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Particulate Pollution Capture by Seventeen Woody Species Growing in Parks or along Roads in Two European Cities

Irene Vigevani [1,2,3,*], Denise Corsini [2], Jacopo Mori [2], Alice Pasquinelli [4], Marco Gibin [1], Sebastien Comin [1], Przemysław Szwałko [5], Edoardo Cagnolati [6], Francesco Ferrini [2] and Alessio Fini [1]

1 Department of Agricultural and Environmental Sciences—Production, Landscape, Agroenergy, University of Milan, 20133 Milan, Italy; marco.gibin@unimi.it (M.G.); sebastien.comin@unimi.it (S.C.); alessio.fini@unimi.it (A.F.)
2 Department of Agriculture, Food, Environment and Forestry, University of Florence, 50144 Florence, Italy; denise.corsini@unifi.it (D.C.); ja.mori@hotmail.it (J.M.); francesco.ferrini@unifi.it (F.F.)
3 Department of Sciences, Technologies and Society, University School for Advanced Studies IUSS Pavia, 27100 Pavia, Italy
4 R3 GIS S.r.l. NOI Techpark, 39100 Bolzano, Italy; alice.pasquinelli@r3gis.com
5 Krakow Municipal Greenspace Authority (ZZM), 30-059 Kraków, Poland; pszwalko@zzm.krakow.pl
6 Anthea S.r.l., 47923 Rimini, Italy; edoardo.cagnolati@anthearimini.it
* Correspondence: irene.vigevani@unimi.it or irene.vigevani@unifi.it or irene.vigevani@iusspavia.it

Abstract: This research aims to extend the existing knowledge on air quality improvement by the arboreal–shrub heritage. The PM accumulation ($PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ ($\mu g \cdot cm^{-2}$)) was measured with consolidated gravimetric techniques during spring, summer, and fall for 2160 leaf samples belonging to the basal, median, and apical part of the crown of 17 species located in the streets and parks of 2 European cities (Rimini and Krakow). On the same samples, the deposition (PM_{10} and $PM_{2.5}$ ($\mu g \cdot cm^{-2} \cdot day^{-1}$)) was evaluated according to a model based on the wash-off rain effect. *Quercus ilex* accumulated more PM_x than the other species in Rimini, while in Krakow, the highest accumulators were *Pinus nigra* for $PM_{10–100}$, *Tilia cordata* for $PM_{2.5–10}$, and *Populus nigra* for $PM_{0.2–2.5}$. Only in Krakow was the capture capacity of some species affected by the street or park growing condition. The basal leaves showed greater $PM_{10–100}$ accumulation than the median and apical ones. In Rimini, the total PM accumulation tended to increase throughout the year, while in Krakow, the opposite occurred. However, as the accumulation increased, the deposition decreased. The PM accumulation was reduced by rainfall and enhanced by the air PM concentration, while the wind speed effect was opposite, depending on the city. These findings are useful for directing decision makers in the design of greener, healthier, and sustainable cities.

Keywords: broadleaves and conifer species; leaf accumulation; meteorological parameters; particulate matter; urban air pollution; urban forest

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1. Introduction

Particulate matter (PM) is the main non-gaseous pollutant in cities and consists of a dynamic and complex aggregate of organic and inorganic particles, either in a solid or liquid phase, suspended in the air [1,2]. The particles aerodynamic diameters range from 0.001 to 100 µm [3], and according to it, PM is usually divided into large (10–100 µm), coarse (2.5–10 µm), and fine (0.2–2.5 µm) [2,4–6], even if in the literature there are other classifications which consider ultrafine particles (<0.1 µm) [7]. The European Environment Agency listed the energy generation sector, industry, and vehicular traffic as some of the most important anthropogenic sources of PM [8]. Due to its ability to penetrate the respiratory system [9] and carry toxic compounds such as polycyclic aromatic hydrocarbons (PAH) and heavy metals (HM) [10], PM is currently considered among the most health-threatening factors in urban areas, causing more than 400,000 premature deaths in Europe [11]. Recently, the high level of PM_x in the atmosphere has been considered a co-factor in the spread of COVID-19 [12], exacerbating the air quality issue worldwide.

Although current policies are trying to reduce emissions, the PM concentration is still very high, making mitigation measures urgent. PM can settle on all kind of surfaces, but plant leaves and bark were shown to be particularly effective for PM trapping [13]. All types of urban forests (peri-urban woodlands, parks, gardens, roadside trees, green roofs, and vertical greening) were shown to be effective passive biological filters against PM [14,15] while providing a wide range of co-benefits, including microclimate amelioration [16] through shading [17] and transpiration [18,19], atmospheric CO_2 uptake and carbon sequestration [20], and absorption of gaseous air pollutants [21]. Although bark may also play a role [22], leaves are the plant organs considered responsible for most PM trapping by vegetation [23]. Polluting particles reach leaf surfaces through rain and snow (wet deposition) or wind force (dry deposition) [24], with the latter process being responsible for most plant capture [25]. The main mechanisms involved are gravity sedimentation, interception, Brownian diffusion, and inertial and turbulent impactions [26]. Intercepted particles can be absorbed by the leaf stomata [27] or, more frequently, retained on the surfaces until they are resuspended in the atmosphere under blowing wind, washed off by rain, or dropped to the ground with falling leaves and twigs [23,28], outlining a dynamic deposition trend [6]. Once resuspended in the air, particles can redeposit on plant organs, and once reaching the ground, organic components may be decomposed by micro-organisms, inorganic components may be immobilized in the soil, or particles can be resuspended again [27].

Many studies showed that air filtering is species-specific [4–6]. Consistently, trapping and the retention efficiency are not affected only by pollutant characteristics like the diameter, shape, or composition [29,30] but also by the leaf features (e.g., shape, stomata density, trichomes, cuticle ornamentations, and epicuticular waxes) [31] and conditions such as stickiness (e.g., due to the presence of honeydew [25]), wettability [32], and humidity [29]. The rougher the surface, the greater the catch. In broadleaved species, for example, the rough-surface leaves are more effective than smooth-surface ones [33]. Conifer needles or scales have been reported to be more effective than broadleaves, as they produce a thicker epicuticular wax layer with frequent longitudinal ridges which promote trapping and retention [4,34,35]. Consistently, Beckett et al. [36] found a higher deposition velocity and capture efficiency in both needle-leaved and scale-leaved species compared with broadleaves. The low tolerance of most conifers to air pollution, however, has raised concerns about the real upscalability of research findings collected in wind tunnels [36] or with small plants in environments protected from real urban conditions [6]. In addition, evergreen species, such as most conifers, have the potential to capture PM throughout the year, but on the other hand, since they keep leaves for several years, there is no possibility of recycling the accumulated particles annually, as is the case for deciduous species [27]. The effect of leaf longevity on the trapping efficiency has not been fully unraveled yet, because several investigations carried out so far evaluated the amount of foliar PM_x in a single measurement, usually carried out at the end of the growing season [4–6,37]. Research based on seasonal sampling campaigns revealed that the leaf PM accumulation (i.e., the total amount of PM adsorbed on a leaf surface) generally increased with the leaf age [38,39], although the capture efficiency may decrease in older leaves [34].

All vegetation types can mitigate air pollution, but trees are considered the most effective for this purpose due to their large total leaf area [24] and the complex structure of their crowns, leading to turbulent air movements which increase PM trapping [40]. The importance of shrubs, however, should not be underestimated because of their canopy structure, which is often branched from the ground, and their limited height. These traits allow for designing shrub barriers very close to the source of a pollutant even in urban canyons, where PM capture can be maximized [5] without negatively impacting airflow and PM dispersion, as can occur when trees with dense canopies are planted [41,42]. It has been shown that the proximity to the pollution source increases the leaf PM accumulation [43,44].

Some studies which considered the leaf position [37,45,46] found more particles adsorbed on leaves in the lower part of the crown compared with the upper part. However, these studies investigated a maximum height of 4.0 m. Few works, to our knowledge, have reported the effect of different growing conditions (e.g., park and street) on the PM trapping capacity of the different plant species in an urban environment [37,47], and most of them are based on models [48,49].

