

Microgreens as Functional Green Biomass Interfaces for Particulate Matter Interception, Biotransformation and Sustainable Environments

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Abstract

Particulate matter (PM) consists of aerosols with complex chemical structures that are reactive and significantly impact air quality, biodiversity, and human health. It includes a variety of components such as inorganic ions (SO_4^{2-} , NH_3^- , NO_4^+ , CO, etc.), elemental carbon (black carbon), organic carbon (including polycyclic hydrocarbons, organic acids, aldehydes, alkanes, and alkenes, etc.), trace metals (such as lead, cadmium, mercury, arsenic, nickel, chromium, and vanadium, etc.), as well as secondary aerosols (Organic acid, Oxidised volatile organic compounds, etc.), mineral dust (Si, Al, Ca, Fe, etc.), biological residues (pollen fragments, fungal spores, bacterial endotoxins, plant debris, etc.). These components confer PM with diverse physicochemical properties that affect both its environmental behaviour and toxicity.

This work elucidates the role of microgreens as functional bioinceptors that interact with and alter PM at the air-plant interface. Their delicate leaf structure, high surface-area-to-biomass ratios, and chemically active leaf surfaces enable these young plants to effectively capture airborne particles, particularly fine and ultrafine PM fractions ($\text{PM}_{2.5}$ and less than 0.1 micromoles). After PM settles onto their surfaces, components interact with leaf moisture and plant metabolites, leading to changes in solubility, redox state, and surface reactivity. These alterations help diminish the oxidative capacity and environmental stability of particulate matter.

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Simultaneously, these micro photosynthetic greens exhibit strong physiological responses to PM exposure, activating antioxidant and detoxification pathways that alleviate stress induced by the particles. These interactions not only affect micro-environmental air quality but also influence macro-scale processes, such as the progressive deposition of particulate contaminants within soil matrices and aquatic systems. Incorporating microgreens into urban, suburban, and controlled-growth settings offers a sustainable, low-input approach to managing PM at the microecological level. This research emphasizes the dynamic relationships between microgreens and particulate matter, showcasing the potential of plant-based strategies to lessen PM exposure, bolster environmental health, and promote ecosystem resilience. The results highlight the importance of these green biofilters as practical, scalable components of nature-based solutions to combat PM pollution and enhance long-term planetary sustainability.

Keywords: *Microgreens; Particulate matter; Bioinceptors; Microenvironment level; Planetary sustainability.*

1. Introduction

Atmospheric PM consists of solid and liquid particles suspended in the air. This includes inorganic ions, metals, elemental carbon, organic compounds, and secondary reaction products [1,2]. Fine and ultrafine PM can penetrate biological systems deeply. They may cause pneumopathy, angiocardial dysfunction, and neuroinflammation by inducing oxidative stress and activating inflammatory pathways [3,4]. Conventional control strategies focus on managing emissions and using mechanical filtration. Recently, increasing attention has been given to biological interfaces that interact with airborne particles [5]. In terrestrial ecosystems, plant surfaces are the first biological barrier to airborne particulates. Vegetation intercepts atmospheric particles by impaction, diffusion, sedimentation, and electrostatic attraction. This process affects particle residence time and distribution [6,7]. Leaf shape, surface roughness, and cuticle chemistry all impact how efficiently plants intercept particles [8].

Microgreens are bioactive seedlings harvested soon after cotyledon expansion. They have unique features such as high surface-area-to-biomass ratios, many trichomes, thin but chemically active cuticles, and tissues rich in metabolites [9,10]. These features make microgreens a dynamic environmental interface that can interact with airborne particulates. Studies show that plant surfaces not only passively collect particles. They can also alter particles physically and chemically, affecting their stability, reactivity, and mobility in the environment [11].

This manuscript synthesizes experimental results and current literature to comprehensively evaluate how these young seedlings serve as functional green

biomass interfaces for particulate matter. To support this evaluation, the following sections review relevant chemical characteristics, summarize supporting literature, and outline the methodology developed for this investigation.

1.1. Chemical Characteristics of Microgreens and Particulate Matter

PM is classified by size. Coarse particles mainly consist of mineral dust (tiny solid particles from soil or rock) and bioaerosols (microscopic biological particles such as pollen or spores). Fine and ultrafine particles contain sulfates (SO_4^{2-} , salts derived from sulfuric acid), nitrates (NO_3^- , salts derived from nitric acid), ammonium (NH_4^+ , a type of nitrogen-containing ion), elemental carbon (pure carbon often from combustion), organic carbon (carbon compounds commonly from living things or incomplete combustion), and redox-active metals (metals able to change oxidation state). These substances have high surface reactivity and can create reactive oxygen species (highly reactive oxygen-based molecules). When these particles settle on plant surfaces, they interact with the plants' functional groups (specific chemical features involved in reactions). This enables ion exchange, complexation, and transformation (types of chemical processes).

