Ficus elastica* and *Ficus lyrata* ( $p = 0.001$  and  $p = 0.003$  at MH and DH sites, respectively) which indicated that *Ficus elastica* captured significantly more PM<sub>1</sub> as compared to *Ficus lyrata* on the abaxial side. The PM<sub>1</sub> accumulation on the adaxial surfaces was higher than the abaxial surfaces for all the species but statistical significant difference was only obtained for *Ficus lyrata* ( $t = 2.9$  and  $p = 0.048$ ;  $t = 4.1$  and  $p = 0.015$  at MH and DH sites, respectively) which could be due to more variation in the proportion of grooves between its adaxial and abaxial surfaces as compared to other plants.

For PM<sub>2.5</sub> number flux, Fig. 4(b) shows that statistical significant difference was not observed between the adaxial and abaxial PM<sub>2.5</sub> accumulation on the foliar surfaces for any of the plants. The statistical analysis further showed that significant inter-species variation for PM<sub>2.5</sub> capture on the adaxial surface was not noted for any site which could be due to similar proportion of grooves on the adaxial foliar surfaces of all the plants (Table 4). However, PM<sub>2.5</sub> accumulation on the abaxial side showed significant inter-species variation ( $F = 9.6$  and  $p = 0.001$ ) between *Ficus lyrata* and *Ficus elastica* ( $p = 0.016$  and  $p = 0.041$  for MH and DH sites, respectively), such that *Ficus elastica* had significantly higher PM<sub>2.5</sub> number flux on its abaxial foliar surfaces as compared to *Ficus lyrata* which could be due to lesser proportion of grooves on the abaxial surface of *Ficus lyrata* among all the plants. *Schefflera arboricola* did not significantly differ from the other two plants for PM<sub>2.5</sub> capture. Fig. 4(c) shows that no significant inter-species difference was observed for PM<sub>10</sub> capture between the three plants at both the sites.

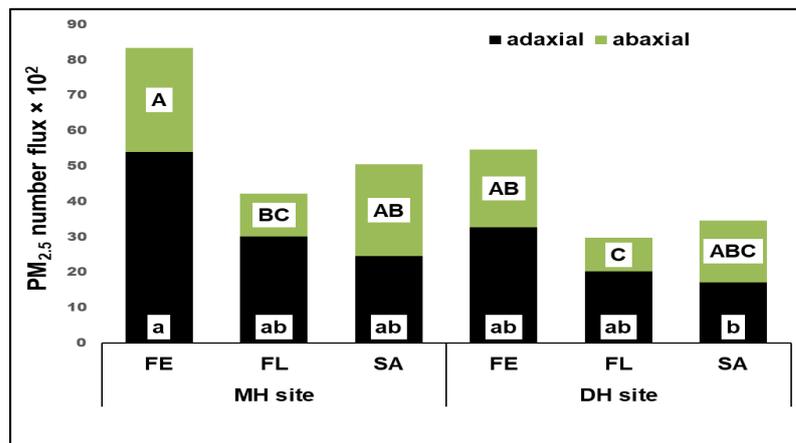
### 3.4 Foliar Surface Micromorphology and its Effect on PM Accumulation

Table 4 shows the average leaf size and the average values of some micro-morphological traits on the upper and lower leaf surfaces of the plant species. It was inferred from the earlier results (Table 3) that the total PM accumulation on the foliar surfaces increased with a decrease in particle size. The particle size dependence of the PM accumulation on the surfaces depends upon the PM abundance in the indoor air. It has been reported in the earlier studies that the number of fine PM is relatively much higher as compared to coarse PM in case of indoor regimes, especially, in residential homes owing to typical residential sources such as cooking, smoking, fuel burning (Morawska et al., 2017; Patel et al., 2020). Additionally, variation in deposition of the PM is dependent on the aerodynamic characteristics of the PM and their elementary interactions with plant surfaces (Freer-Smith et al., 2005; Weerakkody et al., 2018b). Leaves with more proportion of grooves have been often cited as better surfaces for capturing PM (Liang et al., 2016; Weerakkody et al., 2018a; Zhang et al., 2017). Liang et al. (2016) reported that groove proportion ranges between 3 to 25% and usually between 10 to 20% and PM capturing potential sharply increases when groove proportion exceeds 20%. Kim (2008) has reported significant morphological variations between the adaxial and abaxial surfaces of *Ficus elastica* foliage. The adaxial surface had no stomata with moderate undulations (Figs. 5(a–b)) whereas the abaxial surface is highly undulated with high stomatal number flux (Figs. 5(c–d)). The present study showed that the adaxial surface had 16.2% grooves while the abaxial surface had 23.5% grooves, which were cumulatively responsible for higher PM capture by *Ficus elastica* as compared to other two plant species in the study. *Schefflera arboricola* had appearance of undulations of the cuticle on adaxial and the abaxial surfaces (Figs. 5(g–j)). The groove proportion for the *Ficus lyrata* foliar surfaces (Figs. 5(e–f)) was least among the studied species on the abaxial surface (7.6%), which could be the reason for the significantly different PM<sub>1</sub> accumulation on the adaxial and abaxial sides leading to lesser PM<sub>1</sub> accumulation on the abaxial surfaces of *Ficus lyrata*.