Although research has recently focused on the assessment of the capture capacity of different species in an urban environment, there is a lack of extensive replicated measurements conducted in situ on established plants. Therefore, this research aims to evaluate PM accumulation and deposition as affected by (1) genotype, and for this purpose, 17 tree and shrub species (*Acer negundo*, *Acer platanoides*, *Aesculus hippocastanum*, *Cornus alba*, *Fraxinus excelsior*, *Ligustrum lucidum*, *Pinus nigra*, *Pinus pinea*, *Platanus* × *acerifolia*, *Populus nigra*, *Prunus laurocerasus*, *Quercus ilex*, *Quercus robur*, *Sorbus aucuparia*, *Tilia cordata*, *Tilia* × *europaea*, and *Ulmus laevis*) widely spread in 2 European cities (Rimini, Italy and Krakow, Poland) were used; (2) urban microclimate, and for this purpose, plants growing in parks or along streets were sampled; (3) leaf positions within the canopy, and (4) seasonality and leaf age. In this research, PM accumulation ($\mu g \cdot cm^{-2}$) refers to the amount of PM_x adsorbed in the unit leaf area at the time leaves were sampled, and this is useful for making a relative comparison between species. PM deposition ($\mu g \cdot cm^{-2} \cdot day^{-1}$) instead refers to the change in accumulation over time, and it is useful for quantifying the amount of PM_x which a species can capture in a specific time frame, such as a day, a season, or a year. For accumulation, three fractions of PM were studied ($PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$), while for deposition, only those most harmful to humans (PM_{10} and $PM_{2.5}$) were studied. Additional aims of this research are (1) to compare the annual trend of accumulation and deposition and (2) to correlate accumulation with the meteorological (e.g., rainfall and wind speed) and environmental (PM_{10} and $PM_{2.5}$ air concentrations) parameters. The main novelty of this research is using entire cities as living laboratories for the in situ monitoring of the contribution of established plants of some woody species arranged according to a replicated experimental design to air quality amelioration.

2. Materials and Methods

2.1. Experimental Sites

The experiment was carried out in Rimini (44°03′34″ N 12°34′06″ E, Italy), a city of about 136 km^2 with about 150,000 inhabitants, and Krakow (50°03′41″ N 19°56′18″ E, Poland), a city of about 327 km^2 with a population of about 780,000 people.

In Rimini, the climate is warm-temperate (Cfa, according to Köppen–Geiger classification) with an even rainfall distribution throughout the year, fairly cold winters, and hot summers. Over the last 30 years, the average minimum and maximum temperatures were 11.88 °C and 18.01 °C, and the average rainfall was 838 mm per year. Krakow enjoys a temperate climate (Cfb, according to Köppen–Geiger classification) with evenly distributed rainfall throughout the year and warm summers. Over the last 30 years, the average minimum and maximum temperatures were 4.74 °C and 12.94 °C, and the average rainfall was 835 mm per year.

In Rimini, air solid pollutants were below the critical European threshold (28.29 and 16.25 $\mu g \cdot m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively, as the annual average in 2018–2019) (data source: Arpae–Agenzia prevenzione ambiente energia Emilia-Romagna). Krakow instead suffers from a severe pollution load, with all the PM fractions assessed at higher concentrations compared with the EU recommendations (40 and 25 $\mu g \cdot m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively). Indeed, in 2019, the annual average air pollution concentration was 42.12 and 29.09 $\mu g \cdot m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively (data source: Główny Inspektorat Ochrony Środowiska). In the province of Rimini, the main emissions of coarse and fine PM derived from combustion processes for public and private heating (70.4% and 76.8%, respectively) and from road transport (20.6% and 16.4% for PM_{10} and $PM_{2.5}$, respectively). A smaller share of PM emissions is linked to agricultural activities (2.9% and 1.5% for PM_{10} and $PM_{2.5}$, respectively), air, sea, and rail transport (1.5% and 1.7% for PM_{10} and $PM_{2.5}$, respectively), and other activities or processes (4.5% and 3.6% for PM_{10} and $PM_{2.5}$, respectively) [50]. The largest sources of PM_{10} and $PM_{2.5}$ emissions in Małopolskie voivodeship, the area in which Krakow is located, are the municipal and housing sectors (77% and 88%, respectively), and this is attributable to the combustion of fuels, mainly coal and wood, for heating. This is followed by emissions from other sources such as agriculture (cultivation and livestock), forests and fires (10% and 4% for PM_{10} and $PM_{2.5}$, respectively), emissions deriving from the combustion of energy fuels and technological processes (8% and 4% for PM_{10} and $PM_{2.5}$, respectively), and transport-related emissions (5% and 4% for PM_{10} and $PM_{2.5}$, respectively) [51].

During the experiment, meteorological data were collected and provided by the Institute for Ubiquitous Meteorology (UBIMET), while air PM concentration data were obtained by Arpae for Rimini (Flaminia and Marecchia PM monitoring stations) and Główny Inspektorat Ochrony Środowiska for Krakow (Aleja Krasińskiego and ulica Dietla PM monitoring stations).

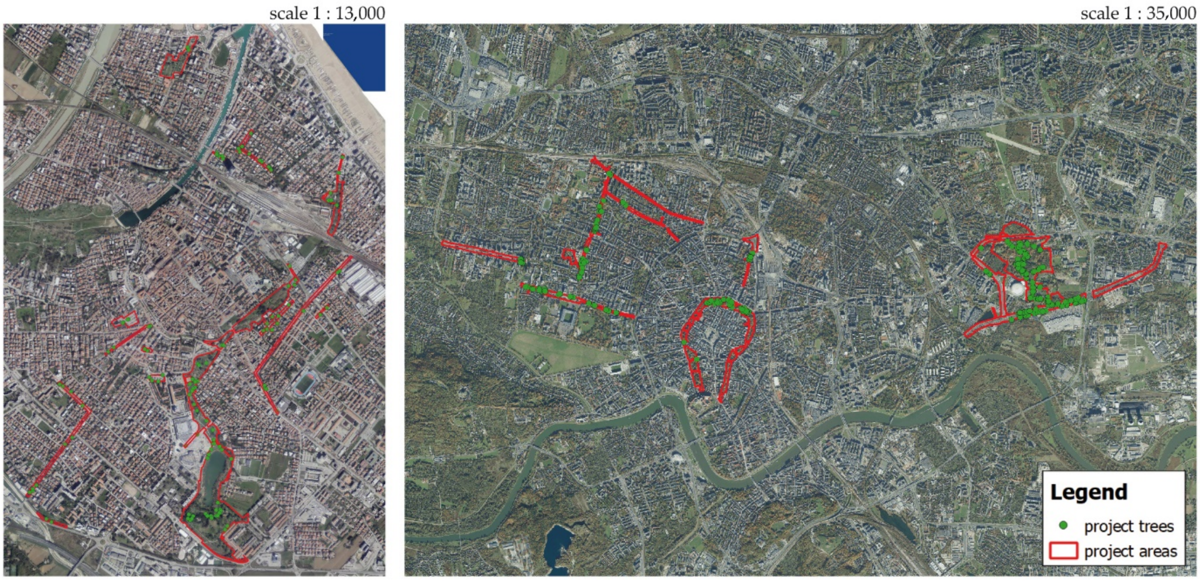
2.2. Plant Material and Experimental Design

Ten species per city were selected based on (1) their relevance in the existing tree inventories of Rimini and Krakow, (2) the interest of a species for municipal planting and management programs, (3) the final size at maturity, and (4) leaf deciduousness or persistence. The species monitored in Rimini were *Platanus* × *acerifolia, Populus nigra, Quercus robur* (large-sized deciduous broadleaves), *Quercus ilex* (large-sized evergreen broadleaf), *Pinus pinea* (large-sized evergreen conifer), *Acer negundo, Aesculus hippocastanum, Tilia* × *europaea* (medium-to-large-sized deciduous broadleaves), *Ligustrum lucidum* (small-sized semi-deciduous broadleaf), and *Prunus laurocerasus* (evergreen broadleaved shrub). In Krakow, the following woody species were selected: *Fraxinus excelsior, Populus nigra, Quercus robur, Ulmus laevis* (large-sized deciduous broadleaves), *Pinus nigra* (large-sized evergreen conifer), *Acer platanoides, Aesculus hippocastanum, Tilia cordata* (medium-to-large-sized deciduous broadleaves), *Sorbus aucuparia* (small-sized deciduous broadleaf), and *Cornus alba* (deciduous broadleaved shrub). Three species (*Aesculus hippocastanum, Populus nigra*, and *Quercus robur*) and 3 genera, although with different species (*Acer platanoides, Acer negundo*; *Tilia cordata, Tilia* × *europaea*; and *Pinus pinea, Pinus nigra*) were selected in both cities in order to allow the comparison of results.

