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Article

The Concentrations and Removal Efficiency of PM_{10} and $PM_{2.5}$ on Wetland in Beijing

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Abstract: Particulate matter is a severe source of atmospheric pollution in urban cities, and it has adverse effects on human health. This study was conducted during the whole year of 2016 to monitor the concentrations of PM_{10} and $PM_{2.5}$ on the Beijing Hanshiqiao wetland and bare land in Beijing to analyze their correlations with meteorological factors and compare the removal efficiency between two land surface types. The results indicated that (1) the PM_{10} and $PM_{2.5}$ concentrations on the bare land were higher than those on wetland as a whole, reaching the highest value both at night and dusk and the lowest value near noon. The average concentration of PM_{10} was higher in winter (wetland: 137.48 $\mu g \cdot m^{-3}$; bare land: 164.75 $\mu g \cdot m^{-3}$) and spring (wetland: 205.18 $\mu g \cdot m^{-3}$; bare land: 244.85 $\mu g \cdot m^{-3}$) and the concentration of $PM_{2.5}$ on the wetland also reached the higher value in winter and spring with the average of 84.52 $\mu g \cdot m^{-3}$ and 98.98 $\mu g \cdot m^{-3}$, whereas, it was higher in spring and summer on the bare land; (2) concentrations of PM_{10} and $PM_{2.5}$ were significantly positively affected by the relative humidity ($P < 0.01$) and negatively influenced by wind speed ($P < 0.05$). The relationship between PM_{10} and $PM_{2.5}$ concentrations and temperature was found complicated: it showed a significantly negative correlation ($P < 0.01$) in winter and spring and was insignificant in autumn, but in summer, only the correlation between the PM_{10} concentration and temperature on wetland was significant ($P < 0.01$); (3) the removal efficiencies of PM_{10} and $PM_{2.5}$ followed the order of spring > winter > autumn > summer on the wetland, and the removal efficiency of PM_{10} was greater than that of $PM_{2.5}$. This study is aim to provide practical measures to improve the air quality and facilitate sustainable development in Beijing.

Keywords: particulates; wetland; concentration; meteorological factors; removal efficiency

1. Introduction

In recent years, with the rapid development of China urbanization, serious atmospheric pollution problem in Beijing has attracted increasing attention from the public, government, and atmospheric researchers in China. The pollution problem is not conducive to the construction of eco-friendly society and the development of sustainability [1]. The atmospheric particles have posed a threat on climate change and human health [2–4], especially PM_{10} and $PM_{2.5}$ with aerodynamic diameters less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$) respectively [5]. As a result, reducing the concentration of PM_{10} and $PM_{2.5}$ or removing them from the atmosphere have become a key issue in improving the air quality and promoting sustainability in urban areas.

Removing mass particles from the atmosphere to the land surface of the earth, which is a complicated process is significantly related to meteorological factors [2]. Meteorological conditions including air temperature, relative humidity and wind conditions usually have strong effects on the transport, diffusion, transformation and deposition of particles [6,7]. The effects of temperature on PM concentrations are complex [8,9]. Generally, temperature has an effect on atmospheric relative humidity and air turbulence [10]. Increased temperature will be followed by decreased humidity and increased turbulence, which as a consequence also affects the decrease in both PM concentration and PM capture by plants [8]. The low temperature and high relative humidity have a negative relationship with particle concentration [11]. The deposition velocity of PM_{10} is faster than that of $PM_{2.5}$ under the same meteorological condition [12–14], particularly on a water surface [15,16]. Besides, wind conditions and relative humidity are important parameters influencing the PM concentrations. The relatively slow wind speed favors accumulation of particles resulting in elevated pollution concentrations [17]. High relative humidity is to the disadvantage of diffusion of PM, besides, high relative humidity combined with high PM conditions could accelerate the further formation of water-soluble ions [18]. It is necessary to understand the mechanism of mass particle movement in the atmosphere for studying how to use vegetation and different land surfaces to remove particles from atmosphere to surfaces more effectively.

