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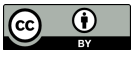
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Atmospheric Pollution Particulate Matter Absorption Efficiency by Bryophytes in Laboratory Conditions

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Abstract: The World Health Organization (WHO) has recognized Particulate Matter (PM) as the main threat to human health from air pollution. One of the solutions is Green Infrastructure (GI), which uses different plants to mitigate pollution. Among these plants are bryophytes (or more commonly used mosses), which have easier maintenance, lighter weight, and durability compared to vascular plants. However, currently, there is limited knowledge of its effectiveness in air pollution mitigation. By addressing this gap in current scientific knowledge, more effective deployment of GI could be introduced by municipalities for society's health benefits. This study aimed to evaluate three species of mosses (*Dicranum scoparium*, *Plagiomnium affine*, and *Hypnum cupressiforme*) and one thuja (*Thuja plicata*) as a control species for a possible GI vertical barrier for local de-pollution. The objective was to assess different moss species' effectiveness in air pollution $PM_{2.5}$ and PM_{10} absorption in a laboratory setting. The practical experiment was conducted from June–July 2024 in the Laboratory of the Physics and Chemistry of Environment and Space in Orleans (LPC2E-CNRS), France. For the experiment, a unique air pollution chamber was engineered and built with a linear barrier of GI inside to measure pollution absorption before and after the barrier. With the obtained data from the sensors, the efficiency of the vegetation barrier was calculated. The total average efficiency of all 18 tests and tested moss species is 41% for $PM_{2.5}$ and 47% for PM_{10} mass concentrations. Efficiency shows moss species' maximum or optimal ability to absorb pollution $PM_{2.5}$ and PM_{10} in laboratory environments, with the limitations indicated in this article. This research is an essential step towards further and more profound research on the effectiveness of GI barriers of mosses in urban environments. It significantly contributes to understanding GI effects on air pollution and presents the results for specific moss species and their capacity for $PM_{2.5}$ and PM_{10} mitigation in the air. The novelty of the study lies in a particular application of the chosen moss species.

Keywords: air pollution; bryophytes; mosses; particulate matter; pollution mitigation

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1. Introduction

Air pollution as a threat to human health [1] has been recognized since the time of Hippocrates around 400 BCE [2] and is currently a global issue [3,4], resulting in more than 8 million deaths per year [5]. A major pollutant [6,7] is Particulate Matter (PM), which can be divisible by its size, for example, PM_{10} are inhalable particles with a diameter that is generally 10 μm and smaller [1], but the most hazardous is $PM_{2.5}$, fine dust particles typically 2.5 μm in diameter or smaller, according to ref. [8–10] that are not visible to

the naked eye [11]. The chemical composition of PM is complex [12,13]—these are tiny particles consisting of both liquid droplets and solid particles composed of carbonaceous materials, metals, mineral dust, and salts [9,14,15]. PM sources are both natural and anthropogenic [16,17]. Man-made PM sources are combustion in mechanical and industrial processes, vehicle emissions, tobacco smoke [18–21], and wood burning for heating, which is a significant PM source [22–27] and is epidemiologically linked to various adverse effects on health and mortality [28–31]. In some countries, wood and coal stoves are the largest source of the pollutant $PM_{2.5}$. This type of pollution consists of tiny particles absorbed deep into human bodies, including the lungs and blood. It has been recognized by the World Health Organization (WHO) as the most severe air pollutant for human health [32].

The biggest issue globally occurs in cities where outdoor air quality in most areas does not meet the WHO's guidelines for healthy living [33]. Although reducing pollutant emissions is always the most direct way to improve urban air quality [34–36], authorities worldwide have struggled to deliver adequate improvements in air quality through emission control strategies alone. Thus, policymakers increasingly turn to additional methods to reduce human exposure to air pollutants, but as cities expand, the number of motor vehicles increases, and the distance traveled enlarges [37,38]. The presence of diesel vehicles, many of which do not comply with emission regulations, becomes a significant additional disadvantage [39,40].

Although air pollution is a global problem, solutions can be found in an urban, local context. For instance, an efficient solution is based on nature—using different plants for air purification with phytoremediation [41–43], green infrastructure (GI), and urban greening methods [44,45]. GI is the network of natural environmental components and green spaces in cities that provide ecosystem services: parks, street trees, gardens, and urban woodland [46–48]. Implementing GI in cities can mitigate exposure to air pollution [49,50], as GI can act as a porous barrier [49,51,52], altering local air dispersion patterns and providing a relatively high surface area for pollutant deposition [49,52,53]. Particularly linear barriers—such as hedges or fences—between source and receptor zones [Figure 1] redirect the air pollutants upwards, effectively extending the length of the air pathway from source to receptor. They may also promote concentration reduction by increasing turbulence [46].

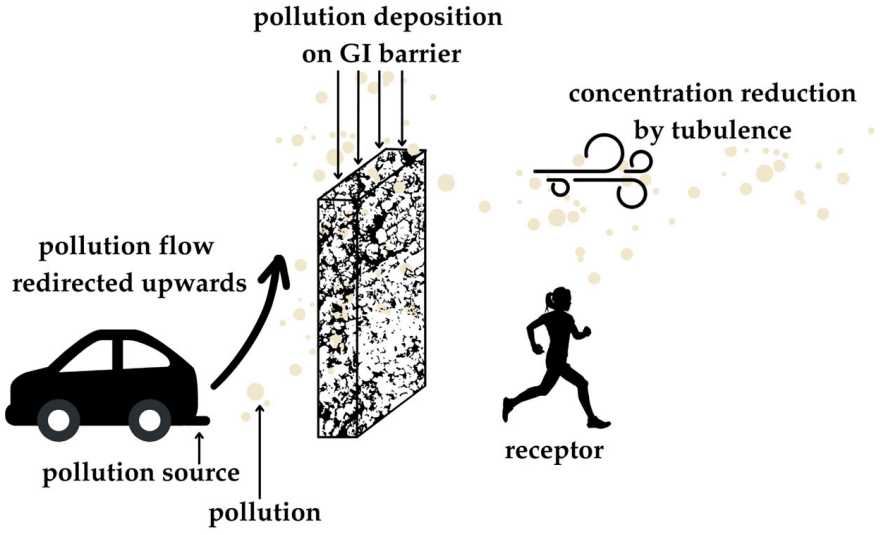


Figure 1. Illustration of air pollution transport, adapted by the authors [54] (p. 46).

Thus, hedges and fences can decrease air pollution concentrations in sidewalks and other pedestrian areas adjacent to traffic [55–58].

However, selecting plants for GI is challenging due to the lack of information on species resilience to heat and water fluctuations and their ability to provide various benefits [59–61], like air pollution mitigation [59,62]. Bryophytes (or mosses, more commonly used) can endure challenging environments, and have easier maintenance, lighter weight, and durability compared to vascular plants [63]; therefore, they might be used for air mitigation purposes, but there is limited data on their efficiency yet. Research has shown that utilizing mosses [63–65] in the GI can enhance ecosystem benefits [66,67]. Some preliminary studies of moss utilization within GI have shown effective rainwater management, the ability to reduce surface temperature [63], and the ability to trap atmospheric pollutants [67–69]. This feature is facilitated by mosses having rhizoids instead of roots [70], which was addressed in a study by Haynes et al. 2019 [71]. The study was conducted by analyzing three highways with high pollution levels, three suburban roads with moderate pollution levels, and three quiet suburban roads with low pollution levels, which were tested to compare the effects of moss and tree leaves on PM levels. Researchers found that when the site was more polluted, the moss cleaned up exponentially higher traces of PM, while the amount in tree leaves did not change as much. Overall, in this experiment, moss removed 3.8 times more PM than a tree leaf of the same dry weight, with higher efficiency of PM size 10–100 μm and lower for PM 0.2–2.5 [71]. On the contrary, another study in Italy in 2021 also evaluated the capacity of three moss species—*Barbula unguiculata*, *Grimmia pulvinata*, and *Homalothecium sericeum* to mitigate urban air pollution. After a three-month exposure in a high-traffic urban setting, samples were examined using Field Emission Scanning Electron Microscopy (SEM) to quantify particle deposition, and results revealed that the mosses collected up to 45,580 particles per mm^2. Approximately 45–55% of captured particles were in the $PM_{0.5}$ μm range, underscoring the potential of these moss species to retain fine particles effectively within urban environments [67]. The study suggests that most of the found particles on the surface are in diameters between 2.5 and 10 μm, rarely more significant than 25 μm [67]. Mosses might be effective in pollution mitigation, but there is a gap in knowledge on the effectiveness, specifically of vertical barrier placement of mosses, and both laboratory and field studies must be conducted. This article represents the results of a laboratory experiment on the effectiveness of mosses on air pollution mitigation and is part of broader research on mosses for urban application of pollution removal.