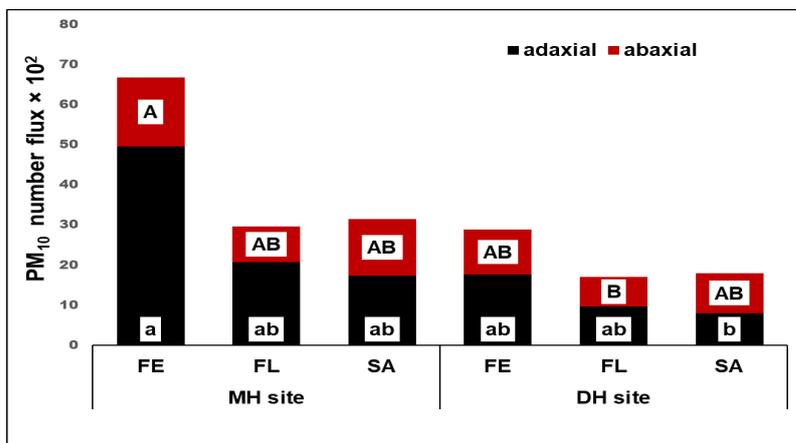
It could be observed from SEM images the plants lacked trichomes or hair like structures which have been usually associated with PM<sub>10</sub> number flux (Barwise and Kumar, 2020; Weerakkody et al., 2017) and it could be the reason for relatively lesser PM<sub>10</sub> accumulation by the selected species for this study. PM capture has also been associated with high stomatal number flux on the leaves as PM < 2 μm are capable of entering stomata. All the plant species in this study were hypostomatic



(a) Average number flux of PM<sub>1</sub> on the foliar surfaces of the plants × 10<sup>3</sup> (mm<sup>-2</sup>) at MH

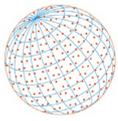


(b) Average number flux of PM<sub>2.5</sub> on the foliar surfaces of the plants × 10<sup>2</sup> (mm<sup>-2</sup>) at MH and DH sites



(c) Average number flux of PM<sub>10</sub> on the foliar surfaces of the plants × 10<sup>2</sup> (mm<sup>-2</sup>) at MH and DH sites