The wetlands which are also regarded as the "kidneys of the earth", have been increasingly attracted to whole PM-related researchers because it plays an important role in regulating, intercepting and removing PM_{10} and $PM_{2.5}$ [19,20]. Many studies [21–25] have drawn the conclusion that wetlands can remove particulate matter from atmosphere to land surfaces to some extent, by changing the micro-meteorological conditions (increasing the atmospheric relative humidity and lowering the temperature within a certain range in wetland), thus promoting particulate matter deposition [2]. Besides, plants grown in wetland, such as *Phragmites australis*, *Typha angustifolia* and *Canna indica* [21,26], tend to reduce the pollutant concentration by absorbing or capturing large quantities of airborne particles and accelerate the dry deposition process [5,22]. Moreover, some water-soluble ions could dissolve in the water, leading to the decrease of particle concentration [17].

The Beijing Hanshiqiao Wetland Nature Reserve is located in southwest of Yang Village, a small town owned by Shunyi District, Beijing. Its core zone has an intact wetland environment that is of the essence in environmental conservation and construction in Beijing [27]. Therefore, it is an ideal site to investigate and study how the wetland regulates and intercepts particle matter on the earth.

In this study, the concentrations of PM_{10} and $PM_{2.5}$ in different seasons within a year and the temperature, relative humidity and wind speed data were recorded on the wetland and bare land during the whole 2016 year. The aims of the current study are as follows: (1) analyzing the daily and quarterly variations of PM_{10} and $PM_{2.5}$ concentrations on the wetland and bare land, (2) exploring the influence of meteorological factors on the concentrations of PM_{10} and $PM_{2.5}$, (3) comparing the removal efficiencies of PM_{10} and $PM_{2.5}$ on the two land types. The results of this study may offer more appropriate indicators to quantify the microclimate regulation services of wetland ecosystems, and could provide us with practical measures for urban landscape design.

2. Experiments

2.1 Study Area

The Beijing Hanshiqiao Wetland Nature Reserve (40°07N,116°48′E) covers 1900 hm^2 area (Figure 1). The core zone, buffer area and experimental zone take up 8.61%, 0.63% and 90.76% of wetland natural reserve, with the area of 163.5 hm^2, 12.1 hm^2 and 1724.4 hm^2 respectively. The dominant species mainly included *Phragmites australis*, *Echinochloa crusgallii* and *Nymphaea tetragona*. This site was semi-humid continental monsoon climate and terrain, high summer temperatures, cold and dry winter with an average temperature of 11.9 °C, annual average rainfall of 603.1 mm, prevailing northwest winter winds, southeast winds in the summer. The control site was bare land in Dasunge Village, away from the Beijing Hanshiqiao Wetland Nature Reserve about 10.5 km. The bare land includes a 70% cement pavement surface and 30% soil surface, with 50 m in length and 20 m in width.

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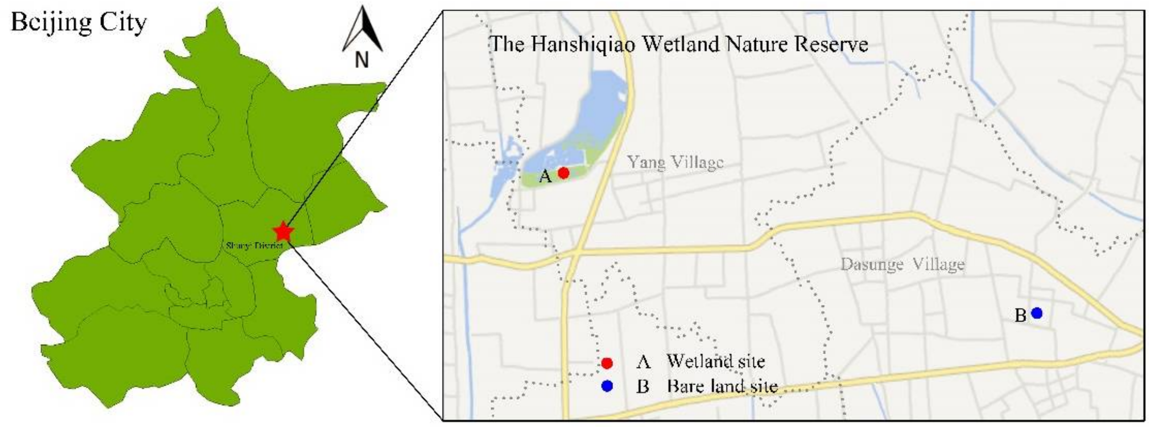

Figure 1. The location of the study area.

