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Identifying Common Trees and Herbaceous Plants to Mitigate Particulate Matter Pollution in a Semi-Arid Mining Region of South Africa

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Abstract: Plants provide long-term and sustainable solutions to mitigate particulate matter (PM) pollution in urban environments. We evaluated total, fine, coarse and large particle trapping abilities of an equal number of common trees (*Carica papaya*, *Citrus limon*, *Moringa oleifera*, *Ozoroa paniculosa*, *Peltophorum africanum*, *Psidium guajava*) and herbaceous species (*Argemone ochroleuca*, *Catharanthus roseus*, *Gomphocarpus fruticosus*, *Ipomoea batatas*, *Senna italica*, *Tribulus terrestris*) to identify dust accumulators for Sekhukhuneland, a mining–smelting region of South Africa where desertification is becoming problematic. Scanning electron microscopy techniques were used to count and measure particles and relate leaf surface micromorphology to dust accumulation. Three tree and three herbaceous species showed superior dust collection capacity (*G. fruticosus* > *P. guajava* > *I. batatas* > *O. paniculosa* > *C. roseus* > *M. oleifera*). Variations in accumulation of PM sizes were noted among these six species and between adaxial and abaxial leaf surfaces. Compared with large PM, all plants accumulated more fine and coarse fractions which are respirable and thus hazardous to human health. Leaf surface roughness, epicuticular wax and epidermal glands improved dust accumulation. The six preferred plants may serve as forerunner species to abate PM pollution in Sekhukhuneland and other arid regions facing similar climate change and pollution challenges.

Keywords: air quality; arid; dust; *Gomphocarpus fruticosus*; *Psidium guajava*; urban

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1. Introduction

Urban populations are continuously exposed to particulate matter (PM) pollution, one of the greatest threats to human health [1,2]. The health risks linked with the inhalation of PM depend on particle size and chemistry [2,3]. The respirable PM fraction (≤10 µm) and specifically the finer particles (≤2.5 µm) pose the greatest risk due to the potential entry into the lungs and circulatory system [2,4–6]. Metalliferous dust generated by mining–smelting activities is widely distributed in the air and may carry toxic elements in different oxidation states [2]. This presents varying degrees of health risk from multifaceted exposures (inhalation, ingestion and dermal contact) in outdoor and indoor environments as indoor air quality can also be poor around these pollution sources [2,7,8].

Aerial dust load is frequently high in arid and semi-arid regions as a consequence of scant vegetation cover, low moisture in soil, lack of soil organic content and loose soil structure [3]. In addition, low atmospheric humidity affects PM retention and transportation by aeolian processes [3,9]. Globally forecasted and experienced climate change effects in arid and semi-arid regions mainly in terms of increased temperature and decreased precipitation aggravate dust pollution challenges [3,10,11]. More arid conditions also increase the risk of hazardous dust generation and dispersion around opencast mines [12].

While some plants can be sensitive to air pollution and thus be used as bioindicators, others can adapt, survive and even thrive due to traits including the ones that enable them to accumulate large quantities of dust particles on leaf surfaces that serve as natural air filters [10,11,13–16]. Of late, much interest and effort have been dedicated to investigating dust accumulation capacity, tolerance and adaptability of trees and herbaceous plants to abate air pollution in a cost-effective, sustainable and safe way [10,11,16–19]. Urban greenery extends these beneficial effects by restoring degraded soils, restricting soil erosion and improving ecosystem services by re-establishing vegetation cover [11,12].

Similar to most other mining regions of South Africa, the effects of air pollution on biota have been poorly studied in Sekhukhuneland, a historic multi-element mining region of global economic importance. It is only very recently that the region has been investigated in terms of hazardous PM pollution, dust deposition on vegetation and the associated health risks [6,20,21]. Health problems related to regular exposure to PM are presumably present among inhabitants of this region, although disregarded so far. Until now, for this region, research on the potential of plants for long-term dust mitigation purposes is non-existent and efforts from relevant management authorities towards solving these issues are negligible.