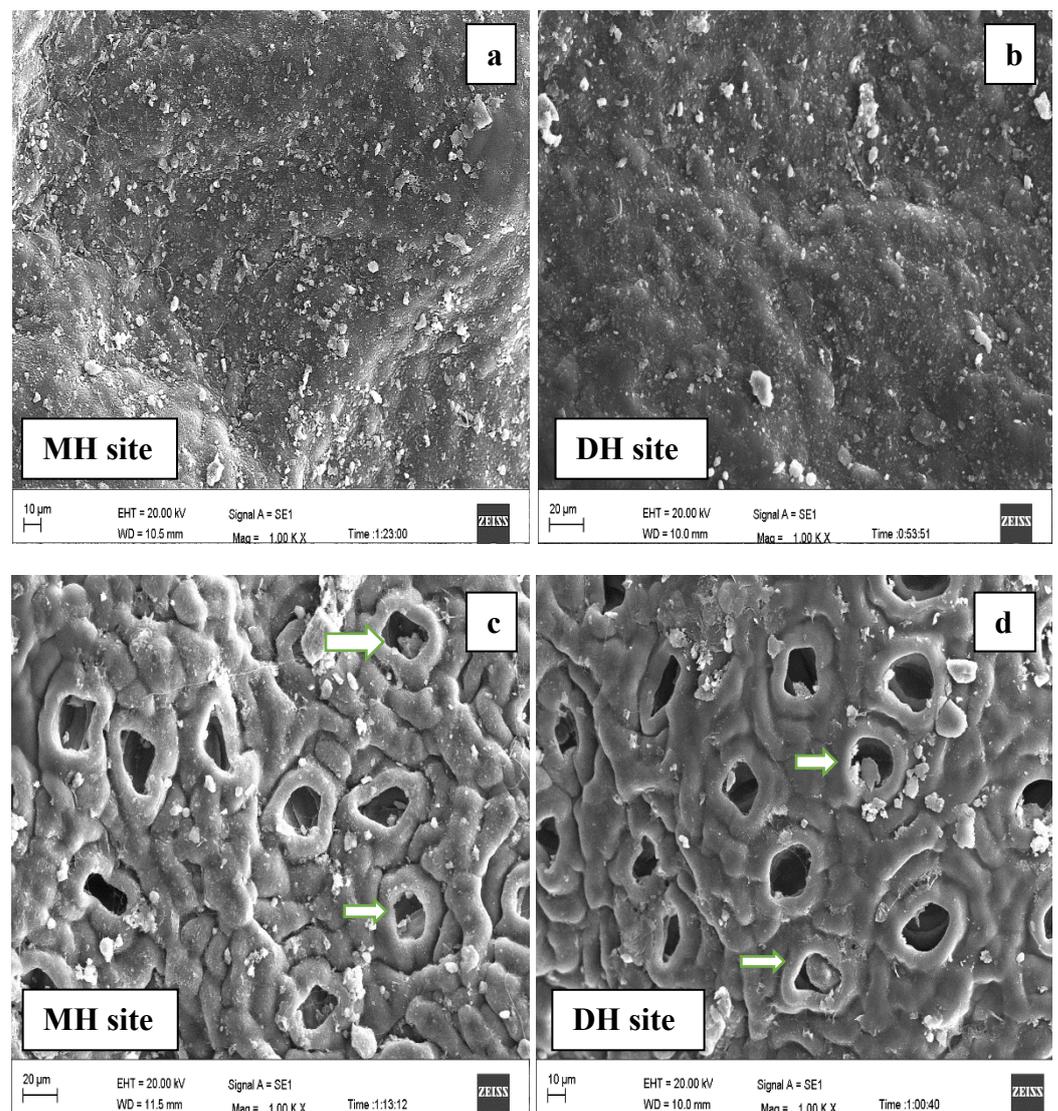
**Fig. 4.** Average values of PM number flux (mm<sup>-2</sup>) of adaxial and abaxial foliar surfaces of the plants in the indoor households, DH and MH sites (PM number fluxes given in different scales): a) PM<sub>1</sub>, b) PM<sub>2.5</sub>, and c) PM<sub>10</sub> Upper case alphabets-Variation between adaxial foliar surfaces; Lower case alphabets-Variation between abaxial foliar surfaces. Plant species marked by identical alphabets are not significantly different from each other ( $p > 0.05$ ). \* indicates the significant difference between the adaxial and abaxial PM densities of respective species. Species code: FE-*Ficus elastica*, FL-*Ficus lyrata* and SA-*Schefflera arboricola*.



with numerous sunken stomata (xeromorphic adaptation) and presence of cuticular thickenings that formed a raised rim around the stomata were observed. *Ficus elastica* (Figs. 5(b–c)) and *Schefflera arboricola* (Figs. 5(i–j)) had nearly similar stomatal number flux with well dispersed stomata on their abaxial surfaces whereas *Ficus lyrata* showed characteristic aggregation or clumped arrangement of stomata (Figs. 5(e–f)) (Klimko and Truchan, 2006).

**Table 4.** Average leaf size and average values of some micro-morphological characteristics present on the surfaces of plant species.

Plant	Average Leaf Area (cm <sup>2</sup> )	Adaxial Surface		Abaxial Surface	
		Stomatal Density (mm <sup>-2</sup> )	Grooves%	Stomatal Density (mm <sup>-2</sup> )	Grooves%
<i>Ficus elastica</i>	137.6 ± 22.5	0	16.2 ± 3.6	238 ± 38.6	23.5 ± 2.8
<i>Ficus lyrata</i>	82.2 ± 26.2	0	13.6 ± 4.3	295.8 ± 32.5	7.6 ± 1.3
<i>Schefflera arboricola</i>	22.4 ± 6.4	0	17.7 ± 0.2	235.9 ± 24.1	15.3 ± 1.6



**Fig. 5.** SEM micrographs of (a–d) *Ficus elastica*, (e–f) *Ficus lyrata* and (g–j) *Schefflera arboricola* at MH and DH sites. Bold arrows show clogged stomatal pores due to PM deposition.