Two city transects representative of the whole municipality were selected as experimental areas in both cities (Figure 1). Transects were stratified into two strata: (1) street (street trees, parking lots, plants near major roads, plants with a clearly delimited planting pit surrounded by pavement or buildings, or where conflicts between plants and the gray infrastructure were clearly visible) and (2) park (plants in parks, where conflicts with the built landscape were limited and where the soil around the plant was mostly unpaved).

In Rimini, the experimental areas covered 250 ha and included the Rosaspina parking lot, Palacongressi parking lot, via della Fiera (Palacongressi entrance), viale Medaglie d'Oro parking lot, via Calatafimi, via Covignano, via Milazzo, via Massaua, via Roma parking lot, via Gamedes, via Flaminia, via Lavatoio, viale Principe Amedeo, via Vittor Pisani, viale Perseo, viale Tripoli, via Melozzo da Forlì parking lot, Irnerio Bertuzzi parking lot, via Donato Bramante parking lot, via del Passero, Peep Acquario, parco Renzi, parco La Cava, parco Briolini, parco Poderi della Ghirlandetta, parco Fabbri, parco Olga Bondi, parco Alcide Cervi. In Krakow, Park Lotników Polskich (a large park located near a highly congested main road), and Planty Krakowskie (the green belt around the city center) were chosen as park areas. These were identified as extremely representative of two contrasting traffic loads typically occurring in Krakow, where high traffic around the suburbs is paralleled by low traffic in the city center, where car circulation is restricted. Street areas were selected in roads with similar land use to those surrounding the selected parks. In total, the experimental areas in Krakow covered 472 ha, including Park Lotników

Polskich, Planty Krakowskie, aleja Pokoju, ulica Lema, ulica Reymonta, aleja Kijowska, ulica Mazowiecka, ulica Armii Krajowej, and ulica Warszawska.



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

Figure 1. Experimental design of measured tree and shrub species in Rimini (**a**) and Krakow (**b**).

Six replicate plots, including at least two plants of the measured species and strata, were identified within the experimental areas. One hundred twenty plants in Rimini and in Krakow were selected from the 10 model species in the above-mentioned areas for a total of 240 plants belonging to different DBH classes (Table 1).

Table 1. Minimum and maximum diameter at breast height (DBH) of measured tree and shrub species in Rimini and Krakow.

City	Species	DBH Min. (cm)	DBH Max. (cm)
Rimini	*Acer negundo*	9.80	44.56
	Aesculus hippocastanum	5.50	49.34
	Ligustrum lucidum	8.00	30.24
	Pinus pinea	21.65	60.16
	Platanus × acerifolia	7.60	63.66
	Populus nigra	7.50	76.08
	Prunus laurocerasus	4.00	37.88
	Quercus ilex	11.50	59.52
	Quercus robur	8.30	48.38
	Tilia × europaea	7.00	58.89
Krakow	*Acer platanoides*	5.00	83.40
	Aesculus hippocastanum	33.00	109.18
	Cornus alba	2.23	7.00
	Fraxinus excelsior	4.50	81.49
	Pinus nigra	4.46	32.15
	Populus nigra	18.00	90.40
	Quercus robur	31.00	87.54
	Sorbus aucuparia	5.00	29.60
	Tilia cordata	7.00	73.21
	Ulmus laevis	4.00	96.45

2.3. Sampling

For PM_x accumulation and deposition determination, a total of 2160 leaf samples were collected in Rimini and Krakow (1) from the 10 species selected for each city, (2) in 2 strata (street and park), (3) in 3 positions of the crown (basal, median, and apical), (4) from 3 seasons (spring, summer, and fall), and (5) from 6 replicate plants per each stratum of each model species. The leaves sampled were fully expanded and were collected in the 2 cities by carrying out 10–11 consecutive days of sampling during spring (14–24 May 2019), summer (25 June–5 July 2019), and fall (10–19 October 2018) in Rimini and spring (4–13 June 2019), summer (16–26 July 2019) and fall (10–20 September 2019) in Krakow. Sampling was conducted from 9:00 a.m. to 12:00 a.m. After dividing the live canopy into 3 portions of equal height, leaves were sampled in the lower, medial, and upper portions so that 3 samples were collected per each plant for each sampling. To access the tree canopies, an aerial work platform (AWP) was used. This made the process extremely time-consuming and required the different replicates to be sampled in different days. Care was taken to sample all species within an individual replicate on the same day. Each leaf sample (of about 300–400 cm^2, the leaf area which was found to be suitable for gravimetric determination of PM_x by Dzierzanowski et al. [4]) was harvested from the petioles to avoid the contact of hands with the leaf blade and stored in disposable paper bags at −20 °C to limit the deterioration of leaf tissues. Contextually with the sample collection, the plant height and height from the ground of the basal sampled leaves were measured using a clinometer (SUUNTO, Vantaa, Finland) and a laser rangefinder (Metrica, Italy), respectively. Subsequently, the height from the ground of the medial leaves was estimated.

2.4. Determination of PM_x Accumulation

In this paper, the term PM_x accumulation refers to the amount of PM_x adsorbed in the unit leaf area at the time the leaves were sampled ($\mu g \cdot cm^{-2}$). To determine this, the procedure by Dzierzanowski et al. [4] and Mori et al. [45] was adopted with some modifications. Each leaf sample, taken out of the freezer and brought to room temperature, was washed for 60 s with 250 mL of deionized water under agitation. The washing solution was then first filtered through a metal sieve (Fritsch analysensieb, Idar-Oberstein, Germany) to eliminate particles larger than 100 µm and sequentially filtered using 3 filters in increasing order of retention capacity (type 1288, retention: 10 µm; type 391, retention: 2.5 µm; and PTFE membrane, retention: 0.2 µm), (Sartorius AG, Goettingen, Germany). Filtration was carried out using a filtration apparatus equipped with a 47-mm glass filter funnel (Sartorius stedim, Sartorius AG, Goettingen, Germany) connected to an MV-50 vacuum pump (Comecta-Ivymen, Barcelona, Spain). Immediately before filtration, the PTFE membranes were moistened with a few droplets of isopropyl alcohol to break the surface forces and speed up the process. Prior to filtration, each filter was dried at 60 °C for 30 min in a drying chamber (WTB binder 7200, Tuttlingen, Germany) and then left at a constant air relative humidity (50%) for weight stabilization before being pre-weighed on a high-precision balance (ED224S-OCE, Sartorius, Germany). The main modification to the method of Mori et al. [45] was letting the filters stabilize for 120 min instead of 60 min; the time was selected based on preliminary tests. After filtration the filters were dried again, weight stabilized, and post-weighed. The amount of PM was represented by the difference between the post-weight and pre-weight. At the end of the entire filtration procedure, three fractions of PM_x were collected: (1) large ($PM_{10–100}$), (2) coarse ($PM_{2.5–10}$), and (3) fine ($PM_{0.2–2.5}$). These were the most evaluated PM fractions obtained with gravimetric techniques found in the literature, making the results of this study comparable with existing works on this topic. Although ultrafine particles (<0.2 µm) are very dangerous to human health, this fraction was excluded from the present research due to intrinsic methodological limitations. The PM_{10} fraction was obtained by adding the second and third fractions; the $PM_{2.5}$ fraction was the same as the third fraction. After washing, the leaf area of each sample was measured using an A3 scanner (HP OfficeJet Pro 7740, HP Development Company, L.P., Palo Alto, CA, USA) and leaf area software (Leaf Area Measurement, version 1.3, University of Sheffield, A.P. Askew, UK). To calculate the area of coniferous leaves, the Leaf Mass per Area (LMA) approach was used. Each needle sample was dried at 70 °C for 72 h (modification of the method in [52]) and then allowed to stabilize for 4 h and weighed. The weight and leaf area of the sub-sample was measured, and the total leaf area of the sample was obtained as a proportion. The amount of PM_x accumulation was expressed per unit leaf area ($\mu g \cdot cm^{-2}$).