2.2 Measurements

Two 610 portable automatic weather stations (Weatherhawk instruments, USA) were installed 1.5 m above the ground in wetland and bare land to record temperature, relative humidity, and wind speed and direction. The instrument could monitor temperature range from -20 to 70 ℃, relative humidity range from 5% to 95%, wind speed range from 0.4 to 40 $m \cdot s^{-1}$ and wind direction range from 0 to 360°. DUSTMATE particle collector (Turnkey instruments, Northwich, UK) is an automatic instrument that can monitor the PM mass of $PM_{2.5}$ (≤ 2.5 μm), PM_{10} (≤ 10 μm). The instrument adopts the technology of scattered light to detect the concentration of dust and inhalable particles with diameter in the range of 0.5 to 15 μm, with maximum of concentration up to 6000 $\mu g \cdot m^{-3}$. The installment of two handheld DUSTMATE particle collectors was same as weatherhawk 610.

The monitoring time was in the late of Jan., Apr., Jul. and Oct. in 2016. The experiment was conducted for five or six consecutive days per quarterly as the mean of replicate measurements. The data were collected every five minutes in consecutive days. The DUSTMATE monitoring instruments and meteorological instruments in the sites are shown in Figure 1. The quarterly and daily patterns of PM mass concentrations on the wetland and bare land during the monitoring period were seen in Figures 2.

2.3 Computation of PM_{10} and $PM_{2.5}$ removal efficiency

In order to effectively compare the deposition of PM, the removal efficiency needs to be calculated on the wetland and bare land. The removal efficiency rates were computed using the following equation [11,28,29]:

$$E = I/\bar{C} \qquad (1)$$

where I is the total deposition of PM (PM_{10} and $PM_{2.5}$) on every type of surface and $\bar{C}$ is the daily average concentration [11,28]:

$$I = (1 - R) \times V_d \times C \times T \qquad (2)$$

where *R* is the resuspension rate of particles (PM_{10} and $PM_{2.5}$); V_d is the deposition velocity; *C* is the particle concentration, and *T* is the evaluated time. In this process, *R* of the bare land can be derived using the regression method, which can be expressed by the following equation [11,28]:

(3)

$$R = -0.01 \times x^2 + 0.17 \times x \quad (R^2 = 0.91; P < 0.001) \qquad (3)$$

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The deposition velocities (V_d) of the particles (PM_{10} and $PM_{2.5}$) on the bare land and wetland can be calculated using the following equation [29–32]:

$$V_d = -0.01 \times x^3 + 0.05 \times x^2 + 0.41 \times x - 0.05 \quad (4)$$

2.4 Statistical Analysis

Data were subjected to one-way analysis of variance using SPSS 21.0 (Chicago, USA) and plotted with SigmaPlot 10.0 (Systat Software, Inc.). Significance of differences between PM mass concentrations mean values was tested using least significant difference test (LSD) at $\alpha = 0.05$. To test relationships between meteorological factors and PM mass concentrations, Person correlation analysis was conducted at $\alpha = 0.05$.

3. Results and discussion

3.1. Meteorological factors

The meteorological factors including the temperature, humidity and wind speed in each season on two different land surfaces were shown in Table 1. The average temperature in each season on the wetland was lower than that on the bare land, due to the freezing or evaporation of wetland waters in winter and spring [33] and the respiration and photosynthesis of wetland plants in summer and autumn. On the wetland, the averages of humidity and wind speed in winter and spring were significantly higher than those on the bare land ($P < 0.05$), with ratios of 36.51%, 37.08%, 68.42% and 100%, respectively. The reason for the differences was probably the lower surface temperature of wetlands at night leading to the condensation of moisture in the air and higher surface temperature on wetlands during the daytime leading to waters evaporation, beneficial for the air flow. Gong et al. [34] found that compared with surrounding dry fields, marsh wetlands have significantly cold and wet microclimate effect characterized by low temperature and high relative humidity.