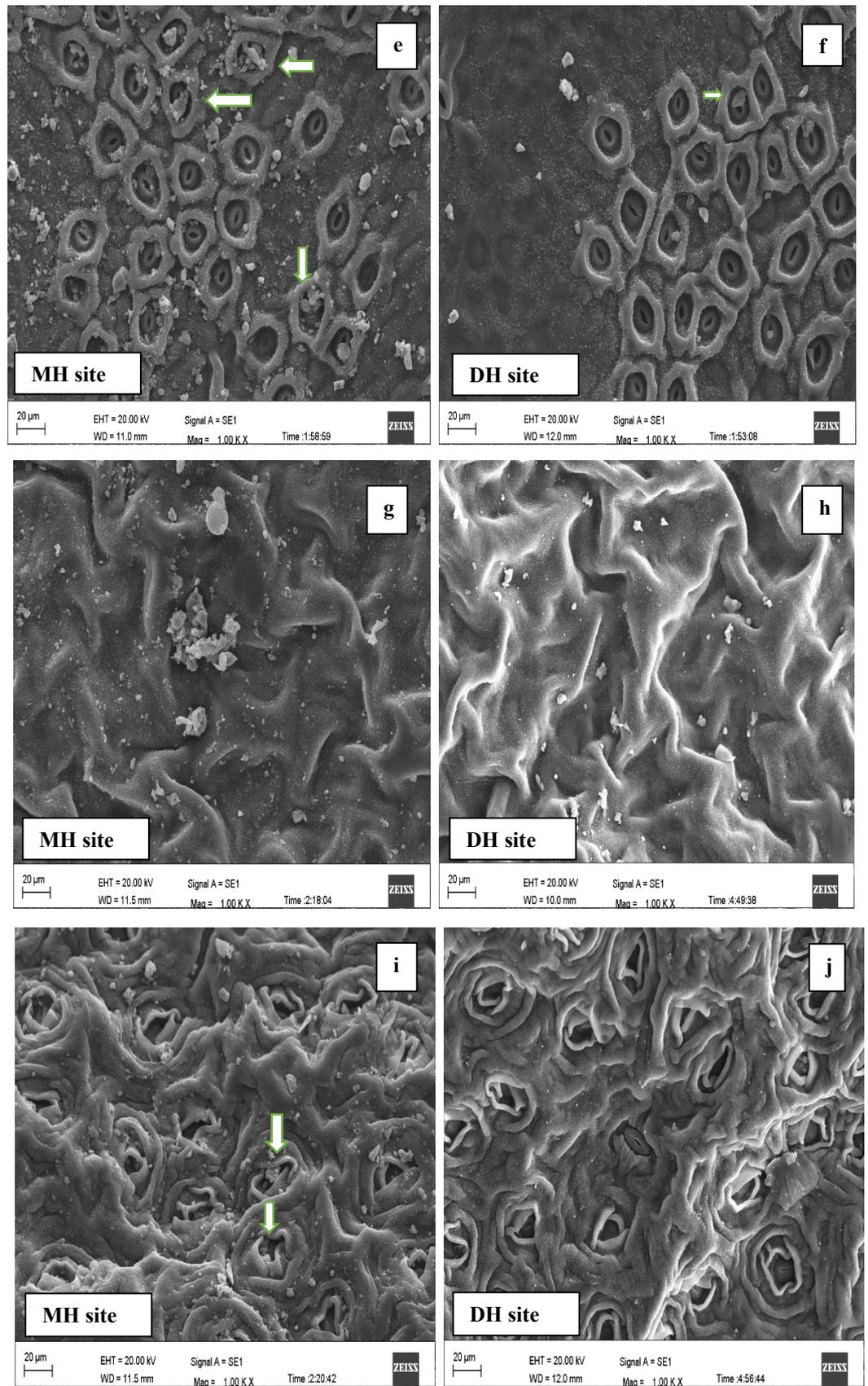
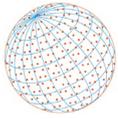
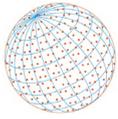


Fig. 5. (continued).