2.5. Determination of PM_x Deposition

In this paper, the term PM_x deposition refers to the change in accumulation over time ($\mu g \cdot cm^{-2} \cdot day^{-1}$). This parameter provides the amount of PM which a plant can capture in a specific time frame. It was calculated for the fractions of PM more dangerous to citizens: PM_{10} (considered $PM_{10} = PM_{0.2–2.5} + PM_{2.5–10}$) and $PM_{2.5}$ (considered $PM_{2.5} = PM_{0.2–2.5}$). To obtain the deposition, a simplified approach was used. Days without rain were counted from the last effective rainfall (i.e., the one assumed to clean the leaves). In this work, the effective rainfall was considered to be higher than 7 mm day^{-1} on the basis of the limited existing literature on this topic [35,53–55] which, however, highlighted differences depending on the species, PM fraction, and rainfall regimes (intensity and duration). Accumulation was plotted against the number of days without rainfall since the last effective rain event (up to a maximum of 12 days were counted). The deposition rate was calculated as the slope of the time course of accumulation, assuming a linear trend of deposition over the measurement period. Thus, the amount of PM_{10} and $PM_{2.5}$ was expressed per unit leaf area and time ($\mu g \cdot cm^{-2} \cdot day^{-1}$).

2.6. Statistical Analysis

To evaluate the effect of the species, strata (street or park), species × stratum interaction, leaf position (basal, median, or apical), and season (spring, summer, or fall) within each city, a mixed model analysis was applied to (1) $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ accumulation per unit leaf area ($\mu g \cdot cm^{-2}$) and (2) PM_{10} and $PM_{2.5}$ deposition per unit leaf area ($\mu g \cdot cm^{-2} \cdot day^{-1}$). The mean values from significant simple factors were separated using Sidak post-hoc tests ($p \leq 0.05$). Significant interactions between factors were investigated by one-way ANOVA, and the mean values were separated by Duncan's post-hoc test ($p \leq 0.05$). A Pearson correlation analysis was performed to evaluate the influence of (1) the height of the leaves from the ground on PM_x accumulation and (2) the cumulative rainfall, average wind speed, and average PM_{10} and $PM_{2.5}$ air concentration (collected 14 days before each sampling day) on PM_x accumulation. All statistics were carried out using SPSS software (IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY, USA), while the graphics were drawn with SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Meteorological Conditions and Air Quality at Experimental Sites

The meteorological and air quality data measured during the sampling period and in the 2 weeks before at both experimental sites are reported in Table 2.

In Rimini, the rainfall and wind speed were higher during spring compared with summer and fall; the opposite occurred for the air PM concentration. In Krakow, the rainfall was higher in spring and fall than in summer when, on the contrary, the highest wind speed was recorded. The air PM concentration was higher in spring compared with fall and summer.

Table 2. Mean air temperature, cumulative rainfall, wind speed, relative humidity, and PM_{10} and $PM_{2.5}$ air concentration at the experimental sites (Rimini and Krakow) in a period of about 24 days (pre-sampling: 14 days; sampling: 10–11 days).

City	Period	Season	T (°C)	Rain (mm)	Wind ($m \cdot s^{-1}$)	RH (%)	PM_{10} ($\mu g \cdot m^{-3}$)	$PM_{2.5}$ ($\mu g \cdot m^{-3}$)
Rimini	30 April–24 May 2019	Spring	14.59	103.74	3.11	74.31	15.60	4.61
	11 June–5 July 2019	Summer	25.34	27.82	2.43	65.31	26.02	10.13
	26 September–19 October 2018	Fall	15.93	25.39	2.32	80.58	33.87	21.10
Krakow	21 May–13 June 2019	Spring	18.63	199.98	2.58	73.15	32.40	18.22
	2–26 July 2019	Summer	18.35	133.21	2.65	65.33	26.40	14.98
	27 August–20 September 2019	Fall	16.63	202.01	2.46	77.50	29.72	17.45

3.2. PM_x Accumulation in Rimini

In Rimini, $PM_{10–100}$ accumulation was significantly affected by the species, leaf position, and season (Table A1). $PM_{2.5–10}$ and $PM_{0.2–2.5}$ accumulation was affected by the species and season and unaffected by the leaf position. The strata never influenced PM_x accumulation.

In general, *Quercus ilex* had a higher PM_x accumulation per unit leaf area than other species, regardless of the PM fraction (Figure 2a).

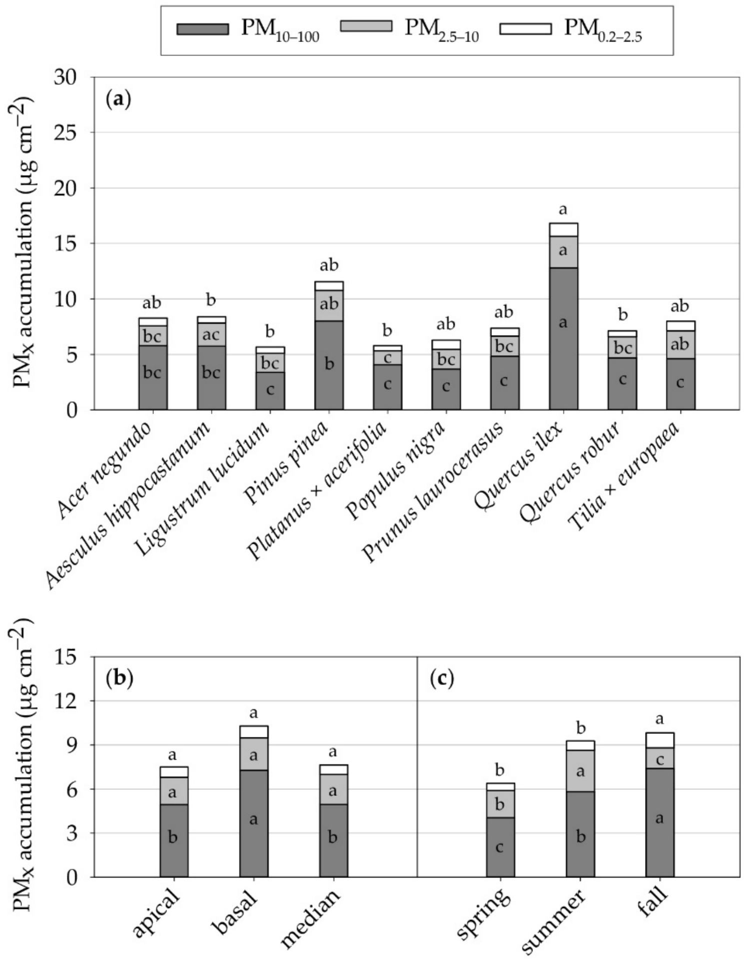


Figure 2. Effect of species (**a**), leaf position (**b**), and season (**c**) on $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ accumulation per unit leaf area ($\mu g \cdot cm^{-2}$) in Rimini. Within each variable, different letters indicate significant differences among species, leaf positions, or seasons at $p \leq 0.05$.