The present study was therefore designed to identify and recommend commonly occurring plant species from Sekhukhuneland that can be planted by communities to enhance urban greenery and achieve some degree of air pollution mitigation around homes in the vicinity of primary dust sources, i.e., mines and tailings, smelters and associated transportation routes. We studied a set of widely cultivated and wild trees and forbs for dust accumulation capacity by quantifying total dust amount and fine (0.1–2.5 μm), coarse (2.5–10 μm) and large particles (10–100 μm) accumulated by leaves. Scanning electron microscopy (SEM) techniques were used to count and measure particles and relate leaf surface micromorphology to dust trapping ability.

2. Materials and Methods

2.1. Urban Conditions

Driven by fast economic growth, the density of urban settlements is very high around mining-industrial centers in Fetakgomo-Tubatse Municipality of Sekhukhune District in Limpopo Province, South Africa. With the continuing expansion of mining and industrial developments, the rural-to-urban transition is taking place at a fast pace in Sekhukhuneland. Consequently, urban greenery is disappearing at an even faster rate due to land degradation [22] and habitat destruction by anthropogenic activities [23,24]. Collectively, land degradation, land use intensification and unvegetated barren land could escalate wind erosion in Sekhukhuneland, especially under the influence of arid conditions and climatic stressors. This can include erratic changes in the wet-dry season water balance due to increased frequency of droughts that may lead to desertification [23,25]. Home gardens and rangelands impacted by more than one of the principal pollution sources in the region (mines and tailings, smelters and transportation routes) were selected randomly at three of the main mining–smelting foci of the region (Figure 1). Since each pollution source emits different proportions of PM of specific size ranges [5], it was decided that the most suitable dust accumulators should be selected on the basis of the higher capacity of plant species to accumulate total dust and various PM sizes thereof.

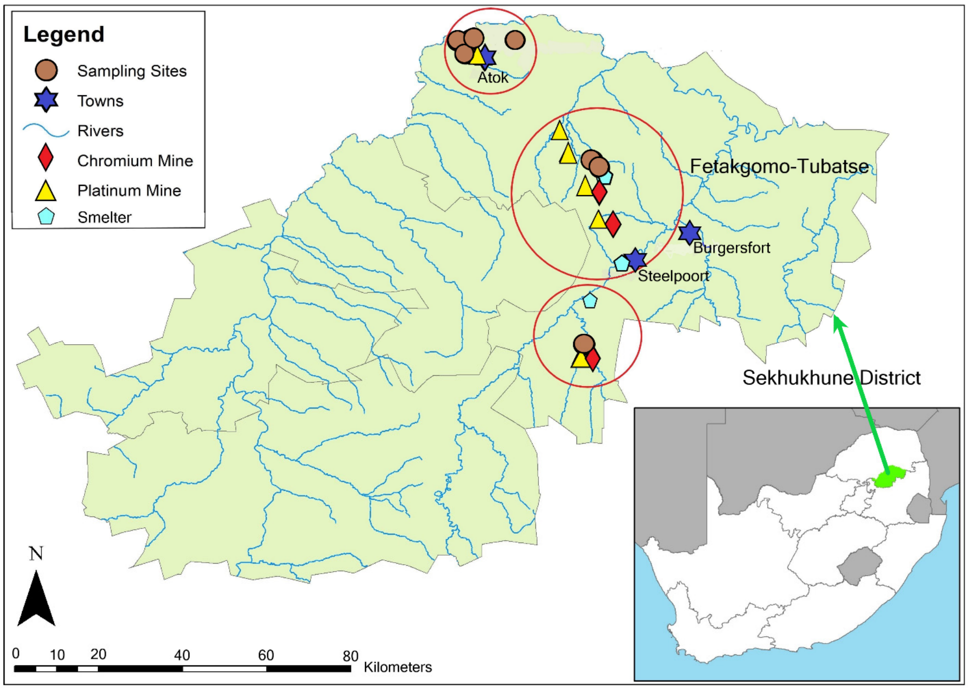

Figure 1. Sampling sites around three mining–smelting agglomerations (red circles) in the Sekhukhune District of Limpopo Province, South Africa.