Wind direction also must be taken into account for GI, as it significantly impacts the dispersion of $PM_{2.5}$ [72]. Prevailing winds can enhance and diminish air pollutants depending on wind strength and duration [73]. Thus, intense and sustained prevailing winds can cleanse the air of contaminants [74]. Still, conversely, they can also transport air pollutants from upwind regions, worsening air quality in the direction of the wind [75,76]. It is also important to determine other variables for the GI linear barrier placement location, such as average wind speed, humidity, atmospheric pressure, cardinal directions, etc. Therefore, measurements at the location must be taken before barrier placement, and later, $PM_{2.5}$ concentration differences between the traffic area and the area next to the barrier must be taken and evaluated. Valid air quality sensors must be used to obtain air quality improvement results [77].

This research rationale, with a practical experiment, is based on the literature analysis and results of existing data on the topic. Models may often and significantly underestimate the contribution of GI to air quality, thus limiting their reliability for application in urban management [78]. The objective of this study was to assess different moss species for their effectiveness of air pollution $PM_{2.5}$ and PM_{10} absorption in a laboratory setting; therefore, a novel laboratory experiment design was created and tested. The study aimed to answer the research question: Can mosses absorb air pollution $PM_{2.5}$ and PM_{10} in a laboratory setting, and what is the average efficiency of moss species *Dicranum scoparium*, *Plagiomnium*

affine, and *Hypnum cupressiforme* in a vertical position? This research provides a clear contribution to further research on GI barriers of mosses in an urban environment and serves as preliminary knowledge for further field research.

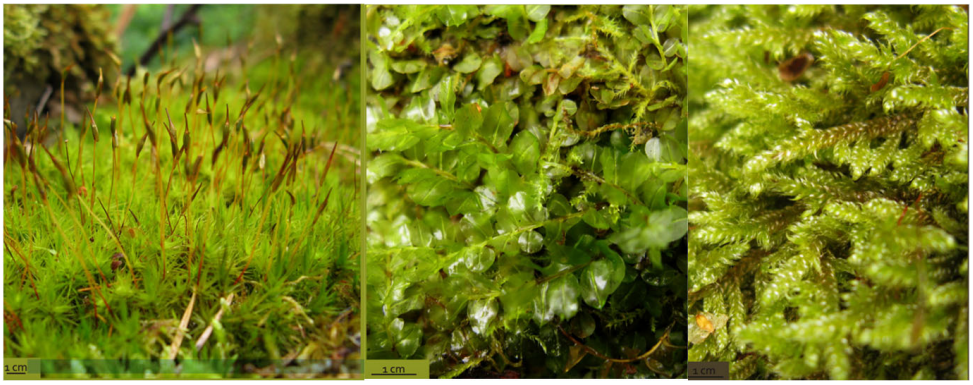
2. Materials and Methods

The practical experiment was conducted from June to July 2024 in the Laboratory of the Physics and Chemistry of Environment and Space in Orleans (LPC2E-CNRS), France. There were 3 bryophyte species tested in a special experimental chamber.

2.1. Selection of Experimental Material

The following bryophyte species—*Dicranum scoparium*, *Plagiomnium affine*. and *Hypnum cupressiforme* (Figure 2)—were chosen based on these specifications:

1. According to the literature review [79–84], selected moss species were identified as most effective in absorbing urban air pollution;
2. Species are cosmopolitan, growing in different parts of the world, commonly widespread in Europe's temperate climate zone and urban environments;
3. Species can sustain different environmental conditions, including hot sun and shading areas, a wide range of temperature fluctuations, and have a high capacity to absorb water.



(**a**) (**b**) (**c**)

Figure 2. Selected moss species for the experiment: (**a**) *Dicranum scoparium*; (**b**) *Plagiomnium affine*; (**c**) *Hypnum cupressiforme.* Photos by the fifth author.

Selected moss species were purchased from a certified moss cultivation company in France ("The Bryophyta Nursery") to ensure the project's sustainability and the moss species' precision. Each moss sample was 4680 cm^2 in size and was stored under appropriate conditions in the laboratory, where the environment was controlled to prevent the moss from drying out before the experiment. Moreover, *Thuja plicata* was collected in Orleans city from a hedge and chosen as a control species for mosses, as thujas are typical for urban hedges in Europe.

2.2. Laboratory Design, Equipment Properties, and Validation

For the experiment, a special air pollution chamber (Figure 3b) was engineered and built with a size of 340 × 65 × 72 cm. The chamber was built from different materials: metal for the main construction (3 × 3 cm); transparent polyethylene film was used for the walls and roof (width of 3 m and a thickness of 50 mkr), and it was rolled over the metal construction 5 times to ensure durability. Adhesive tape was used all over the chamber connection places to ensure it was hermetically sealed. Inside the chamber, a linear barrier of vegetation was displayed, with a size of 65 × 72 cm. Vegetation was placed between the

metal mesh (Figure 3a), also referred to as a tile. One tile was prepared for each species and tested repeatedly for all tests (6 tests for each species, 18 in total).



(**a**) (**b**)

Figure 3. Photos by the second author. (**a**) Prepared tiles of a linear vegetation barrier outside the chamber; (**b**) experimental chamber.

The experimental chamber (Figure 4) had a fan to create traction with 2 levels of speed (lower speed created traction speed of 0.5 m s^{-1}, higher speed created traction speed of 1.2 m s^{-1}), and pollution was injected from the other side of the chamber using a manual nebulizer. During the experiment, different types of pollution were injected: Icelandic volcanic dust, granite, and concrete, for each test, 1 g of pollution. Pollution was injected directly towards the vegetation tile (distance between 200 cm). To clean the chamber after each test, an extractor was used, which cleaned the chamber with the airflow. Before the beginning of each test, the background concentration was measured using both Pollutrack sensors, and tests started only when the concentrations in both sensors for either $PM_{2.5}$ or PM_{10} were less than 5 µm (mass concentration). To obtain the data, atmospheric pressure daily data were taken directly from Meteo France's daily web, and for other measurements, several instruments were used: a wind speed measurement device (Anemometer (manufactured by XRCLIF, China) certified by CE, RoHS, and FC), humidity and temperature station (ThermPro TP358-GB, manufactured by ThermoPro, Toronto, Canada), two calibrated $PM_{2.5}$ and PM_{10} measurement sensors Pollutrack (manufactured by company Pollutrack, Bretigny-sur-Orge, France) [85], one installed before vegetation, another after. Both fractions, $PM_{2.5}$ and PM_{10} mass concentrations, were measured by Pollutrack sensors in parallel at the same session. The Pollutrack sensor is a compact optical particle counter that measures PM concentrations by analyzing light scattered from particles crossing a laser beam. It detects particle sizes from 0.5 to 10 µm and converts counts into $PM_{2.5}$ and PM_{10} mass concentrations using internal calibrations [86]. Measurements from sensors were also taken once every 10 s. Each test was conducted for 20 min: (a) background concentration in the chamber was measured for the first 10 min; (b) pollution injection was performed; (c) to measure changes in background concentration, measurements were taken for 9–10 more minutes. The key target of these tests was to obtain data on different moss species absorption effectiveness of $PM_{2.5}$ and PM_{10}.