In particular, *Quercus ilex* accumulated 37% more $PM_{10–100}$ than *Pinus pinea*. *Ligustrum lucidum*, *Populus nigra*, *Prunus laurocerasus*, *Quercus robur*, and *Tilia* × *europaea* accumulated, on average, 67% and 47% less $PM_{10–100}$ than *Quercus ilex* and *Pinus pinea*, respectively. *Quercus ilex* accumulated 55% more $PM_{2.5–10}$ than *Platanus* × *acerifolia*, which showed the lower accumulation among the tested species. Finally, the $PM_{0.2–2.5}$ accumulation was significantly higher (on average 54%) in *Quercus ilex* than *Aesculus hippocastanum*, *Ligustrum lucidum*, *Platanus* × *acerifolia*, and *Quercus robur*.

The leaf position affected the $PM_{10–100}$ accumulation, with leaves attached in the lower third of the live canopy height showing a higher accumulation than those attached in the median and distal portions (Figure 2b). This was also confirmed by correlation analysis between the PM_x accumulation and the height of the leaves from the ground. At increasing heights from the ground, only the $PM_{10–100}$ accumulation decreased (data not shown). Conversely, the leaf position did not affect the accumulation of $PM_{2.5–10}$ and $PM_{0.2–2.5}$. The basal, median, and apical leaves were in a height range from the ground of 0.20–11.00 m, 1.00–14.20 m, and 1.80–22.00 m, respectively.

The season of sampling affected PM_x accumulation. The $PM_{10–100}$ and $PM_{0.2–2.5}$ accumulations were higher in fall, followed by summer and spring. The $PM_{2.5–10}$ accumulation, however, was higher in summer, followed by spring and fall (Figure 2c).

3.3. PM_x Accumulation in Krakow

In Krakow, $PM_{10–100}$ accumulation was affected by the species, stratum, leaf position, and season (Table A1). $PM_{2.5–10}$ and $PM_{0.2–2.5}$ were only affected by the species and season, whereas the effects of the stratum and leaf position were not significant. A significant species × stratum interaction was found for $PM_{10–100}$ and $PM_{2.5–10}$.

Species with higher accumulations were different depending on the particulate size fraction (Figure 3a). Considering the $PM_{10–100}$ accumulation, *Pinus nigra* displayed a higher accumulation than the other species. *Tilia cordata* ranked second for $PM_{10–100}$ accumulation. $PM_{10–100}$ of *Acer platanoides* and *Fraxinus excelsior* was, on average, 70% and 32% lower than that in *Pinus nigra* and *Tilia cordata,* respectively. *Tilia cordata* displayed a 20% higher $PM_{2.5–10}$ accumulation than *Sorbus aucuparia* and *Ulmus laevis*. *Pinus nigra* displayed an intermediate $PM_{2.5–10}$ capture capacity compared with *Tilia cordata*, *Sorbus aucuparia* and *Ulmus laevis*. *Fraxinus excelsior* was the lower accumulator of $PM_{2.5–10}$ among the tested species. $PM_{0.2–2.5}$ accumulation was significantly higher in *Populus nigra* compared with *Acer platanoides*, which was 42% less effective. The other species displayed intermediate performances.

In Krakow, the different species showed different capture capacities depending on the stratum and PM fraction (Figure 3b). *Pinus nigra* was more efficient in parks compared with streets for the $PM_{10–100}$ accumulation per unit leaf area. By contrast, *Fraxinus excelsior, Quercus robur*, and *Ulmus laevis* showed higher $PM_{10–100}$ accumulations in the street stratum. For $PM_{2.5–10}$, the only species with significantly higher values in the street than the park stratum was *Populus nigra*, and the opposite occurred with *Cornus alba*. No difference among species depending on the stratum was found in $PM_{0.2–2.5}$.

The basal leaves accumulated more $PM_{10–100}$ compared with the median and apical ones (Figure 3c). No differences were found among the leaf positions for other PM fractions. Correlation analysis between the PM_x accumulation and the height of the leaves from the ground confirmed that at increasing heights from the ground, the $PM_{10–100}$ accumulation decreased. In addition, it revealed the same trend for $PM_{2.5–10}$ (data not shown). The basal, median, and apical leaves were in a height range from the ground of 0.20–16.00 m, 0.55–18.00 m, and 0.80–27.00 m, respectively.

Accumulation was higher in spring compared with other seasons for all PM fractions (Figure 3d). $PM_{10–100}$ accumulation was higher in fall than in summer, whereas the opposite was found for $PM_{2.5–10}$. During fall, a lower $PM_{0.2–2.5}$ accumulation was also observed.

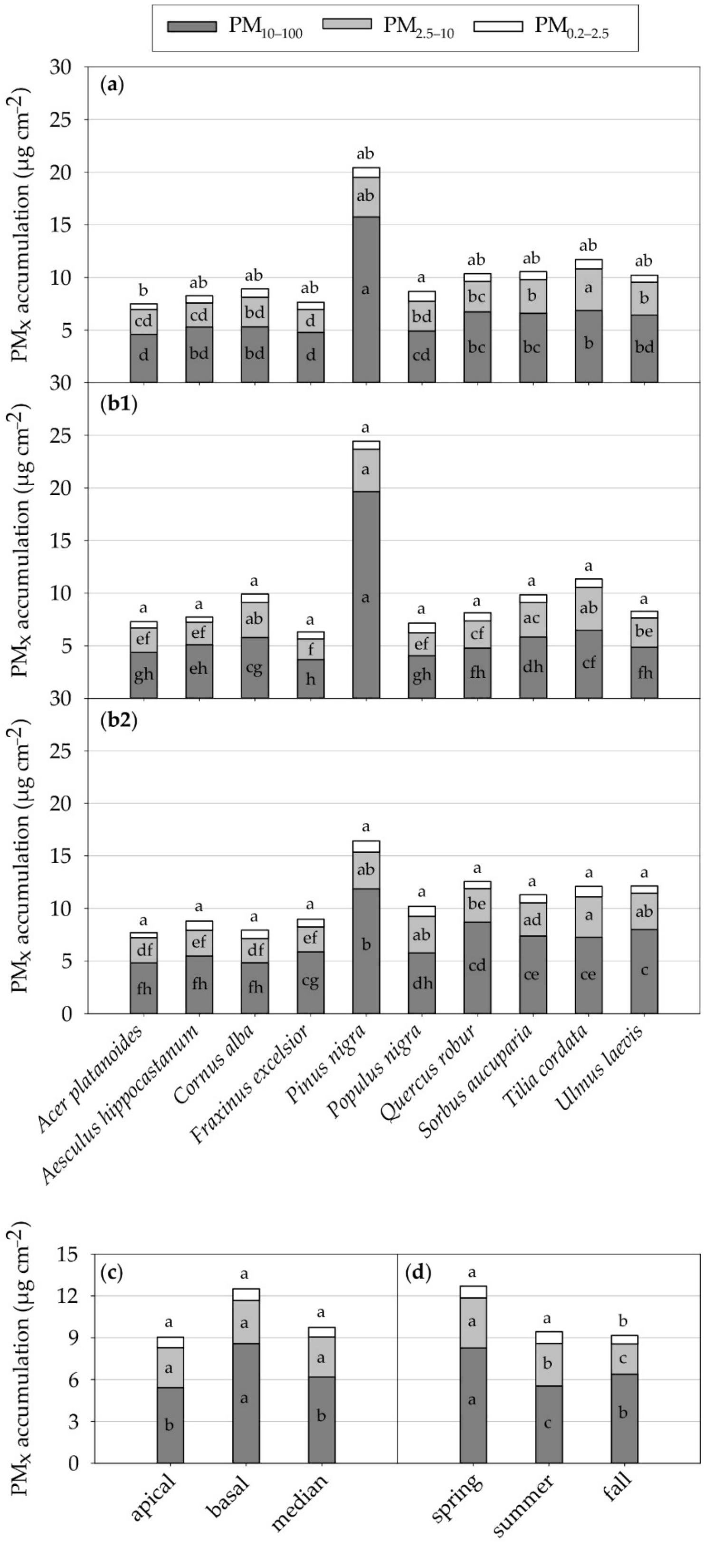


Figure 3. $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ accumulation per unit leaf area (µg·cm^{-2}) in Krakow by the different species (**a**) in parks (**b1**) and streets (**b2**) with different leaf positions (**c**) and seasons (**d**). Within each variable, different letters indicate significant differences among species, species and strata, and leaf positions and seasons at $p \leq 0.05$.