2.2. Sampling and SEM Analysis of Leaves

Leaves of the 12 most common plant species that included six trees (*Carica papaya*, *Citrus limon*, *Moringa oleifera*, *Ozoroa paniculosa*, *Peltophorum africanum*, *Psidium guajava*) and six forbs (*Argemone ochroleuca*, *Catharanthus roseus*, *Gomphocarpus fruticosus*, *Ipomoea batatas*, *Senna italica*, *Tribulus terrestris*), were sampled during the summer season of 2018. After measuring the heights of five individuals per species at each sampling site, 20 leaves were sampled from each individual, mixed into a composite sample for each species and immediately fixed in 70% ethanol. Since the same number of samples were collected at each site for each species, it was anticipated that site specific differences in PM exposure would impact all the plants equally at each site and would not bias results in terms of varying dust deposition and accumulation capacity of plant species.

Recently described methods were followed to prepare and conduct SEM analysis of ethanol-fixed leaves [26]. Briefly, 70% ethanol fixed leaves were dehydrated with up to 100% ethanol and leaf strips were prepared. Thereafter leaf strips were critical point dried using CO_2 and coated with gold/palladium and carbon. An FEI Quanta 250 FEG SEM was used to capture images of the adaxial and abaxial leaf surfaces (1) to count and measure dust particles (mean ± SD of five readings) with the help of ImageJ software and (2) to study leaf surface microstructures that favor dust adhesion.

3. Results and Discussion

3.1. Dust Accumulation Capacity of Plants

Mean total dust counts were made of adaxial and abaxial leaf surfaces of target plant species (Figure 2). For the adaxial surface, mean total dust counts in descending order were *P. guajava* > *G. fruticosus* > *O. paniculosa* > *I. batatas* > *C. roseus* > *T. terrestris* > *A. ochroleuca* > *M. oleifera* > *C. papaya* > *P. africanum* > *C. limon* > *S. italica* and for the abaxial surface, *I. batatas* > *G. fruticosus* > *P. guajava* > *M. oleifera* > *C. roseus* > *O. paniculosa* > *T. terrestris* > *P. africanum* > *C. limon* > *A. ochroleuca* > *C. papaya* > *S. italica* (Figure 2a). Although all 12 species showed some degree of dust accumulation potential, based on the sum of the mean total dust counts of both leaf surfaces (number per mm^2), six plants, three each from the tree (*P. guajava* > *O. paniculosa* > *M. oleifera*) and forb (*G. fruticosus* > *I. batatas* > *C. roseus*) categories stood out as the most preferable ones for dust mitigation purposes (Figure 2b). During the selection process of preferable species, *T. terrestris* with the sixth highest total dust count was replaced by the next best option *M. oleifera* because of the recognition of the former as a weed and the popularity of the latter as a cultivated plant in home gardens in the study locality.