To calculate the efficiency of the vegetation barrier, the following equation was used:

$$E = 100 \times \frac{M_{before} - M_{after}}{M_{before}}$$

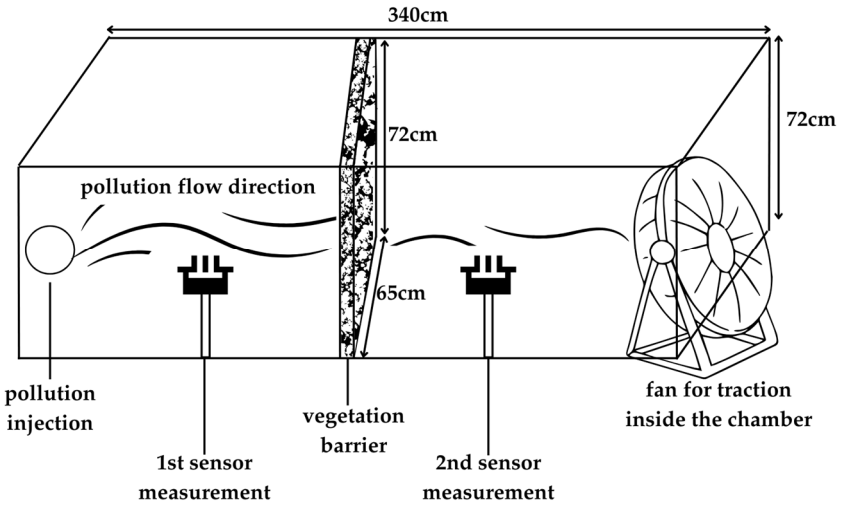


Figure 4. Built an experimental chamber. Drawing by the first author.

E = efficiency;

M_{before}—measurements before the injection;

M_{after}—measurements after the injection.

To determine total efficiency, it is valuable to analyze the efficiency during the injection and calculate the average injection efficiency for each species at different wind speeds. This experiment had limitations such as temperature, humidity, and atmospheric pressure in laboratory conditions. Each parameter was measured, and all data on the limitations are presented in Table 1. The limitation of vegetation samples was considered, as there was one sample for each of the vegetation types after each test chamber cleaning with the extractor fan was conducted.

Table 1. Experiment limitations.

Wind Speed (WS)	Humidity Inside the Chamber	Temperature Inside the Chamber	Atmospheric Pressure
Two WS tested: 0.5 m s^{-1} and 1.2 m s^{-1}	78–93% (mostly around 82–87%)	20.2–21.2 °C	1012 to 1015 Pa

After efficiency data were calculated, statistical analysis of variance (ANOVA) was conducted to assess the difference between the means of these three test groups (each test group represents each moss species). For each moss species, a separate group was created, and four variables to this group were added (average efficiency for wind speed 0.5 m s^{-1} for $PM_{2.5}$, wind speed 1.2 m s^{-1} for $PM_{2.5}$, wind speed 0.5 m s^{-1} for PM_{10}, wind speed 1.2 m s^{-1} for PM_{10}). Further, each of the numbers in each group (x) was squared (x^2), and then the Data Summary table was created using the following formulas:

$$\sum x = x1 + x2 + x3 + x4 \quad (1)$$

$$\text{Mean} = \frac{\Sigma}{n} \quad (2)$$

$\sum$ = the total of all values in the group;

N = number of observations (in this case, 4).

$$\sum x^2 = {x_1}^2 + {x_2}^2 + {x_3}^2 + {x_4}^2 \quad (3)$$

$$\text{Std.Dev. or s} = \sqrt{\frac{\Sigma(x_i - \overline{x})^2}{n-1}} \quad (4)$$

x_i = each value;

$\overline{x}$ = mean of the group;

n = number of values in the group (4).

As a last step, the ANOVA summary table was filled in by following calculations with a target to calculate F and *p* values. It is important to obtain these values to determine how much the group means differ from each other relative to how much the values vary within each group (F value) and to calculate the probability that the differences between group means happened by chance (*p* value).

$$\text{F value F} = \frac{\text{MS}_{\text{between}}}{\text{MS}_{\text{within}}}$$

$$\text{MS}_{\text{between}} = \frac{\text{SS}_{\text{between}}}{\text{df}_{\text{between}}}$$

$$\text{MS}_{\text{within}} = \frac{\text{SS}_{\text{within}}}{\text{df}_{\text{within}}}$$

SS = sum of squares;

Df = degrees of freedom;

MS = mean square (variance estimate).

To obtain all the needed variables for F value calculations, it is necessary to obtain DF (degrees of freedom) and SS (Sum of squares) using calculations, that are standard for ANOVA analysis.

A validation session was conducted using the Light Optical Aerosol Counter (LOAC) instrument to obtain validation of the measurements taken by the Pollutrack sensors during this experiment. LOAC is an instrument used for scientific purposes, and it is involved in several atmospheric research programs for the determination of the concentration and properties of tropospheric and stratospheric aerosols [87]. This aerosol counter uses a laser beam and two scattering angles, 12°, and 60°, respectively, which allow the determination of aerosol concentration (number of aerosols per cm^3) in 19 size classes from 0.2 to 30 µm, as well as identify the typology of the aerosols according to five leading particle families (Carbons, Droplets, Ice, Salt, and Minerals).

Overall, the selected materials and methods proved effective in collecting data for analysis and interpretation of results.

3. Results

Results are depicted in graphs (Figure 5) where three different color lines show different $PM_{2.5}$ efficiency after injection: Efficiency AB shows the first 10 s of injection, followed by Efficiency CD with the next 10 s of injections (second 20), and Efficiency EF shows the last 10 s (second 30). PM_{10} injection was performed in the same manner as Efficiency GH in the first 10 s of injection, Efficiency JK in the second 10 s, and Efficiency LM in the last 30 s after the start of injection. After the first 30 s, the pollution level drops significantly to a level close to the initial amount of pollution. Each of the six tests on each moss species shows slightly different efficiency, although there is a correlation between all tests and the timing after pollution injection. For example, the graph shows that in the first 10 s (Efficiency AB), the average efficiency of the *Dicranum scoparium* moss species linear barrier is 33% (Figure 5a).