3.4. PM$_x$ Deposition in Rimini and Krakow

In Rimini, the species and season significantly affected both PM_{10} and $PM_{2.5}$ deposition. In addition, a species × stratum interaction was observed in PM_{10} (Table A1). *Quercus ilex* showed significantly higher deposition values for both PM_{10} and $PM_{2.5}$ than other species (except *Pinus pinea*), which were more than two times less efficient (Table 3). *Pinus pinea* ranked intermediately between *Quercus ilex* and other species for PM_x deposition values. The street trees of *Pinus pinea* showed a PM_{10} deposition 1.2 times higher than the park trees of the same species, while the $PM_{2.5}$ deposition did not differ among the strata within each species (data not shown).

Table 3. PM_{10} and $PM_{2.5}$ deposition (μg·cm^{-2}·day^{-1}) in Rimini and Krakow by the different species.

City	Species	PM_{10} Deposition (μg·cm^{-2}·day^{-1})		$PM_{2.5}$ Deposition (μg·cm^{-2}·day^{-1})	
Rimini	*Acer negundo*	0.879	c	0.236	b
	Aesculus hippocastanum	0.673	c	0.150	b
	Ligustrum lucidum	0.706	c	0.146	b
	Pinus pinea	1.477	ab	0.335	ab
	Platanus × acerifolia	0.529	c	0.126	b
	Populus nigra	0.688	c	0.205	b
	Prunus laurocerasus	0.749	c	0.195	b
	Quercus ilex	1.932	a	0.435	a
	Quercus robur	0.976	bc	0.182	b
	Tilia × europaea	0.759	c	0.182	b
Krakow	*Acer platanoides*	1.369	bd	0.248	d
	Aesculus hippocastanum	1.548	ad	0.374	ad
	Cornus alba	1.777	ac	0.405	ab
	Fraxinus excelsior	1.098	d	0.252	cd
	Pinus nigra	1.978	ab	0.450	a
	Populus nigra	1.628	ac	0.398	ac
	Quercus robur	1.620	ac	0.378	ab
	Sorbus aucuparia	1.321	cd	0.276	cd
	Tilia cordata	2.062	a	0.380	ad
	Ulmus laevis	1.642	ac	0.294	bd

Within each variable and city, different letters indicate significant differences among species at $p \leq 0.05$.

In Krakow, the PM_{10} and $PM_{2.5}$ deposition were significantly affected by the species and season, while the strata were only significant for PM_{10} deposition. Additionally, a significant species × strata interaction was observed for both fractions (Table A1). *Tilia cordata* displayed almost two times higher PM_{10} deposition values than *Fraxinus excelsior* (Table 3). The remaining species showed intermediate deposition capacities.

Pinus nigra showed a significantly higher deposition of $PM_{2.5}$ compared with *Acer platanoides*, which was almost two times less efficient, while the other species displayed intermediate deposition rates. *Acer platanoides*, *Aesculus hippocastanum*, *Quercus robur*, and *Ulmus laevis* trees located in the street stratum showed higher PM_{10} deposition (about 1.6 times higher on average) than those in the park stratum (data not shown). On the contrary, the park trees of *Pinus nigra* and *Sorbus aucuparia* displayed 1.5 and 1.8 times higher deposition values, respectively, compared with the street ones. *Aesculus hippocastanum* displayed a 2.5 times higher $PM_{2.5}$ deposition in streets than in parks.

3.5. Comparison among Accumulation and Deposition Trends throughout the Year

The season significantly affected the annual PM_{10} and $PM_{2.5}$ accumulation and deposition in both cities. Although the accumulation peaked at different times of the year, depending on the city and PM fraction, an inverse trend between accumulation and deposition was found in both cities for both PM fractions (Figure 4).

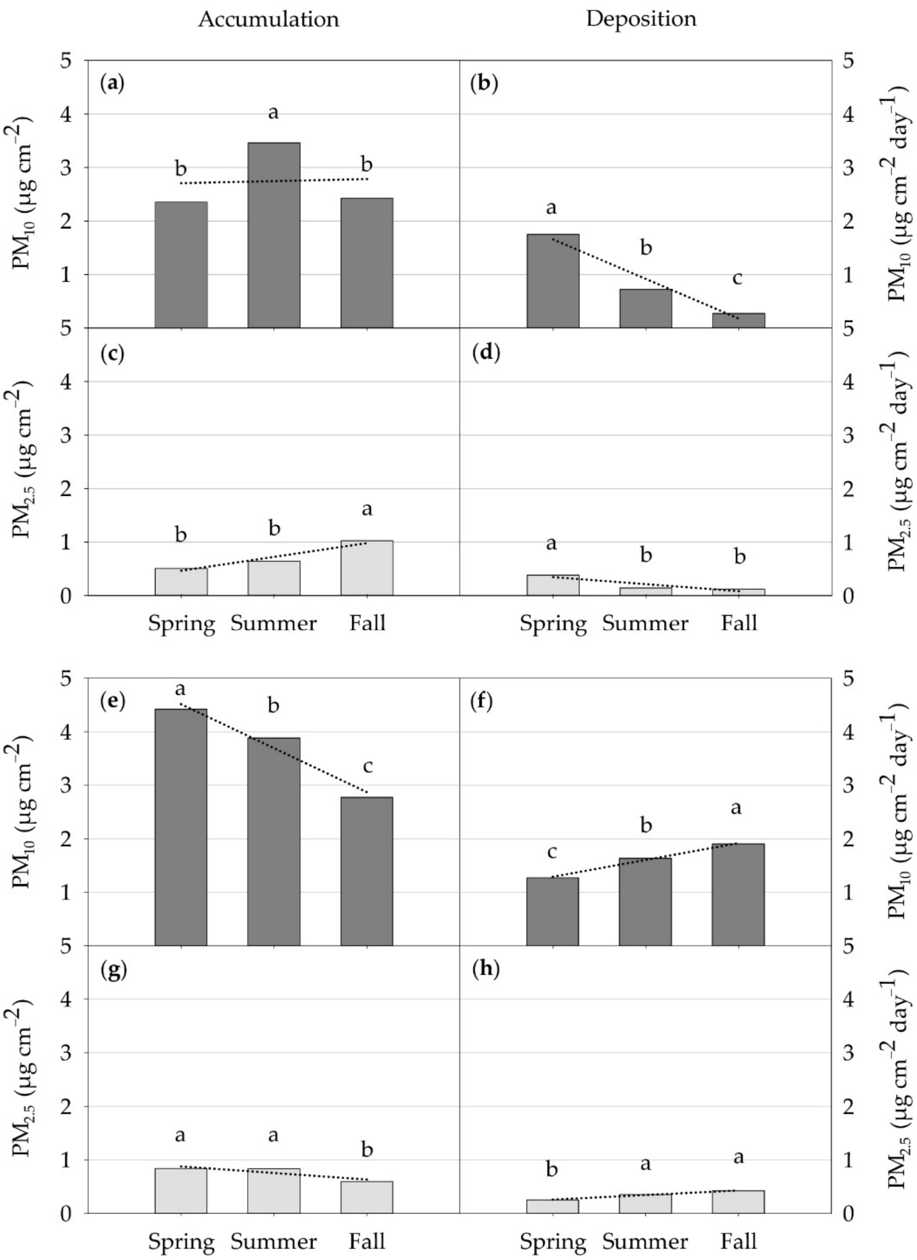


Figure 4. PM_{10} accumulation (**a**,**e**) and deposition (**b**,**f**) and $PM_{2.5}$ accumulation (**c**,**g**) and deposition (**d**,**h**) per unit leaf area in Rimini and Krakow, respectively. Within each variable, different letters indicate significant differences among seasons at $p \leq 0.05$. The dotted line represents the annual trend.