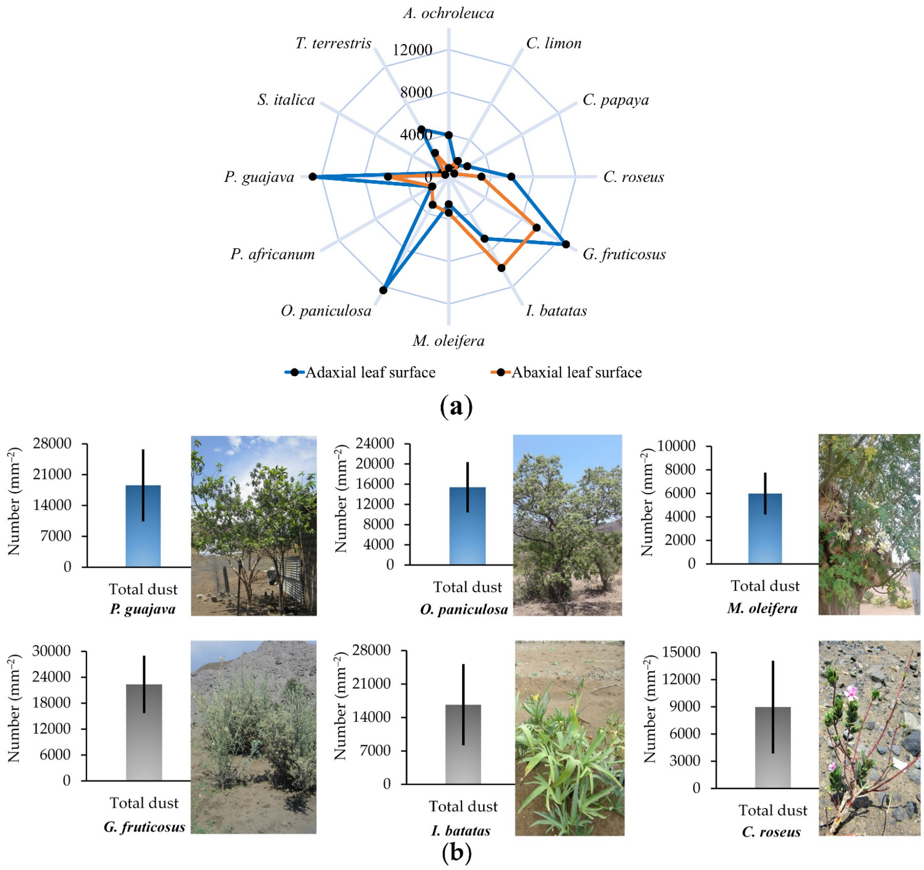

Figure 2. Dust particle accumulation by plants: (**a**) Mean total dust values (per mm^2) on adaxial and abaxial leaf surfaces of all assessed species; (**b**) Sum of mean particle counts (±SD) of both leaf surfaces of six species with higher dust collection in descending order. Trees (in blue) are followed by forbs (in gray).

In this study, an equal number of species of trees and forbs were recognized as superior dust accumulators. Forb species have been suggested as a better option to cultivate on slopes, while trees might be more suitable for flat regions [12]. The selection of both trees and forbs therefore complement one another in the mountainous terrain of the study locality. This group of plants included the tallest tree (*O. paniculosa*, height ranged between 11.5−12.0 m), two medium-sized trees (*M. oleifera*, 4.8−5.0 m; *P. guajava*, 4.7−5.0 m) and forbs of which one was comparatively taller (*G. fruticosus*, 1.4−1.5 m) than the other two (*C. roseus*, 0.42−0.50 m; *I. batatas*, 0.17−0.20 m). Weber et al. (2014) reported higher dust collection by leaves of herbaceous plants at heights above 0.17 m, which holds for all three selected forbs from Sekhukhuneland. The present study proposes the prospect of cultivating common trees and forbs with considerable height variations to intercept and capture sufficiently high quantities of dust particles from the atmosphere up to 12 m above ground level.

The combined advantages of planting evergreen trees and herbaceous plants as dust filters are expected to maximize cumulative mitigation effects in heavily air-polluted mining–smelting environments of the study locality. Evergreen trees collect dust all year round, tree canopies act as a sink of PM, complex tree structures resist wind movement resulting in greater dust deposition on foliage and tree bark could absorb toxic metal containing

PM [14,15,27–29]. Herbaceous plants immobilize dust at ground level, especially along roads because traffic is a major source of PM at surface level, limit hazardous dust resuspension from the soil, are feasible for inclusion in most outdoor urban spaces, and are recognized as ruderal species to re-establish vegetation in disturbed habitats [11,13,16,18,19].

Previously reported air pollution tolerance of *M. oleifera* [30], dust pollution resistance of *C. roseus* [31], comparatively high PM adsorption capacity of leaves of *I. batatas* [32], and elevated foliar dust loadings of *P. guajava* and its recognition as an urban green filter [33,34], justifies the inclusion of these four species in the list of suitable plants for improving air quality in the study region. However, to the best of our knowledge, this study is the first to report on the value of the naturally occurring species, *O. paniculosa* and *G. fruticosus* as potential filters of airborne particles.