Table 1. Temperature, humidity and wind speed (mean ± standard error) in each season on two different land surfaces

Type	Season	Temperature	Humidity	Wind speed
Wetland	Winter	-6.43 ± 0.47	52.38 ± 3.01	0.32 ± 0.05
	Spring	17.27 ± 0.47	55.49 ± 2.63	0.38 ± 0.04
	Summer	26.92 ± 0.31	67.19 ± 2.45	0.06 ± 0.01
	Autumn	1.98 ± 0.51	50.89 ± 3.69	0.16 ± 0.03
Bare land	Winter	-3.95 ± 0.42	38.37 ± 1.53	0.19 ± 0.03
	Spring	18.94 ± 0.46	40.48 ± 1.63	0.19 ± 0.03
	Summer	28.41 ± 0.36	67.85 ± 2.08	0.23 ± 0.04
	Autumn	3.42 ± 0.47	49.22 ± 2.92	0.38 ± 0.06

3.2. PM mass concentration

The average concentration variations of PM_{10} and $PM_{2.5}$ on the wetland and bare land during different seasons are presented in Figure 2. During the whole year (Figure 2), the daily change trends of the concentrations of PM_{10} and $PM_{2.5}$ in each season on the wetland and bare land were approximately similar, with the highest value at night and dusk and the lowest near noon, which was similar to the results in the Cuihu wetland [33] and Shelterbelt Site in Beijing [17]. This is probably because that the temperature is relatively lower and the humidity higher during the night and dusk which is to the disadvantage of the air flow and diffusion of PM_{10} and $PM_{2.5}$ [35], besides, the heavy traffic event during rush hours in the early morning and at dusk is another reason [36].

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Nguyen et al. also concluded that the $PM_{2.5}$ concentration is highest in the morning [37]. In terms of PM_{10}, its average concentrations reached the higher values in winter and spring both on the two land types, which were 20.05 μg·m^{-3} and 100.15 μg·m^{-3} higher than those in summer, 16.69 μg·m^{-3} and 96.79 μg·m^{-3} higher than those in autumn, respectively. The concentrations of $PM_{2.5}$ on the wetland also came up to the higher value in winter and spring with the average of 84.52 μg·m^{-3} and 98.98 μg·m^{-3}, whereas, $PM_{2.5}$ concentration on the bare land were higher in spring and summer. There was much coal combustion in winter and according to Witkowska's study [38], carbonaceous aerosols, regarded as the important component of PM_{10} and $PM_{2.5}$ pollution, are durable and probably transported far away from the source. In spring, with the increase of temperature, primary organic carbon, calcium, potassium and ammonium nitrate increased in aerosols due to emission from surrounding fields and forests, leading to the raise of PM_{10} and $PM_{2.5}$ concentrations.