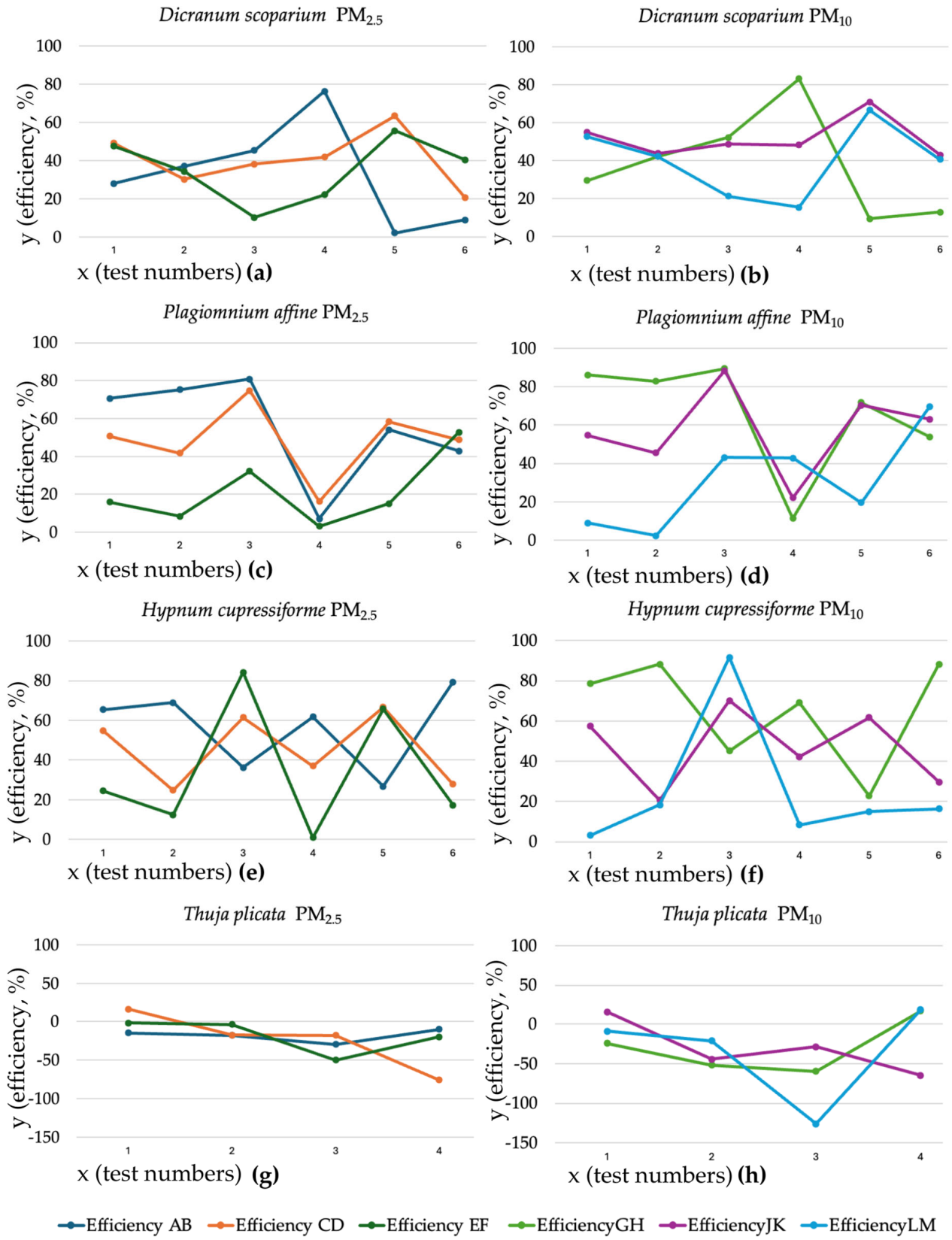


Figure 5. Three moss species, *Dicranum scoparium*, *Plagiomnium affine*, *Hypnum cupressiforme*, and a tree species *Thuja plicata* $PM_{2.5}$ and PM_{10} absorption efficiency in the first 10 (AB/GH); 20 (CD/JK); and 30 (EF/LM) seconds after pollution injection. Graphs represent all tests for both wind speeds, each of the subfigures (**a**–**h**) represent each species result.

In this round of tests (Figure 5), two wind speeds were tested: 0.5 m s^{-1} and 1.2 m s^{-1}, which show different efficiency results. Table 2 shows all the data on the limitations. The moss species *D. scoparium* showed higher PM_{10} absorption efficiency compared to $PM_{2.5}$. The average absorption efficiency for PM_{10} was 43% against the average efficiency for $PM_{2.5}$ of 36%, indicating that the moss species *D. scoparium* better absorbs larger particles. Similarly, another moss species showed better results for the efficiency of larger particles. For example, during the tests on the moss species *Plagiomnium affine* $PM_{2.5}$ absorption, correlations were found between the tests, showing an average overall efficiency of 46.5% (Figure 5c). At the same time, *P. affine* PM_{10} absorption efficiency was found to be even higher, with similar results between all three tests with a wind speed of 0.5 m s^{-1}, showing a significant result of an average of 86% in efficiency AB (Figure 5d). Furthermore, the moss species *Hypnum cupressiforme* showed the highest efficiency (45%), among all three tested moss species during the seven tests with $PM_{2.5}$ pollution (Figure 5e). However, there were different patterns across the tests, which are explained in the Discussion paragraph. Data on all three moss species tests are available in the Supplementary Material. As a control species against mosses to assess differences (Figure 5g,h), the coniferous tree species Thuja plicata was tested. The same experimental protocol was applied, and each test with thuja showed the same result, with no absorption capacity and additional pollution detected in the second sensor. Thus, indicating that *T. plicata* has no efficiency in pollution absorption. *T. plicata* obtained a negative result (−20% for $PM_{2.5}$ and −35% for PM_{10}), which means that the existing pollution was displaced due to the traction force created by the fan (wind speed 1.2 m s^{-1}). This leads to the conclusion that *T. plicata* does not absorb any pollution in the laboratory environment, and the air is even more polluted on the other side of the barrier because it is closer to the fan that created the traction. Further research is needed to analyze the pollution absorption of *T. plicata* in the outdoor environment. Still, this study shows that *T. plicata* cannot remove $PM_{2.5}$ and/or PM_{10} pollution from the air. The average efficiency per two wind speeds for separately $PM_{2.5}$ and PM_{10} and all tested vegetation is shown in Table 2. The table depicts that the most effective is the moss species *P. affine* for PM_{10} in wind speed 0.5 m s^{-1}, followed by *H. cupressiforme* in 1.2 m s^{-1}.

Table 2. Total average efficiency for both sizes of PM, different wind speeds, and different vegetation.

		$PM_{2.5}$			**PM_{10}**		
Moss Species	**Number of Tests**	**Average Efficiency (WS 0.5 m s^{-1})**	**Average Efficiency (WS 1.2 m s^{-1})**	**Average Efficiency**	**Average Efficiency (WS 0.5 m s^{-1})**	**Average Efficiency (WS 1.2 m s^{-1})**	**Average Efficiency**
D. scoparium	6	36.82	35.54	36.18	43.30	42.99	43.15
P. affine	6	50.06	33.19	41.63	55.73	47.16	51.45
H. cupressiforme	6	42.58	48.06	45.32	39.28	52.58	45.93
3 moss species	18	43.15	38.93	41.04	46.10	47.58	46.84
T. plicata	4	No data	−20.34	−20.34	No data	−34.57	−34.57

Analysis of variance (ANOVA) statistical test was used to assess the difference between the means of three tested moss species and their effectiveness in $PM_{2.5}$ and PM_{10} absorption (Table 3).

Table 3. Three species efficiency values for both $PM_{2.5}$ and PM_{10} absorption effectiveness, ANOVA test.

Group 1 (*D. scoparium*)	Group 2 (*P. affine*)	Group 3 (*H. cupressiforme*)
37	50	43
36	33	48
43	56	39
43	47	53

Table 3 shows the average efficiency of each moss species for $PM_{2.5}$ and PM_{10} absorption, and Table 4 depicts the groups (moss species) square summary based on the ANOVA test.

Table 4. Groups (3 species) square summary, ANOVA test.

Group 1^2	Group 2^2	Group 3^2
1369	2500	1849
1296	1089	2304
1849	3136	1521
1849	2209	2809

Table 5 shows a data summary based on an ANOVA test, which consists of such values as: N (sample Size) represents the number of observations (data points) in each group (species). Each group has 4 observations, and the total number of observations is 12; Σx (sum of values) shows the sum of all individual values in each group. The mean represents the mean (average) efficiency for each moss species. Σx^2 (sum of squared values) illustrates the sum of the squares of individual values in each group and Std.Dev. stands for standard deviation, this value measures the dispersion or spread of values in each group. Standard deviation depicts how dispersed the data are against the mean.

Table 5. Data summary, ANOVA test.

Groups	N	∑x	Mean	$\sum x^2$	Std.Dev.
Group 1	4	159	39.75	6363	3.7749
Group 2	4	186	46.5	8934	9.7468
Group 3	4	183	45.75	8483	6.0759
Total	12	528	44	23,780	

From the data summary (Table 5), it is visible that Group 2 (*P. affine*) has the highest mean (45.5) and the highest standard deviation (9.7), indicating more variation in values. Group 1 (*D. scoparium*) has the lowest mean (40) but the lowest standard deviation. The total mean (44) gives the average across all groups combined. ANOVA summary is shown in Table 6 and it depicts five values: DF (degrees of freedom) represents the number of independent values; SS (Sum of Squares) represents the total variation; MS (Mean Square) shows the average variance for each source, calculated between and within groups; F-Stat (F-Ratio) measures whether the between-group variability is significantly larger than the within-group variability and *p*-value shows the probability of obtaining the observed results assuming the null hypothesis (no difference between groups) is true.

Table 6. ANOVA test summary.

Source	DF	SS	MS	F-Stat	*p*-Value
Between Groups	2	109.5	54.75	1.12	0.36665
Within Groups	9	438.5	48.72		
Total	11	548			

In the ANOVA test (Table 6), a larger F-value indicates a more significant difference among the group means and suggests that the group variations are significant. Since the *p*-value (0.37) is much higher than 0.05, there is no significant difference between the group means. At the same time, if the *p*-value is less than the chosen significance level (set at 0.05), it indicates statistically significant differences among the groups, which gives evidence to reject the null hypothesis, which assumes no significant differences. Since $p > 0.05$, the result is not statistically significant, meaning there is no strong evidence that moss species differ in their effectiveness in absorbing $PM_{2.5}$ and $PM_{10.}$ Therefore, the authors focus on all three moss species' average efficiency.