3.2. Accumulation of PM Size Fractions by Plants

To evaluate the fine, coarse and large PM trapping potential of the six species with superior total dust collection ability, SEM micrographs of adaxial and abaxial leaf surfaces were taken to measure the diameters of randomly selected particles. Figure 3 illustrates the percentages of aforementioned PM sizes accumulated on leaf surfaces per species. Variations were noted among species and between adaxial and abaxial leaf sides. Except for *M. oleifera*, the other two trees (Figure 3b,c) and taller forbs (*C. roseus*, Figure 3d; *G. fruticosus*, Figure 3e) were indicated as competent accumulators of fine particles on both leaf surfaces. The medium-sized tree *M. oleifera* (Figure 3a) and the tallest (*G. fruticosus*, Figure 3e) and the shortest forb species (*I. batatas*, Figure 3f) showed better removal capacity of coarse PM. Among the three evaluated sizes, the collected quantity of large PM was the lowest for all six species. In general, most species collected comparable amounts of large PM fraction and the lowest accumulation percentages were determined for two comparatively taller forbs, *C. roseus* (Figure 3d) and *G. fruticosus* (Figure 3e). Relatively higher accumulation of most of the PM sizes by both leaf surfaces of *O. paniculosa* (Figure 3b), *P. guajava* (Figure 3c) and *G. fruticosus* (Figure 3e) reflected their reasonably better overall dust filtering ability. This is an important factor to consider when choosing plants to address widespread PM pollution challenges in mining regions.

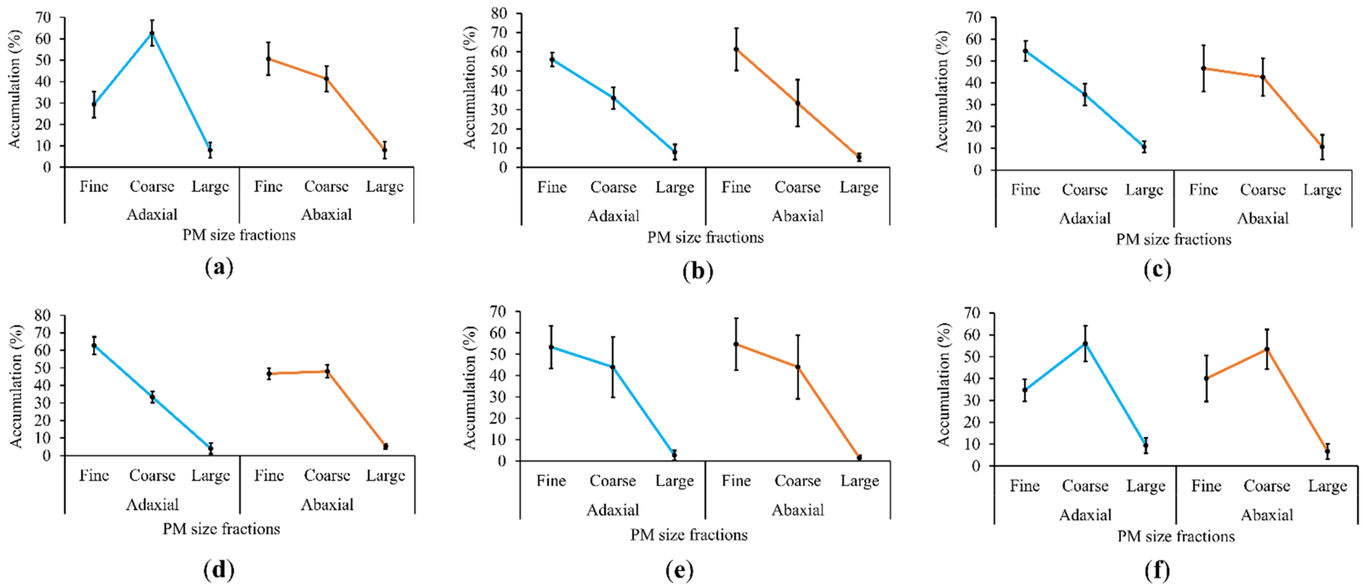

Figure 3. Accumulation of assessed PM sizes (mean ± SD) by adaxial and abaxial leaf surfaces of plant species: (**a**) *M. oleifera*; (**b**) *O. paniculosa*; (**c**) *P. guajava*; (**d**) *C. roseus*; (**e**) *G. fruticosus*; (**f**) *I. batatas*. Trees first then forbs.