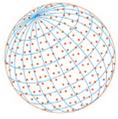


### 3.5 SEM Imaging of the Foliar Surfaces

Fig. 5 presents the SEM micrographs of the foliar surfaces of *Ficus elastica*, *Ficus lyrata* and *Schefflera arboricola* showing their micro-morphological traits and PM deposition at DH and MH sites. In this study, relatively more PM deposition was seen on the adaxial and abaxial foliar surfaces at MH site as compared to DH site (Fig. 5). Clogging of stomatal pores is quite visible on the abaxial foliar surfaces of the plant species in Fig. 5. It may lead to stomatal deformation, hinder stomatal opening and closing or may increase stomatal conductance which alters plant physiology (Farmer, 1993). It has been reported that larger PM mainly adhere to outside surface of plants which is in contrast to gaseous pollutants and very fine PM ( $< 0.1 \mu\text{m}$ ) that usually get assimilated through stomata into the leaves (Ottel  et al., 2010). PM that accumulate on the foliar surfaces and block stomatal pores affect gaseous exchange, water retention, photosynthesis and plant growth (Tomašević et al., 2005). Abrasive effect of the particle deposition is borne by the cuticle and epicuticular wax which get damaged. The epicuticular waxes are reported to be favorable for capturing PM as the wax quantity, composition and structure present on the foliar surfaces play a key role in the PM deposition on them (Barwise and Kumar, 2020; Liang et al., 2016; S eb  et al., 2012). Several findings have suggested that plant species having leathery leaves with densely arranged grooves and presence of epicuticular wax are suitable for PM accumulation (Liang et al., 2016; Weerakkody et al., 2017). The plant species in the current study have the presence of epicuticular wax layers on their foliar surfaces but its detailed analysis and role in PM accumulation has not been included in the scope of this study which could be a topic of future interest. *Ficus elastica* has large, leathery and glossy foliage with a thick layer of epicuticular waxes and densely arranged grooves. *Schefflera arboricola* has palmately compound leaves, radiating outwards from the end of the petiole, with the presence of epicuticular wax. *Ficus lyrata* has fiddle shaped leathery leaves with highest stomatal density among the selected species but its PM accumulation was not high which could also be due to orientation of its alternately arranged leaves, such that they grow at an angle of 45 degrees with each other which reduces the ability of PM accumulation of this plant (Paull et al., 2018). It can be inferred that plant leaves and their surface characteristics are key to pollutant absorption by plants. Desirable plant species can also be incorporated in designing passive systems such as vertical green walls for pollution abatement, which are likely to cause minimal alterations or adjustments in the urban built environment. A growing interest in such feasible mitigation measures requires in depth analysis of multiple parameters of indoor plants which can provide air quality improvement benefits in urban landscapes during all seasons due to their evergreen nature.

## 4 CONCLUSIONS

The complex micromorphology of foliar surfaces plays a key role in efficient capturing of fine PM by plants. It was shown in this study that the dustfall fluxes on the foliar surfaces of indoor plants were significantly higher at MH site as compared to DH site. Seasonal variations showed that these fluxes were maximum during winter and minimum during monsoon season. The balance between cationic and anionic components in the average dustfall flux deposited on the plant foliar surfaces, was calculated at DH and MH sites and it was observed that  $\Sigma^+/\Sigma^-$  ratios were lower at MH site due to the presence of more anionic species in the dustfall flux. PM number flux was used for reporting the smaller PM based on size using SEM images and the mean PM accumulation followed the order,  $\text{PM}_1 > \text{PM}_{2.5} > \text{PM}_{10}$  for the selected plants at both the sites. The SEM micrographs showed that the plants lacked trichomes or hair like structures which are usually associated with  $\text{PM}_{10}$  number flux and it could be the reason for relatively lesser  $\text{PM}_{10}$  accumulation by the selected species for this study. PM number flux was higher at MH site as compared to DH site for  $\text{PM}_1$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  but this increase was observed to be statistically insignificant ( $p > 0.05$ ) for all the selected plants. Diversity between the plant species pertaining to several aspects of the surface morphology leads to variations in the interception and capturing of PM which is evident in the results obtained from their scanning electron micrographs in this study. *Ficus elastica* showed statistically higher  $\text{PM}_1$  and  $\text{PM}_{2.5}$  accumulation on its large and leathery foliar surfaces as compared to other plants due to densely arranged undulations in the form of grooves, ridges and presence of epicuticular wax. Micromorphological features of leaves



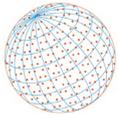
such as stomatal density, trichomes, density of undulations on the foliar surfaces, variations in epicuticular waxes and their composition etc. should be studied in detail to ascertain their roles in capturing PM and differences in adherence capacity between leaves. A comparative study of indoor plants efficiency and air purification effectiveness involving different indoor plants and their combinations would help in forming the 'Green Infrastructure' such as vertical greenery systems, living walls, for improving air quality in urban areas.

## ACKNOWLEDGEMENTS

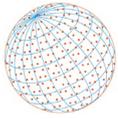
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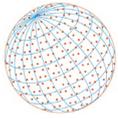
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