4. Discussion

Based on the results, it is possible to elaborate on the efficiency or the optimal ability of mosses to absorb pollution $PM_{2.5}$ and PM_{10} in laboratory environments with the limitations indicated above in the article (such as humidity, atmospheric pressure, temperature) and under conditions when the pollution is injected directly towards the moss tile.

Different effectiveness across tests could be explained by the different forces of injection for each test. As injection was performed manually (using a hand nebulizer), speed and force did differ, but traction from the fan equated to the force. To validate the results obtained from Pollutrack sensors, another session was organized using the LOAC tool.

LOAC Instrument Testing

The same experiment protocol was used to obtain results with the LOAC instrument, and LOAC sessions were carried out in parallel with a Pollutrack experiment. As the mean values of $PM_{2.5}$ mass concentrations may change from the first to the second session, the LOAC values had to be adjusted for direct comparison. LOAC values for the second session are multiplied by the total value of the Pollutrack sensor in the first session before the moss wall and divided by the total value of the Pollutrack sensor in the second session before the moss wall. Average de-pollution efficiency with Pollutrack sensors in the first session: 4% considering all values and 10% considering values above 20 $\mu g/cm^3$ (thus during dust injections). Average de-pollution efficiency with Pollutrack sensors in the second session: 15% considering all values and 35% considering measurements above 20 $\mu g/cm^3$ (thus during injections). At the same time, the average de-pollution efficiency with LOAC sensors was 13% considering all values and 31% considering measurements above 20 $\mu g/cm^3$ (thus, during injections). These values are close to Pollutrack results, providing a validation of the experiment, as well as LOAC sessions depict a broader view of the pollution that vegetation barriers absorb. For example, the figure below (Figure 6) shows the size distribution of the LOAC measurement. Squares represent the error bars. The coarse code of the sample ("Blanc de Meudon", composed of $CaCO_3$) is visible between 1 and 20 µm. This shows that the moss wall absorbs the largest and heaviest particles, increasing efficiency with increasing size (if the size distribution remains the same in the absence of the moss wall, which is a plausible hypothesis given the particle transport wind system used in the experiment).

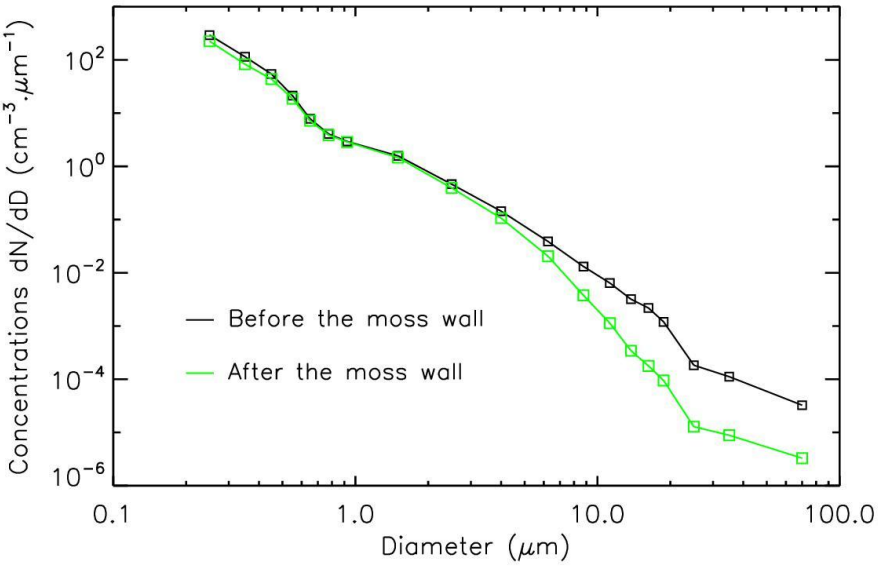


Figure 6. Size distribution of LOAC instrument data.

During the experiment, it was found that the moss absorption of the pollution is prompt, and the efficiency increases with larger particles. This experiment shows that the selected moss species can de-pollute in closed conditions with stable traction under stable meteorological conditions.

The results from the three moss species tiles absorbing fine dust pollution $PM_{2.5}$ and PM_{10} experiment are promising for scientific purposes and the practical application of mosses in indoor or outdoor air quality improvement. The lessons from this experiment could also validate existing technologies using these three moss species. Further research is needed on other moss species and a more in-depth analysis of how mosses absorb, store, and remove pollution. For the experiment, different wind speeds were used to test all three moss species, yet there is no clear correlation between different wind speeds and all three moss species for example, *Dicranum scoparium* showed similar results within different wind speeds: 37% average efficiency at 0.5 m s^{-1} and 36% at 1.2 m s^{-1} for $PM_{2.5}$ and similarly for PM_{10} with 43% for either lower and higher wind speed. Therefore, the authors conclude that this moss species is equally efficient in both tested wind speeds (0.5 and 1.2 m s^{-1}). On the contrary, moss species *Plagiomnium affine* depict different patterns with higher efficiency (50%) at lower wind speeds for $PM_{2.5}$ and 56% for PM_{10} versus significantly lower efficiency for $PM_{2.5}$ at higher wind speed (33%) and less significant for PM_{10} (47%). For the moss species *Hypnum cupressiforme*, the opposite pattern versus *Plagiomnium affine* was detected with higher efficiency (48% versus 43%) for higher wind speed for $PM_{2.5}$ and 53% versus 39% for PM_{10}. The authors conclude that three different patterns across three different species were observed: *D. scoparium* showed similar results for both wind speeds, *P. affine* species were more effective at lower wind speeds, and *H. cupressiforme* was more efficient at lower wind speeds. The authors observed that there were differences between efficiency for different sizes of particles: all three moss species demonstrated higher efficiency for PM_{10} absorption vs. $PM_{2.5}$, with the highest difference for *P. affine*, with almost a 10% difference (41.63% for $PM_{2.5}$ versus 51.45% for PM_{10}). *D. scoparium* showed a similar pattern with the highest efficiency for PM_{10} (43.15%) vs. $PM_{2.5}$ (36.18%). On the other hand, moss species, *H. cupressiforme*, showed just a slight difference in efficiency, with 45.93% for PM_{10} versus 45.32% for $PM_{2.5}$. From all tests that were conducted, the moss species *Plagiomnium affine* obtained the highest efficiency, at 56%, during lower wind and PM_{10} absorption; this is the highest result in this experiment.

Overall, the authors observed slight differences in different moss species and their effectiveness, but as per ANOVA test results, these differences are insignificant to view each moss species separately; therefore, the authors conclude that these three tested moss species are effective on air pollution $PM_{2.5}$ and PM_{10} absorption in laboratory settings under the described controlled conditions. As the objective of this study was to assess different moss species on their effectiveness of air pollution $PM_{2.5}$ and PM_{10} absorption in a laboratory setting, a novel laboratory experiment design was created and tested. The study answered the proposed research question with the clear understanding that moss species *Dicranum scoparium*, *Plagiomnium affine*, and *Hypnum cupressiforme* in a vertical position have an average absorption efficiency for $PM_{2.5}$ pollution of 41%, and for PM_{10}, it is 47%. Further research on the same three moss species in experiments outside the controlled environment is needed to determine absorption efficiency under outdoor conditions.

Supplementary Materials: Supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16040479/s1. Data on all three moss species tests are available in the Supplementary Material.