On the basis of the frequently emitted PM sizes by mines and tailings, smelters and associated transportation routes, we further identified the most useful combinations of species that can be planted around each of the main sources to decrease PM levels in Sekhukhuneland (Table 1). Coarse and large particles followed by fine PM are the most common sizes found around mining sites [3,12,35]. Therefore, combinations of all six selected plant species that showed different potentials to capture the three PM sizes should be cultivated near mines in Sekhukhuneland. High to moderate capacity of *O. paniculosa*, *P. guajava*, *C. roseus* and *G. fruticosus* to accumulate fine and coarse PM suggests their suitability around smelters, which are well-known emitters of finer particles but may also disseminate coarse particles [2,3,7,36]. As recommended in the present study, past reports have advocated the potential of taller plants to alleviate fine and coarse PM pollution in urban centers [14,37]. Often coarse PM is the prevalent size fraction in road dust surrounding mines that generally contain elevated concentrations of toxic elements [3,38]. However, transportation of tailings pollutes the air with fine particles [3,4]. Hence, planting the woody species *M. oleifera* and the three forbs (*C. roseus*, *G. fruticosus* and *I. batatas*) that have shown efficiency in accumulating larger and fine PM fractions, could be the best choice to immobilize dust along haul roads in the study region [13,18,19,39].

Table 1. Recommended plant species for PM mitigation around major pollution sources in Sekhukhuneland.

Source	PM Sizes	Plant Species
Mines	Ultrafine (<0.1 µm, tailings); fine (high temperature processes); coarse and large PM (excavation and grinding)	All six species
Smelters	Ultrafine, fine and coarse PM	*C. roseus*, *G. fruticosus*, *O. paniculosa*, *P. guajava*,
Transportation	Fine (tailings) and coarse PM (mines)	*C. roseus*, *G. fruticosus*, *I. batatas*, *M. oleifera*

3.3. Leaf Micromorphology Favoring Dust Accumulation

The study of SEM micrographs (Figure 4) revealed leaf surface micromorphological features of the six preferred trees and herbaceous species. Rough surfaces created by epicuticular cell outlines (in all six species, Figure 4a–l), deep veins and grooves (*M. oleifera*, Figure 4b; *O. paniculosa*, Figure 4d; *P. guajava*, Figure 4e,f; *C. roseus*, Figure 4h), epidermal glands (*I. batatas*, Figure 4k,l), epicuticular wax (in all six species) and non-glandular (*M. oleifera*, Figure 4a; *O. paniculosa*, Figure 4d; *P. guajava*, Figure 4e) and glandular trichomes (*G. fruticosus*, Figure 4i, not visible on the selected image of abaxial side, Figure 4j) were indicated as the key traits that increased dust deposition on both leaf surfaces of these species [1,14,29,33,40,41]. Micrographs further clarified that densely packed trichomes on abaxial leaf surfaces of *O. paniculosa* (Figure 4d) and *P. guajava* (Figure 4f) created a protective layer that could have restricted dust adhesion [42,43], which explains their comparatively low dust counts (see Section 3.1, Figure 2a).

More importantly, corroborating past reports, our study also suggests that foliar dust accumulation capacity is largely determined by species traits rather than the type of life form [13,40]. As found in the present study, plants that possess multiple features that favor dust adhesion can be studied further to identify the most effective plant species for PM removal.