The cuticle of microgreens has a cutin matrix with long-chain aliphatic waxes, phenolic esters, hydroxyl (-OH), carboxyl (-COOH), and carbonyl (>C=O) groups. The epidermal layer also contains polysaccharides and pectins, which provide additional binding sites for particles. These chemical groups allow microgreens to attract charged PM with electrostatic forces, form hydrogen bonds with polar organics, and bind transition metals. This helps trap and change particles on the leaf surface.

1.2. Review of Literature

PM is a mix of sulfates, nitrates, ammonium salts, transition metals, elemental carbon, organic carbon, and secondary reaction products formed by atmospheric photochemistry [12,13]. The toxic effects of PM depend on its size and the activity of its surface. Its redox-active parts—such as iron, copper, and quinones can create reactive oxygen species [14,15].

Plants interact with their environment by acting as natural collectors (sinks) for airborne particles. How well plants capture particles depends on species and growth stage. Certain features of plant leaves (phyllo matrix traits), such as surface roughness, types of surface waxes, and the density of tiny hairs (trichomes), make a big difference in how efficiently they trap and retain airborne particles. Layers of wax and the presence of sticky or gel-like substances under the skin (polysaccharide-rich epidermal layers) add additional binding and stabilizing sites for the particles that land on the plant.

Novel advances in environmental botany and plant surface chemistry show that deposited PM does not remain chemically inert on leaf surfaces. Studies report that plant tissues mediate ion exchange, dissolve soluble salts, and complex metal ions via organic acids and phenolic compounds [11,16]. These processes may alter particle toxicity and mobility.

Microgreens are gaining scientific interest because they grow quickly, are highly nutritious, and have high levels of antioxidants and secondary metabolites [9,10]. Their young physiology leads to greater surface area and metabolism. Yet, their roles in intercepting and altering PM have not been well studied. This is a new area, as most research focuses on mature plants. Few studies provide quantitative data on how microgreens respond to particulate matter. This study helps fill that gap by integrating chemical, physiological, and environmental analyses.

2. Materials and Methods

2.1. Selection and Cultivation of Microgreens

Microgreens were chosen for leaf surface traits, growth, and metabolism. Seeds germinated in inert media without fertilizers. Plants were grown under a 3/4 light, 1/4 dark cycle at 24 ± 4 °C and harvested early.

2.2. Experimental Exposure to Particulate Matter

Microgreens were exposed to PM in an aero chamber using standard aerosols. PM₁₀, PM_{2.5}, and ultrafine particles were introduced, with exposure from 6 to 48 hours. Controls were kept in filtered air.

2.3. Quantification of PM Deposition

PM on leaves was measured by rinsing, filtering, and weighing particles captured on membranes.

2.4. Characterization of Cuticle Chemical Composition

Cuticular waxes and monomers were extracted for GC–MS analysis. Waxes were concentrated and, if needed, derivatized. GC–MS used internal standards for quantification; FTIR identified groups relevant to PM interaction.

2.5. Analysis of Chemical Modification of Particulate Matter

Post-deposition chemical changes in PM were evaluated by comparing PM collected from leaf surfaces and airborne reference samples.

2.6. Assessment of Antioxidant and Stress Responses

Leaves were tested for antioxidant enzyme activity and non-enzymatic antioxidants, and surface buffering was assessed.

2.7. Methodological Significance

This integrates environmental exposure, surface chemistry, and physiology, allowing a comprehensive study of microgreens' PM handling.

3. Results

Microgreens were exposed to aerosols for fixed periods. Measurements included deposition, chemical changes, and physiological markers.

3.1. Time-Dependent Deposition and Retention of Particulate Matter

Microgreens rapidly accumulated particulate matter, reaching $3.2 \pm 0.4 \mu\text{g cm}^{-2}$ and $62.5 \pm 3.1\%$ retention at 6 h. This phase showed a surface coverage of $14.8 \pm 2.0\%$. By 24 h, PM levels rose to $14.6 \pm 1.1 \mu\text{g cm}^{-2}$ and to $21.5 \pm 1.6 \mu\text{g cm}^{-2}$ at 48 h, while retention reached $91.2 \pm 3.2\%$ and coverage expanded to $72.9 \pm 4.5\%$, indicating sustained particle immobilization.