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References

1. Air Pollution: How It Affects Our Health. Available online: https://www.eea.europa.eu/en/topics/in-depth/air-pollution/eow-it-affects-our-health (accessed on 20 November 2024).
2. Fowler, D. A Chronology of Global Air Quality. *Philos. Trans. R. Soc. A.* **2020**, *378*, 20190314. [CrossRef] [PubMed]
3. Brunekreef, B. Air Pollution and Human Health: From Local to Global Issues. *Proc. Soc. Behav. Sci.* **2010**, *2*, 6661–6669. [CrossRef]
4. Air Pollution. Available online: https://www.who.int/health-topics/air-pollution#tab=tab_1 (accessed on 20 November 2024).
5. Environment, U.N. Pollution and Health. Available online: https://www.unep.org/topics/chemicals-and-pollution-action/pollution-and-health (accessed on 20 November 2024).
6. Nazarenko, Y.; Pal, D.; Ariya, P.A. Air Quality Standards for the Concentration of Particulate Matter 2.5, Global Descriptive Analysis. *Bull. World Health Organ.* **2020**, *99*, 125–137. [CrossRef]

7. Henning, R.J. Particulate Matter Air Pollution Is a Significant Risk Factor for Cardiovascular Disease. *Curr. Probl. Cardiol.* **2024**, *49*, 102094. [CrossRef] [PubMed]
8. Xing, Y.-F.; Xu, Y.-H.; Shi, M.-H.; Lian, Y.-X. The Impact of PM2.5 on the Human Respiratory System. *J. Thorac. Dis.* **2016**, *8*, E69–E74. [CrossRef]
9. Li, B.; Ma, Y.; Zhou, Y.; Chai, E. Research Progress of Different Components of PM2.5 and Ischemic Stroke. *Sci. Rep.* **2023**, *13*, 15965. [CrossRef]
10. Zhou, J.; Huebner, G.; Liu, K.Y.; Ucci, M. Heart Rate Variability, Electrodermal Activity and Cognition in Adults: Association with Short-Term Indoor PM2.5 Exposure in a Real-World Intervention Study. *Environ. Res.* **2024**, *263*, 120245. [CrossRef]
11. Particulate Matter (PM) Basics. Available online: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics (accessed on 20 November 2024).
12. Alves, C.; Evtyugina, M.; Vicente, E.; Vicente, A.; Rienda, I.C.; de la Campa, A.S.; Tomé, M.; Duarte, I. PM2.5 Chemical Composition and Health Risks by Inhalation near a Chemical Complex. *J. Environ. Sci.* **2023**, *124*, 860–874. [CrossRef]
13. Juda-Rezler, K.; Reizer, M.; Maciejewska, K.; Błaszczak, B.; Klejnowski, K. Characterization of Atmospheric PM2.5 Sources at a Central European Urban Background Site. *Sci. Total. Environ.* **2020**, *713*, 136729. [CrossRef]
14. Dominici, F.; Wang, Y.; Correia, A.W.; Ezzati, M.; Pope, C.A.; Dockery, D.W. Chemical Composition of Fine Particulate Matter and Life Expectancy. *Epidemiology* **2015**, *26*, 556–564. [CrossRef]
15. Zhang, H.; Li, Z.; Liu, Y.; Xinag, P.; Cui, X.; Ye, H.; Hu, B.; Lou, L. Physical and Chemical Characteristics of PM2.5 and Its Toxicity to Human Bronchial Cells BEAS-2B in the Winter and Summer. *J. Zhejiang Univ. Sci. B* **2018**, *19*, 317–326. [CrossRef] [PubMed]
16. Sources of Indoor Particulate Matter (PM). Available online: https://www.epa.gov/indoor-air-quality-iaq/sources-indoor-particulate-matter-pm (accessed on 20 November 2024).
17. Mukherjee, A.; Agrawal, M. World Air Particulate Matter: Sources, Distribution and Health Effects. *Environ. Chem. Lett.* **2017**, *15*, 283–309. [CrossRef]
18. Anderson, J.O.; Thundiyil, J.G.; Stolbach, A. Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. *J. Med. Toxicol.* **2011**, *8*, 166–175. [CrossRef] [PubMed]
19. Karagulian, F.; Belis, C.A.; Dora, C.F.C.; Prüss-Ustün, A.M.; Bonjour, S.; Adair-Rohani, H.; Amann, M. Contributions to Cities' Ambient Particulate Matter (PM): A Systematic Review of Local Source Contributions at Global Level. *Atmos. Environ.* **2015**, *120*, 475–483. [CrossRef]
20. Kleeman, M.J.; Schauer, J.J.; Cass, G.R. Size and Composition Distribution of Fine Particulate Matter Emitted from Wood Burning, Meat Charbroiling, and Cigarettes. *Environ. Sci. Technol.* **1999**, *33*, 3516–3523. [CrossRef]
21. Fernández, E.; Ballbè, M.; Sureda, X.; Fu, M.; Saltó, E.; Martínez-Sánchez, J.M. Particulate Matter from Electronic Cigarettes and Conventional Cigarettes: A Systematic Review and Observational Study. *Curr. Environ. Health Rep.* **2015**, *2*, 423–429. [CrossRef]
22. Fadel, M.; Ledoux, F.; Seigneur, M.; Oikonomou, K.; Sciare, J.; Courcot, D.; Afif, C. Chemical Profiles of PM2.5 Emitted from Various Anthropogenic Sources of the Eastern Mediterranean: Cooking, Wood Burning, and Diesel Generators. *Environ. Res.* **2022**, *211*, 113032. [CrossRef]
23. Canha, N.; Almeida, S.M.; do Carmo Freitas, M.; Wolterbeek, H.T.; Cardoso, J.; Pio, C.; Caseiro, A. Impact of Wood Burning on Indoor PM2.5 in a Primary School in Rural Portugal. *Atmos. Environ.* **2014**, *94*, 663–670. [CrossRef]
24. Villalobos, A.M.; Barraza, F.; Jorquera, H.; Schauer, J.J. Wood Burning Pollution in Southern Chile: PM 2.5 Source Apportionment Using CMB and Molecular Markers. *Environ. Pollut.* **2017**, *225*, 514–523. [CrossRef]
25. Sun, J.; Shen, Z.; Zhang, Y.; Zhang, Q.; Lei, Y.; Huang, Y.; Niu, X.; Xu, H.; Cao, J.; Ho, S.S.H.; et al. Characterization of PM2.5 Source Profiles from Typical Biomass Burning of Maize Straw, Wheat Straw, Wood Branch, and Their Processed Products (Briquette and Charcoal) in China. *Atmos. Environ.* **2019**, *205*, 36–45. [CrossRef]
26. Favez, O.; Cachier, H.; Sciare, J.; Sarda-Estève, R.; Martinon, L. Evidence for a Significant Contribution of Wood Burning Aerosols to PM2.5 during the Winter Season in Paris, France. *Atmos. Environ.* **2009**, *43*, 3640–3644. [CrossRef]
27. Molnar, P.; Gustafson, P.; Johannesson, S.; Boman, J.; Barregard, L.; Sallsten, G. Domestic Wood Burning and PM Trace Elements: Personal Exposures, Indoor and Outdoor Levels. *Atmos. Environ.* **2005**, *39*, 2643–2653. [CrossRef]
28. Singh, D.; Tassew, D.D.; Nelson, J.; Chalbot, M.-C.G.; Kavouras, I.G.; Tesfaigzi, Y.; Demokritou, P. Physicochemical and Toxicological Properties of Wood Smoke Particulate Matter as a Function of Wood Species and Combustion Condition. *J. Hazard. Mater.* **2023**, *441*, 129874. [CrossRef]
29. Martins, N.R.; Carrilho da Graça, G. Health Effects of PM2.5 Emissions from Woodstoves and Fireplaces in Living Spaces. *J. Build. Eng.* **2023**, *79*, 107848. [CrossRef]
30. Borchers-Arriagada, N.; Vander Hoorn, S.; Cope, M.; Morgan, G.; Hanigan, I.; Williamson, G.; Johnston, F.H. The Mortality Health Burden Attributable to Wood Heater Smoke Particulate Matter (PM2.5) in Australia. *Sci. Total Environ.* **2024**, *921*, 171069. [CrossRef] [PubMed]
31. Renard, J.-B.; Surcin, J.; Annesi-Maesano, I.; Poincelet, E. Temporal Evolution of PM2.5 Levels and COVID-19 Mortality in Europe for the 2020–2022 Period. *Atmosphere* **2023**, *14*, 1222. [CrossRef]