Even though other species from this region may have greater dust mitigation potential, the observed ability of the six recommended species to accumulate all three PM sizes and specifically higher percentages of the most problematic fine and coarse PM support their suitability in this regard. Furthermore, these trees and forbs from the same region have shown promising capabilities to accumulate several hazardous elements in leaf tissue [21]. These six preferred plant species may therefore serve the dual purpose of mitigating polluted air and soil. Although it is important to prove the long-term dust mitigation prospects of the recommended species in field-based experiments and to collect evidence of satisfactory PM mass removal by leaves, cultivating these species holds great potential as a practical and affordable solution to hazardous PM pollution in Sekhukhuneland where dust pollution is increasing due to longer drier spells and rapidly progressing land degradation [44].

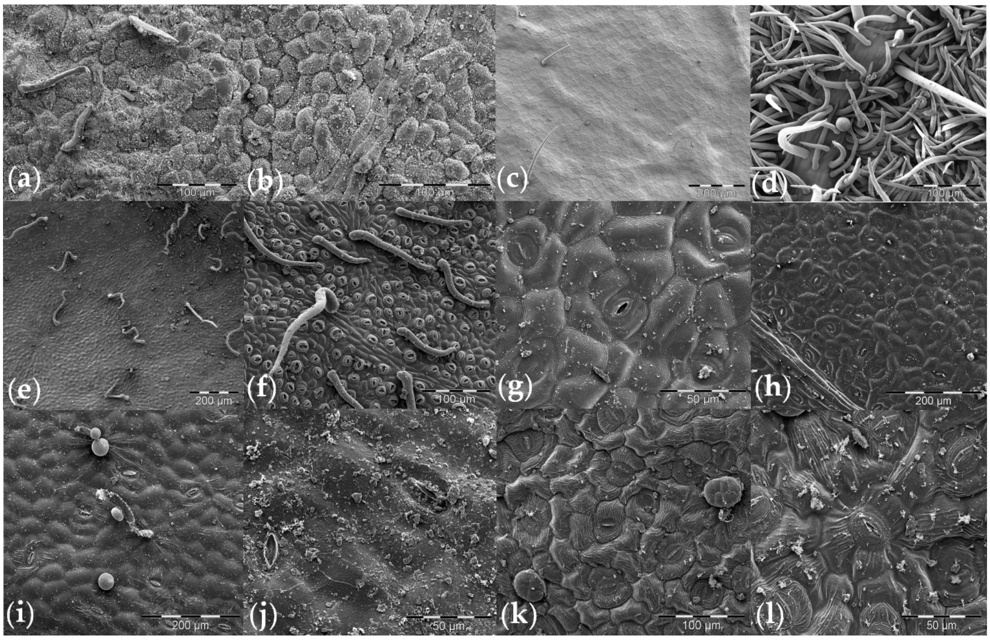

Figure 4. Prominent leaf micromorphological features of six highest dust collecting plant species: (**a**) *M. oleifera*—Ad; (**b**) *M. oleifera*—Ab; (**c**) *O. paniculosa*—Ad; (**d**) *O. paniculosa*—Ab; (**e**) *P. guajava*—Ad; (**f**) *P. guajava*—Ab; (**g**) *C. roseus*—Ad; (**h**) *C. roseus*—Ab; (**i**) *G. fruticosus*—Ad; (**j**) *G. fruticosus*—Ab; (**k**) *I. batatas*—Ad; (**l**) *I. batatas*—Ab. Ad, adaxial and Ab, abaxial leaf surface. Trees are followed by forbs.

4. Conclusions

This study assessed total, fine, coarse and large particle accumulation capacities of 12 common plant species in severely air-polluted urban environments around mines and smelters in Sekhukhuneland. Findings revealed that selected trees and forbs differed considerably in dust accumulation potential. With notable height variations, the top six dust accumulating species may intercept different atmospheric levels and PM size fractions to maximize mitigation effects. It is recommended that assemblages of preferred trees and forbs are cultivated around major pollution sources (mines and tailings, smelters and associated transportation routes) in Sekhukhuneland to reintroduce greenery and improve air quality. Moreover, these green barriers will address desertification in this region. Selected trees and herbaceous plants could also serve as forerunner cultivated species to combat air pollution in other arid regions impacted by similar challenges related to anthropogenic activities and climate change.

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