The accumulation of $PM_{2.5}$ increased as the growing season proceeded in Rimini, whereas the trend of PM_{10} was less clear (Figure 4a,c). Conversely, the deposition of both fractions decreased with leaf aging in Rimini (Figure 4b,d). In Krakow, the accumulation of both PM fractions peaked in spring and then progressively declined as the season progressed (Figure 4e,g), while PM deposition increased (Figure 4f,h).

3.6. Correlation among PM_x Leaf Capture and Meteorological and Environmental Parameters

The accumulation of each PM fraction was positively correlated with the accumulation of other PM fractions.

In Rimini, the wind speed and rainfall were negatively correlated with the accumulation for $PM_{10–100}$ and $PM_{0.2–2.5}$ but not with the accumulation of $PM_{2.5–10}$ (Table 4). The PM_{10} and $PM_{2.5}$ air concentrations were positively correlated with the accumulation of all

PM fractions (except for $PM_{2.5–10}$, which was not correlated with the PM_{10} air concentration and slightly negatively correlated with the $PM_{2.5}$ air concentration).

Table 4. Correlation matrix (Pearson's coefficient) among leaf PM accumulation ($PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$) and mean wind speed, cumulative rainfall, and mean PM_{10} and $PM_{2.5}$ air concentrations in Rimini and Krakow. Meteorological and air quality data refer to a period of 14 days before sampling day.

City	Factor	$PM_{10–100}$	$PM_{2.5–10}$	$PM_{0.2–2.5}$	Wind Speed	Rainfall	Air PM_{10}	Air $PM_{2.5}$
Rimini	$PM_{10–100}$		0.374 **	0.259 **	−0.202 **	−0.207 **	0.222 **	0.219 **
	$PM_{2.5–10}$			0.177 **				−0.092 **
	$PM_{0.2–2.5}$				−0.148 **	−0.162 **	0.162 **	0.179 **
	Wind speed					0.978 **	−0.873 **	−0.814 **
	Rainfall						−0.891 **	−0.837 **
	Air PM_{10}							0.978 **
	Air $PM_{2.5}$							
Krakow	$PM_{10–100}$		0.492 **	0.194 **		−0.262 **	0.176 **	
	$PM_{2.5–10}$			0.411 **	0.248 **	−0.325 **	0.094 *	
	$PM_{0.2–2.5}$				0.206 **	−0.098 **		
	Wind speed					−0.579 **	−0.503 **	−0.608 **
	Rainfall						0.195 **	0.478 **
	Air PM_{10}							0.930 **
	Air $PM_{2.5}$							

Only significant correlations are shown. * and ** indicate a significant correlation at $p \leq 0.05$ and $p \leq 0.01$, respectively.

In Krakow, the wind speed was positively correlated with the accumulation of $PM_{2.5–10}$ and $PM_{0.2–2.5}$ but did not correlate with the $PM_{10–100}$ accumulation. Rainfall, as observed in Rimini, was negatively correlated with the accumulation of all PM fractions. The air PM_{10} concentration, as observed in Rimini, was positively correlated with all PM accumulation fractions (except for $PM_{0.2–2.5}$). No correlation was found among the PM accumulation and $PM_{2.5}$ air concentration.

4. Discussion

4.1. Effect of Species and Strata on PM_x Accumulation and Deposition

By providing the results from extensive sampling campaigns conducted in situ on established trees and shrubs, this research corroborated previous findings that species largely differ in their capacity to adsorb atmospheric particulate matter [6,31,32,56]. Larger differences among species were observed for coarser PM fractions compared with finer fractions, reflecting the different aerodynamics properties of the particles and their interactions with different leaf characteristics [30].

Some species displayed high efficiency regardless of particle size, as was the case of *Quercus ilex* in Rimini. The high accumulation and deposition displayed by this species in all the PM fractions can probably be attributed to the co-occurrence of favorable leaf traits for PM adsorption and retention [57], such as the presence of hairs and trichomes on leaf surfaces, small leaf size, and a thick epicuticular wax layer [5]. Consistently, several authors highlighted that dense leaf hairs, which cover the abaxial side of *Quercus ilex* leaves, affected the PM_x leaf accumulation, increasing the interception surface area and reducing PM re-suspension [4–6,34,58,59]. If the PM_x accumulation of *Quercus ilex* is compared to that of *Platanus* × *acerifolia*, which also displayed a dense trichome cover in the lower leaf epidermis, our results conform to the idea that the leaf length and width are negatively related to accumulation [30].

Needle-leaved species have been reported to be more effective in PM_x accumulation than broadleaves because of their aerodynamic properties, the complex shoot structures, leaf morphology (e.g., the higher surface/volume ratio of needles), and the thicker epicuticular wax layer [4,5,34,39,60,61]. Consistently, in this experiment, *Pinus pinea* in Rimini and *Pinus nigra* in Krakow showed higher accumulations and depositions compared with most of the broadleaved species.

Extrinsic factors may also play a role in determining the amount of PM adsorbed on leaves. The accumulations of $PM_{10–100}$ and $PM_{2.5–10}$ by *Tilia cordata* in Krakow (annual average of 6.87 and 3.95 $\mu g \cdot cm^{-2}$, respectively) were similar to those previously reported for *Tilia cordata* in Poland (about 8 and 2.5 $\mu g \cdot cm^{-2}$, respectively; see Dzierzanowski et al. [4]) and ranked among the highest observed in this research. This was surprising because its smooth leaf surface, with only small tufts of hair on the abaxial side of the leaf blade, should have made *Tilia cordata* an inefficient sink for PM [2,5]. A possible explanation for the high amount of particles found in *Tilia cordata* in this work could be attributable to the honeydew produced by aphids, which was abundant on the foliar surface of the sampled plants and could have increased the trapping efficiency because of its stickiness [25]. Similarly, the high $PM_{0.2–2.5}$ accumulation observed in Krakow on *Populus nigra*, another smooth-leaved species with no trichomes, can be explained by the presence of honeydew on the leaf surface, which was also detected in this species. On the other hand, some authors point out that the presence of honeydew may be overestimated by the vacuum filtration method, because honeydew residuals might be weighted together with washed PM [62].

PM accumulation can be also affected by species-specific differences (e.g., leaf traits, canopy shape, and density) within a genus. Sæbø et al. [5] found that *Tilia cordata* and *Tilia* × *europaea* 'Pallida' differed for PM accumulation. This may be due to large differences in the leaf properties between the *Tilia* species. Consistently, high values were observed in Krakow in *Tilia cordata*, and low or intermediate values were found in *Tilia* × *europaea* in Rimini.

By considering the common species investigated in the two cities (*Aesculus hippocastanum*, *Populus nigra*, and *Quercus robur*), the plants in Krakow displayed higher accumulations and depositions than those in Rimini, consistently with higher values of pollution in the city. This underlines that the filter attitude of a species strongly depends on the level of pollution in which it is located [39,61,63].

Different from Rimini, where no differences between street and park particle accumulations were detected, in Krakow, more PM_x was captured by plants in the street stratum rather than in park sites, likely because of their proximity to the emission source [64]. An exception was represented by *Pinus nigra*, which accumulated more $PM_{10–100}$ in park areas than in the streets. The low tolerance to urban sites of this species made established trees chronically grown in street environments less efficient for air quality amelioration compared with established trees growing in parks. Although having high PM_x accumulation capacities, conifers are in general less tolerant to high traffic-related pollution than broadleaves, and they are not recommended for roadside plantings by several authors [5,14,34,65].