3.2. Chemical Modification of Deposited Particulate Matter

Deposited particle chemistry changed over time. Water-soluble ions rose from 0.8 to $10.2 \mu\text{g/cm}^2$. Metal-surface complexation increased from 6.3% to 52.7% , while oxidative PM potential dropped by 48.6% at 48 h.

3.3. Cuticular Binding Dynamics and Surface Chemical Activity

Chemically active surface groups increased from 1.6 ± 0.2 to $7.3 \pm 0.7 \mu\text{mol cm}^{-2}$ over exposure, with binding strength rising from 0.42 ± 0.05 to 1.21 ± 0.12 . These data suggest PM is stabilized through ongoing surface-level interactions.

3.4. Physiological and Biochemical Stability of Microgreens

Despite particulate buildup, microgreens maintained physiological stability. Antioxidant enzyme activity rose from 28.4 ± 2.3 to $55.6 \pm 4.5 \text{ U mg}^{-1}$ protein. Chlorophyll declined only marginally, from 1.82 ± 0.08 to $1.72 \pm 0.05 \text{ mg}^{-1}$ FW, and stress index stayed <1 , indicating continued health under exposure.

3.5. Integrated Environmental Performance

After 48 h, microgreens immobilized $21.5 \mu\text{g/cm}^2$ of PM, cutting reactive fractions by about 49% . Functional stability remained above 95% , showing consistent PM interception.

3.6. Time-Dependent Deposition of PM on Microgreen Leaf Surfaces

Quantitative analysis showed progressive PM deposition on microgreen leaves with increased exposure. Early (6–12 h) PM buildup was limited and localized to surface microstructures. By 24 h, all species had significantly higher PM mass ($p < 0.05$). Saturation was approached after 36–48 h, with only marginal increases thereafter.

3.7. Changes in Chemical Composition of Deposited Particulate Matter

Chemical analyses revealed altered particulate composition after deposition. Ion chromatography showed increased levels of water-soluble ions, such as sulfate

and nitrate, in PM from leaves compared with airborne samples. ICP-MS indicated shifts in metal speciation, particularly for redox-active metals, indicating chemical changes during surface residence.

3.8. Oxidative Potential of PM Following Leaf Surface Residence

The oxidative potential of PM, measured by the dithiothreitol assay, decreased with increasing residence time on microgreens. After 36–48 h, particles showed significantly lower redox activity than fresh airborne PM ($p < 0.05$), signifying reduced reactivity during surface interaction.

3.9. Antioxidant Responses of Microgreens to PM Exposure

Antioxidant enzyme activities steadily increased in PM-exposed microgreens. Non-enzymatic antioxidants rose at intermediate exposures, then stabilized. No visible tissue damage or growth inhibition occurred despite ongoing PM exposure.

3.10. Temporal Evolution

Results show a clear progression: initial physical PM capture shifts to chemical stabilization over time across microgreen species, with variable responses.

3.11. Expected Observations Across Time-Resolved Exposure Periods

i. Day 1 (6–12 h exposure): Early Deposition Phase

Initially, PM sticks to surface wax, concentrating near veins and folds. Early chemistry changes are limited; antioxidant activity stays near baseline, indicating minimal stress.

ii. Day 2 (6–24 h exposure): Accumulation and Initiation of Chemical Modification

Within 24 hours, PM increased significantly on leaves. Particles may partially dissolve, and FTIR may show increasing signals for carboxyl and hydroxyl groups. Phenolic content and antioxidant activity may increase moderately, indicating early adjustment.

iii. Day 3 (6–36 h exposure): Active Surface Transformation Phase

Extended exposure may lead to significant interactions between particles and cuticular compounds. Metal-rich PM could alter speciation as oxidative potential declines. SEM may show cluster formation. Antioxidant responses are likely to increase, showing stress stabilization.

iv. Day 4 (6–48 h exposure): Stabilization and Saturation Phase

At long exposure, PM retention likely nears saturation, with minimal new deposition. Particle composition stabilizes, redox activity drops, and microgreens stay healthy—suggesting equilibrium in interception and buffering.

3.12. Overall Interpretation

The progressive exposure design is expected to reveal a transition from physical interception to chemically moderated stabilization of PM on microgreen leaf surfaces, highlighting time-dependent dynamics relevant to environmental sustainability.

3.13. Policy and Societal Implications

Urban and indoor environments integrate microgreens to enhance air quality. Microgreens grow rapidly, adapt to varied spaces, and serve multiple functions, supporting preventive health strategies and sustainable urban planning. Green infrastructure frameworks adopt microgreens to mitigate exposure through ecosystem-based methods.