32. Government Takes Action to Cut Pollution from Household Burning. Available online: https://www.gov.uk/government/news/government-takes-action-to-cut-pollution-from-household-burning (accessed on 20 November 2024).
33. *Air Quality Guidelines for Europe*, 2nd ed.; World Health Organization: Copenhagen, Denmark, 2000; Regional Office for Europe; Available online: https://iris.who.int/handle/10665/107335 (accessed on 20 November 2024).
34. Manzueta, R.; Kumar, P.; Ariño, A.H.; Martín-Gómez, C. Strategies to Reduce Air Pollution Emissions from Urban Residential Buildings. *Sci. Total Environ.* **2024**, *951*, 175809. [CrossRef]
35. Li, T.; Fellini, S.; van Reeuwijk, M. Urban Air Quality: What Is the Optimal Place to Reduce Transport Emissions? *Atmos. Environ.* **2023**, *292*, 119432. [CrossRef]
36. Ren, Z.; Zheng, J.; Jiao, L.; He, M.; Hou, X.; Coffman, D.; Wang, S. The Synergic Impacts of Air Pollution Control Policies on Pollutants and Carbon Emissions. *J. Environ. Manag.* **2024**, *370*, 122730. [CrossRef]
37. Khreis, H.; Sanchez, K.A.; Foster, M.; Burns, J.; Nieuwenhuijsen, M.J.; Jaikumar, R.; Ramani, T.; Zietsman, J. Urban Policy Interventions to Reduce Traffic-Related Emissions and Air Pollution: A Systematic Evidence Map. *Environ. Int.* **2023**, *172*, 107805. [CrossRef]
38. Ercan, T.; Onat, N.C.; Keya, N.; Tatari, O.; Eluru, N.; Kucukvar, M. Autonomous Electric Vehicles Can Reduce Carbon Emissions and Air Pollution in Cities. *Transp. Res. D Transp. Environ.* **2022**, *112*, 103472. [CrossRef]
39. Krecl, P.; Targino, A.C.; Landi, T.P.; Ketzel, M. Determination of Black Carbon, PM2.5, Particle Number and NOx Emission Factors from Roadside Measurements and Their Implications for Emission Inventory Development. *Atmos. Environ.* **2018**, *186*, 229–240. [CrossRef]
40. Kim, I.; Lee, K.; Lee, S.; Kim, S.D. Characteristics and Health Effects of PM2.5 Emissions from Various Sources in Gwangju, South Korea. *Sci. Total Environ.* **2019**, *696*, 133890. [CrossRef]
41. McCutcheon, S.C.; Jørgensen, S.E. Phytoremediation. In *Encyclopedia of Ecology*; Jørgensen, S.E., Fath, B.D., Eds.; Academic Press: New York, NY, USA, 2008; Volume 1, pp. 2751–2766.
42. James, A.; Rene, E.R.; Bilyaminu, A.M.; Chellam, P.V. Advances in Amelioration of Air Pollution Using Plants and Associated Microbes: An Outlook on Phytoremediation and Other Plant-Based Technologies. *Chemosphere* **2024**, *358*, 142182. [CrossRef]
43. Irga, P.J.; Morgan, A.; Fleck, R.; Torpy, F.R. Phytoremediation of Indoor Air Pollutants from Construction and Transport by a Moveable Active Green Wall System. *Atmos. Pollut. Res.* **2023**, *14*, 101896. [CrossRef]
44. Prigioniero, A.; Zuzolo, D.; Niinemets, Ü.; Guarino, C. Nature-Based Solutions as Tools for Air Phytoremediation: A Review of the Current Knowledge and Gaps. *Environ. Pollut.* **2021**, *277*, 116817. [CrossRef]
45. Biswal, B.K.; Bolan, N.; Zhu, Y.-G.; Balasubramanian, R. Nature-Based Systems (NbS) for Mitigation of Stormwater and Air Pollution in Urban Areas: A Review. *Resour. Conserv. Recycl.* **2022**, *186*, 106578. [CrossRef]
46. Encyclopedia of the Anthropocene | ScienceDirect. Available online: https://www.sciencedirect.com/referencework/9780128135761/encyclopedia-of-the-anthropocene (accessed on 20 November 2024).
47. Kaveh, S.; Habibi, A.; Nikkar, M.; Aflaki, A. Optimizing Green Infrastructure Strategies for Microclimate Regulation and Air Quality Improvement in Urban Environments: A Case Study. *Nat. Based Solut.* **2024**, *6*, 100167. [CrossRef]
48. Wu, H.-W.; Kumar, P.; Cao, S.-J. The Role of Roadside Green Infrastructure in Improving Air Quality in and around Elderly Care Centres in Nanjing, China. *Atmos. Environ.* **2024**, *332*, 120607. [CrossRef]
49. Tomson, M.; Kumar, P.; Barwise, Y.; Perez, P.; Forehead, H.; French, K.; Morawska, L.; Watts, J.F. Green Infrastructure for Air Quality Improvement in Street Canyons. *Environ. Int.* **2021**, *146*, 106288. [CrossRef]
50. Tiwari, A.; Kumar, P.; Baldauf, R.; Zhang, K.M.; Pilla, F.; Di Sabatino, S.; Brattich, E.; Pulvirenti, B. Considerations for Evaluating Green Infrastructure Impacts in Microscale and Macroscale Air Pollution Dispersion Models. *Sci. Total Environ.* **2019**, *672*, 410–426. [CrossRef]
51. Khalili, S.; Kumar, P.; Jones, L. Evaluating the Benefits of Urban Green Infrastructure: Methods, Indicators, and Gaps. *Heliyon* **2024**, *10*, e38446. [CrossRef]
52. Abhijith, K.V.; Kumar, P.; Gallagher, J.; McNabola, A.; Baldauf, R.; Pilla, F.; Broderick, B.; Di Sabatino, S.; Pulvirenti, B. Air Pollution Abatement Performances of Green Infrastructure in Open Road and Built-up Street Canyon Environments—A Review. *Atmos. Environ.* **2017**, *162*, 71–86. [CrossRef]
53. Tiwari, A.; Kumar, P. Integr Atmospheric Environment ed Dispersion-Deposition Modelling for Air Pollutant Reduction via Green Infrastructure at an Urban Scale. *Sci. Total Environ.* **2020**, *723*, 138078. [CrossRef]
54. Karklina, J.; Karklins, E.; Abele, L.; Strazdina, L. Bryophytes for the Linear Barrier as a PM2.5 Mitigation Technology in the Urban Landscape. *Landsc. Archit. Art.* **2024**, *24*, 45–50. [CrossRef]
55. Sheikh, H.A.; Maher, B.A.; Woods, A.W.; Tung, P.Y.; Harrison, R.J. Efficacy of Green Infrastructure in Reducing Exposure to Local, Traffic-Related Sources of Airborne Particulate Matter (PM). *Sci. Total Environ.* **2023**, *903*, 166598. [CrossRef]
56. Ottosen, T.-B.; Kumar, P. The Influence of the Vegetation Cycle on the Mitigation of Air Pollution by a Deciduous Roadside Hedge. *Sustain. Cities Soc.* **2019**, *53*, 101919. [CrossRef]