4.2. Effect of Leaf Position on PM_x Accumulation

Leaves in the lower third of the live crown height showed higher $PM_{10–100}$ accumulations than those in the upper crown, in agreement with other works [45,46]. Due to their higher size and weight, large particles show a clearer source—sink relationship than coarse and fine ones and settle within a limited vertical distance from the source. This underlines the importance of the barrier density, rather than the barrier height, for the reduction of larger PM fractions and highlights the role of evergreen shrub barriers in air quality improvement along roads [45]. Conversely, finer fractions are easily dispersed in the atmosphere since height does not affect the probability of impact [60]. Dust resuspension caused by human activities like garden maintenance or running in parks [47] and vehicular traffic in streets [45,66] could promote higher accumulations of large PM in the basal leaves, which are close to the ground [67]. Indeed, the concentration of PM in urban environments decreases with increasing height [68]. Moreover, the interception of rainfall by apical leaves and branches decreases the precipitation intensity [66] in the lower crown parts, which results in them being subjected to washing off less. Furthermore, PM intercepted by drops in the apical part of the crown could promote wet deposition on the basal leaves. Above all, these findings support the importance of vegetation at the pedestrian level.

4.3. Effect of the Season on PM_x Accumulation and Deposition

The lack of a consistent trend in seasonal accumulation between the two cities denotes that leaf ontogeny alone poorly relates with leaf PM accumulation, unless site-specific environmental factors are considered.

In Rimini, the total PM accumulation (i.e., the sum of all PM_x fractions) tended to increase throughout the year, confirming previous findings [38,55]. However, meteorological and environmental conditions can affect the yearly trend of accumulation. In Rimini, the rainfall was higher in spring and then progressively decreased until fall, while the PM_{10} and $PM_{2.5}$ air concentrations tended to increase. Heavy rainfall and strong wind, indeed, can remove particles accumulated on the leaf blade [39], and in addition, high levels of pollution can favor PM_x accumulation [13,23,25]. In Krakow, where rainfall was evenly distributed through the growing season, the total PM accumulation was higher in spring, when both the air PM_{10} and $PM_{2.5}$ concentrations were at their maximum, and then progressively declined until fall.

It is worth noting that the deposition rate was low in leaves displaying high PM accumulations, indicating that if active sites for PM trapping are almost clogged due to a high level of accumulation, less PM deposition can occur. PM is preferentially adsorbed on specific microstructures, such as cuticle ridges, trichomes, grooves, and glands [34]. Thus, although PM often covers a very small fraction of the leaf area [64], the deposition rate decreases as soon as active sites are saturated [69].

4.4. Effect of the Meteorological and Environmental Parameters on PM_x Accumulation

The complex dynamics of PM accumulation, wash-off, and re-suspension affect the contribution of vegetation to the air quality. Meteorological and environmental parameters play an important role in this process [55,58,70,71].

As the rain increased, foliar accumulation decreased in both cities as a result of the wash-off effect, making leaves ready for more deposition. However, the effect of precipitation on PM removal depends on the rainfall duration and intensity [54]. After a precipitation event, washed PM reaches the ground. Here, it can be immobilized if the surface is permeable (e.g., open soil or covered with vegetation), or it can be more probably re-suspended in the case of an impermeable surface (e.g., asphalt and other paved surfaces widespread in urban environments) [39]. Considering that most of the urban surfaces are generally sealed, it is important to combine phytoremediation with other techniques (e.g., phytotechnologies such as drainage systems or porous paving) to allow the immobilization of pollutants in urban areas.

Unlike what was observed for the rainfall, the influence of the wind speed on PM capture was opposite in the two cities selected in this work. In Rimini, a coastal town where the wind speed reaches high peaks, wind blew off particles from the foliage, while in Krakow, a continental metropolis where the wind speed is generally lower, it promoted PM accumulation. Indeed, some authors pointed out that strong wind can remove PM from leaves, while weaker wind may enhance the PM load on vegetation [69,72]. However, Sgrigna et al. [67] found that the wind direction influenced particle accumulation more than the wind speed. Consistently, a possible explanation of the positive correlation between wind speed and PM accumulation in Krakow could be the polluted air flow, which moves from coal-fired power stations in the suburbs to the city. For this reason, future experiments should also consider this parameter.

Finally, in this research, PM accumulation on leaves was enhanced by increasing the levels of air PM (with some exceptions). Mitchell et al. [25] observed an increase in leaf PM accumulation until it was in equilibrium with the surrounding air pollution concentration. Thus, the greater the presence of pollutants in the air, the greater the capacity of plants to act as filters.

Above all, it should be considered that meteorological and environmental data were obtained by the representative pollution control units of each city and not by sensors punctually located near each examined plant. For future studies, it will be essential to detect for each sampled plant the microclimatic (rainfall intensity and duration, wind speed and direction, relative humidity, and temperature) and air pollution data as parameters to consolidate and further explore their influence on accumulation dynamics.

5. Conclusions

This research was conducted with extensive in situ measurements on 240 established trees and shrubs belonging to 17 species in 2 cities (Rimini, Italy and Krakow, Poland) used as living laboratories, highlighting the relevance of planning choices for maximizing air filtering by urban forests. It revealed that needle-leaved species (*Pinus nigra* and *Pinus pinea*) and broadleaves with small, hairy, and waxy leaves (*Quercus ilex*) should be preferred, as they displayed the higher potential for air quality amelioration. Extrinsic factors, such as the presence of honeydew, can increase the adsorption of leaves whose functional traits are normally poorly suited for PM removal, such as occurred in this research for *Tilia cordata* and *Populus nigra*. A quantitative analysis on the effective surface area for PM retention, including microstructures (e.g., hairs, cuticle ridges, and grooves) and honeydew presence, is required in future studies to address the remaining gaps on this topic.

The trend of PM accumulation throughout the year was inverse among the two cities, indicating that leaf ontogeny alone poorly relates with particle accumulation on leaves, unless site-specific meteorological and environmental factors are considered (e.g., rainfall, wind speed, and air PM concentration). Street trees of some species (e.g., *Fraxinus excelsior* and *Ulmus laevis*) were particularly effective at PM capture, but for those species whose health was harmed by growing in a street environment (e.g., *Pinus nigra*), PM removal declined compared with plants of the same species growing in parks. Careful planning is required to maximize the benefit-to-cost ratio of using vegetation in an urban environment.

A higher accumulation of large PM was found in the lower third of the canopy, underlying the need of trees and shrubs branched from the ground to avoid PM re-suspension and dispersion issues at the pedestrian level, especially along roads affected by vehicular traffic emissions. However, it is worth noting that there may be different design configurations depending on the site characteristics, such as the type of use and available space. In pedestrian spaces or driveways with low planting space, for example, trees with free trunks could be integrated with shrubs branched from the ground to avoid interference with users. This work gives urban planners the possibility to take advantage of many species to design functional arrangements of space for living, answering the air pollution challenge in cities.

Considering the complex and dynamic cycle of PM in urban landscapes, it must be pointed out that this cycle does not end once particles reach plant surfaces. To ensure an effective role of vegetation in air quality improvement, both planning and management measures are needed to definitively remove PM from the environment. At the planning level, it is important to integrate the design of greening with the design of a permeable surrounding environment using, for example, stabilized soils, drainage systems, or porous paving. At the management level, frequent removal of fallen leaves must be favored. How much do planning and management techniques affect the air filtering potential of vegetation in modern cities? Future research could focus on this topic.

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Appendix A

Table A1. Results of the mixed models for $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$ accumulation (µg·cm^{-2}) and for PM_{10} and $PM_{2.5}$ deposition (µg·cm^{-2}·day^{-1}) in Rimini and Krakow.

City	Factor	Accumulation			Deposition	
		$PM_{10–100}$	$PM_{2.5–10}$	$PM_{0.2–2.5}$	PM_{10}	$PM_{2.5}$
Rimini	Species	**	**	**	**	**
	Strata	n.s.	n.s.	n.s.	n.s.	n.s.
	Position	**	n.s.	n.s.	n.s.	n.s.
	Season	**	**	**	**	**
	Species × Strata	n.s.	n.s.	n.s.	**	n.s.
Krakow	Species	**	**	*	**	**
	Strata	*	n.s.	n.s.	**	n.s.
	Position	**	n.s.	n.s.	n.s.	n.s.
	Season	**	**	**	**	**
	Species × Strata	**	**	n.s.	**	**

* Significant differences at $p \leq 0.05$. ** Significant differences at $p \leq 0.01$. n.s. = not significant differences.

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