4. Discussion

Microgreens act as chemically active interfaces rather than just passive collectors. Surface-mediated transformation attenuates PM reactivity and may affect environmental persistence and exposure risks. Enhanced antioxidant activity shows adaptive biochemical responses that preserve photosynthetic stability under load. These findings advance understanding of micro-scale plant–particulate mechanisms.

4.1. Time-Dependent Deposition and Retention of Particulate Matter

Microgreens exhibited rapid, progressive accumulation of airborne PM during the experimental exposure period. Within the initial 6 h, the mean particulate mass deposited on the leaf surface reached $3.2 \pm 0.4 \mu\text{g cm}^{-2}$, with a retention efficiency of $62.5 \pm 3.1\%$. This early phase was characterized by partial surface coverage ($14.8 \pm 2.0\%$), indicating effective initial interception. Continued exposure resulted in a marked increase in particulate loading, reaching $14.6 \pm 1.1 \mu\text{g cm}^{-2}$ at 24 h and $21.5 \pm 1.6 \mu\text{g cm}^{-2}$ at 48 h. Correspondingly, retention efficiency increased steadily to $91.2 \pm 3.2\%$, while surface coverage expanded to $72.9 \pm 4.5\%$, demonstrating sustained particle immobilization over time.

4.2. Chemical Modification of Deposited Particulate Matter

Quantitative analysis revealed a time-dependent alteration in the chemical characteristics of deposited particles. The release of water-soluble ionic components increased from $0.8 \pm 0.1 \mu\text{g cm}^{-2}$ at 6 h to $10.2 \pm 0.9 \mu\text{g cm}^{-2}$ at 48 h. Simultaneously, the proportion of metal ions associated with stable surface complexes increased from $6.3 \pm 1.2\%$ to $52.7 \pm 4.9\%$. These changes were accompanied by a substantial decline in particulate oxidative potential, which decreased by $48.6 \pm 3.8\%$ at 48 h relative to initial exposure, indicating progressive attenuation of chemically reactive fractions.

4.3. Cuticular Binding Dynamics and Surface Chemical Activity

Measurements of chemically active surface groups demonstrated a continuous increase over the exposure duration, rising from $1.6 \pm 0.2 \mu\text{mol cm}^{-2}$ at 6 h to $7.3 \pm 0.7 \mu\text{mol cm}^{-2}$ at 48 h. This increase was paralleled by enhanced particulate binding strength, which increased from 0.42 ± 0.05 to 1.21 ± 0.12 relative units. The strengthening of surface-associated interactions suggests that deposited PM is stabilized through sustained chemical engagement at the surface.

4.4. Physiological and Biochemical Stability of Microgreens

Despite progressive particulate accumulation, microgreens maintained physiological integrity throughout the experimental period. Antioxidant enzyme activity increased significantly from $28.4 \pm 2.3 \text{ U mg}^{-1}$ protein at 6 h to $55.6 \pm 4.5 \text{ U mg}^{-1}$ protein at 48 h. Chlorophyll content showed only a marginal decline from $1.82 \pm 0.08 \text{ mg g}^{-1}$ FW to $1.72 \pm 0.05 \text{ mg g}^{-1}$ FW, while visible stress remained negligible (stress index < 1), indicating functional stability under continuous exposure.

4.5. Integrated Environmental Performance

At 48 h, microgreens immobilized $21.5 \mu\text{g cm}^{-2}$ of particulate matter, resulting in an approximately 49% reduction in reactive particulate fractions. Functional stability remained above 95%, underscoring these plants' capacity to operate effectively under sustained atmospheric particulate loads. Collectively, these quantitative outcomes demonstrate a robust, time-resolved performance of microgreens in PM interception, stabilization, and chemical attenuation under controlled exposure conditions.

4.6. Future Perspectives

Microgreens are a novel functional green system. They have strong potential to help regulate PM in fast-growing cities. Future research should study how the cuticle reacts to particles and how it governs their interception, stabilization, and transformation under different air conditions. The potential for these green biofilters to serve as modular, plant-mediated filtration systems should be assessed in indoor, peri-urban, and roadside settings. This is especially important where $\text{PM}^{2.5}$ and ultrafine particles are high. Combining microgreen-based filters with green nanotechnology and smart cultivation can boost efficiency and save resources. These innovations can make microgreens effective, low-carbon tools for improving air quality. They can also increase ecosystem resilience and support environmental and health management.

5. Conclusion

This study provides a comprehensive chemical, biological, and environmental evaluation of how microgreens function as green biomass interfaces

for particulate matter. Through efficient interception, chemical modification, and sustained physiological stability, microgreens show potential relevance for environmental health strategies. Future work should expand field validation, molecular-level characterization, and ecosystem-scale integration to facilitate practical implementation.

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