57. Kumar, P.; Zavala-Reyes, J.C.; Tomson, M.; Kalaiarasan, G. Understanding the Effects of Roadside Hedges on the Horizontal and Vertical Distributions of Air Pollutants in Street Canyons. *Environ. Int.* **2022**, *158*, 106883. [CrossRef]
58. Mobarhan, M.; Yeganeh, M.; Motie, M.B.; Ahmadi, S. Assessing the Efficacy of Green Walls versus Street Green Lanes in Mitigating Air Pollution: A Critical Evaluation. *Environ. Sustain. Indic.* **2024**, *24*, 100475. [CrossRef]
59. Farrell, C.; Livesley, S.J.; Arndt, S.K.; Beaumont, L.; Burley, H.; Ellsworth, D.; Esperon-Rodriguez, M.; Fletcher, T.D.; Gallagher, R.; Ossola, A.; et al. Can We Integrate Ecological Approaches to Improve Plant Selection for Green Infrastructure? *Urban. For. Urban Green* **2022**, *76*, 127732. [CrossRef]
60. Ndayambaje, P.; MacIvor, J.S.; Cadotte, M.W. Plant Diversity on Green Roofs: A Review of the Ecological Benefits, Challenges, and Best Management Practices. *Nat. Based Solut.* **2024**, *6*, 100162. [CrossRef]
61. Nagase, A.; Katagiri, T.; Lundholm, J. Investigation of Moss Species Selection and Substrate for Extensive Green Roofs. *Ecol. Eng.* **2023**, *189*, 106899. [CrossRef]
62. Zuberbier, T.; Stevanovic, K.; Ansotegui, I.J.; Anto, J.M.; Bergmann, K.-C.; D'Amato, G.; Grüntuch-Ernst, A.; Haahtela, T.; Maurer, M.; Pietikäinen, S.; et al. Green Roof Gardens—Selecting Allergy Friendly Vegetation: A GA2LEN Position Paper. *J. Allergy Clin. Immunol.* **2023**, *12*, 347–354. [CrossRef]
63. Perini, K.; Castellari, P.; Gisotti, D.; Giachetta, A.; Turcato, C.; Roccotiello, E. MosSkin: A Moss-Based Lightweight Building System. *Build. Environ.* **2022**, *221*, 109283. [CrossRef]
64. Yin, H.; Perera-Castro, A.; Randall, K.; Turnbull, J.D.; Waterman, M.J.; Dunn, J.W.; Robinson, S.A. Basking in the Sun: How Mosses Photosynthesise and Survive in Antarctica. *Photosyn. Res.* **2023**, *158*, 151–169. [CrossRef]
65. Eldridge, D.J.; Guirado, E.; Reich, P.B.; Ochoa-Hueso, R.; Berdugo, M.; Sáez-Sandino, T.; Blanco-Pastor, J.L.; Tedersoo, L.; Plaza, C.; Ding, J.; et al. The Global Contribution of Soil Mosses to Ecosystem Services. *Nat. Geosci.* **2023**, *16*, 430–438. [CrossRef]
66. Drake, P.; Grimshaw-Surette, H.; Heim, A.; Lundholm, J. Mosses Inhibit Germination of Vascular Plants on an Extensive Green Roof. *Ecol. Eng.* **2018**, *117*, 111–114. [CrossRef]
67. Perini, K.; Castellari, P.; Calbi, M.; Prandi, S.; Roccotiello, E. Fine Dust Collection Capacity of a Moss Greening System for the Building Envelope: An Experimental Approach. *Build. Environ.* **2024**, *267*, 112203. [CrossRef]
68. Wang, A.; Wang, J.; Zhang, R.; Cao, S.-J. Mitigating Urban Heat and Air Pollution Considering Green and Transportation Infrastructure. Transportation research. *Transp. Res. Part A Policy Pract.* **2024**, *184*, 104079. [CrossRef]
69. Haughian, S.R.; Lundholm, J.L. Mosses for Minimalist Green Roofs: A Preliminary Study of the Effects of Rooftop Exposure, Species Selection, and Lab-Grown vs. Wild-Harvested Propagule Sources. *Nat. Based Solut.* **2024**, *5*, 100119. [CrossRef]
70. Crandall-Stotler, B.; Stotler, R.E.; Long, D.G.; Goffinet, B. Morphology and classification of the Marchantiophyta. In *Bryophyte Biology*; Cambridge University Press: Cambridge, UK, 2008; pp. 1–54.
71. Haynes, A.; Popek, R.; Boles, M.; Paton-Walsh, C.; Robinson, S.A. Roadside Moss Turfs in South East Australia Capture More Particulate Matter along an Urban Gradient than a Common Native Tree Species. *Atmosphere* **2019**, *10*, 224. [CrossRef]
72. Hong, B.; Qin, H.; Lin, B. Prediction of Wind Environment and Indoor/Outdoor Relationships for PM2.5 in Different Building–Tree Grouping Patterns. *Atmosphere* **2018**, *9*, 39. [CrossRef]
73. Guo, X.; Gao, Z.; Buccolieri, R.; Zhang, M.; Shen, J. Effect of Greening on Pollutant Dispersion and Ventilation at Urban Street Intersections. *Build. Environ.* **2021**, *203*, 108075. [CrossRef]
74. Wang, L.; An, X.; Li, Y.; Jing, K.; Wang, Q.; Sun, F.; Liu, B. Hourly Variation Characteristics of PM2.5 and Main Components in Beijing Based on Wind Direction. *Atmos. Environ.* **2024**, *327*, 120493. [CrossRef]
75. Quantitative Evaluation of Impacts of the Steadiness and Duration of Urban Surface Wind Patterns on Air Quality. *Sci. Total Environ.* **2022**, *850*, 157957. [CrossRef] [PubMed]
76. Li, L.; Zheng, M.; Zhang, J.; Li, C.; Ren, Y.; Jin, X.; Chen, J. Effects of Green Infrastructure on the Dispersion of PM2.5 and Human Exposure on Urban Roads. *Environ. Res.* **2023**, *223*, 115493. [CrossRef]
77. Keyes, T.; Domingo, R.; Dynowski, S.; Graves, R.; Klein, M.; Leonard, M.; Pilgrim, J.; Sanchirico, A.; Trinkaus, K. Low-Cost PM2.5 Sensors Can Help Identify Driving Factors of Poor Air Quality and Benefit Communities. *Heliyon* **2023**, *9*, e19876. [CrossRef]
78. Gaglio, M.; Pace, R.; Muresan, A.N.; Grote, R.; Castaldelli, G.; Calfapietra, C.; Fano, E.A. Species-Specific Efficiency in PM2.5 Removal by Urban Trees: From Leaf Measurements to Improved Modeling Estimates. *Sci. Total Environ.* **2022**, *844*, 157131. [CrossRef] [PubMed]
79. Demková, L.; Árvay, J.; Bobuľská, L.; Hauptvogl, M.; Michalko, M.; Michalková, J.; Jančo, I. Evaluation of Soil and Ambient Air Pollution Around Un-Reclaimed Mining Bodies in Nižná Slaná (Slovakia) Post-Mining Area. *Toxics* **2020**, *8*, 96. [CrossRef]
80. Florek, M.; Mankovska, B.; Frontasyeva, M.; Oprea, K.; Pavlov, S.; Sýkora, L.; Kluciarova, D. Air Pollution Studies in Slovakia Using the Moss Technique. In Proceedings of the NAA and AAS Conference: "Vývoj v Rádioenvironmentalistike a Súvisiace Problémy Energetiky", III Banskoštiavnicke dni 2001, Bratislava, Slovak Republic, 1–10 October 2001.
81. Chaudhuri, S.; Roy, M. Global Ambient Air Quality Monitoring: Can Mosses Help? A Systematic Meta-Analysis of Literature about Passive Moss Biomonitoring. *Environ. Dev. Sustain.* **2023**, *26*, 5735–5773. [CrossRef]

82. Garton, C.; Rausch, J.; Shaw, C. *Analysis of Lead Uptake by Dicranum Scoparium from Contaminated Soil Solutions*; University of Michigan Biological Station: Pellston, MI, USA, 2019.
83. Payne, R.J.; Stevens, C.J.; Dise, N.B.; Gowing, D.J.; Pilkington, M.G.; Phoenix, G.K.; Emmett, B.A.; Ashmore, M.R. Impacts of Atmospheric Pollution on the Plant Communities of British Acid Grasslands. *Environ. Pollut.* **2011**, *159*, 2602–2608. [CrossRef] [PubMed]
84. Leith, I.D.; Mitchell, R.J.; Truscott, A.-M.; Cape, J.N.; van Dijk, N.; Smith, R.I.; Fowler, D.; Sutton, M.A. The Influence of Nitrogen in Stemflow and Precipitation on Epiphytic Bryophytes, Isothecium Myosuroides Brid., Dicranum Scoparium Hewd. And Thuidium Tamariscinum (Hewd.) Schimp of Atlantic Oakwoods. *Environ. Pollut.* **2008**, *155*, 237–246. [CrossRef] [PubMed]
85. Renard, J.-B.; Marchand, C. High Resolution Mapping of PM2.5 Concentrations in Paris (France) Using Mobile Pollutrack Sensors Network in 2020. *Atmosphere* **2021**, *12*, 529. [CrossRef]
86. Renard, J.B.; Poincelet, E.; Annesi-Maesano, I.; Surcin, J. Spatial Distribution of PM2.5 Mass and Number Concentrations in Paris (France) from the Pollutrack Network of Mobile Sensors during 2018–2022. *Sensors* **2023**, *23*, 8560. [CrossRef] [PubMed] [PubMed Central]
87. Renard, J.B.; Dulac, F.; Berthet, G.; Lurton, T.; Vignelles, D.; Jégou, F.; Tonnelier, T.; Jeannot, M.; Couté, B.; Akiki, R.; et al. LOAC: A Small Aerosol Optical Counter/Sizer for Ground-Based and Balloon Measurements of the Size Distribution. *Atmos. Meas. Tech. Discuss.* **2015**, *8*, 1203–1259. [CrossRef]

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