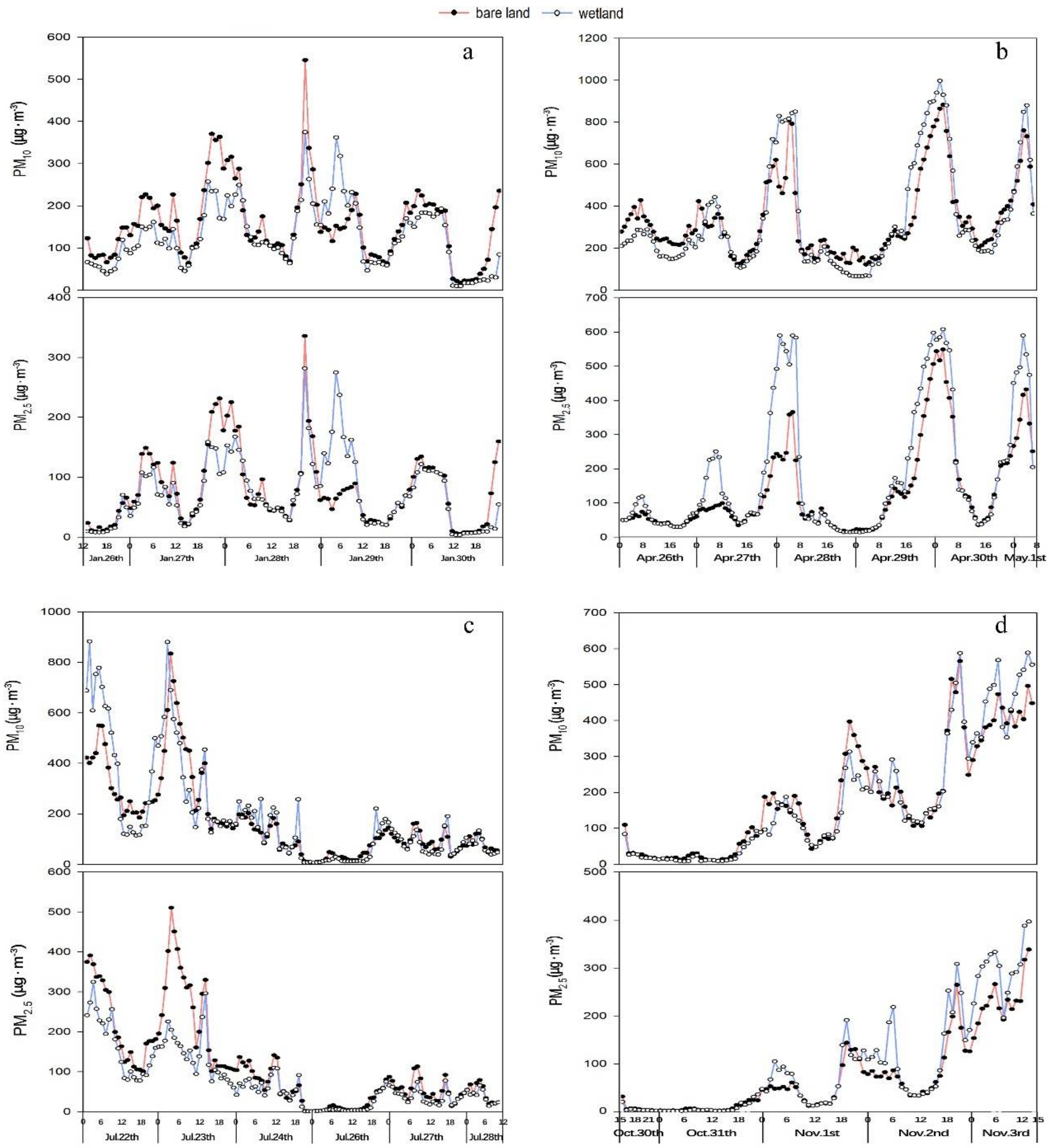

Figure 2. The average concentration variations of PM_{10} and $PM_{2.5}$ on the wetland and bare land during different seasons. (a)~(d) is Winter, Spring, Summer and Autumn.

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In winter, PM_{10} and $PM_{2.5}$ on the bare land were higher than those on the wetland (Figure 2a). The average value of PM_{10} on the bare land was 27.27 $\mu g \cdot m^{-3}$ higher than that on the wetland with the ratio of 19.84%. The $PM_{2.5}$ of bare land was 4.70% higher than that of wetland. This is because the wind speed on wetland is higher than that on bare land (Table 1), especially at 8:00-17:00 in winter. The average of wind speed on wetland is 0.32 $m \cdot s^{-1}$, approximately twice as high as bare land of 0.19 $m \cdot s^{-1}$. Due to higher wind speed is conducive to air flow and particulate matter diffusion [39], PM_{10} and $PM_{2.5}$ on wetland are lower than that on bare land, and the effect of wetland on the diffusion of PM_{10} is more obvious. However, PM_{10} and $PM_{2.5}$ of the wetland on 29th January were significantly higher than those of the bare land, which was because the air relative humidity continued to be 100% on the wetland from 1:00 to 8:00 in the morning on 29th January, while 60%-70% on the bare land, and there was no wind on the wetland. The weather condition was conducive to the accumulation of particulate matter instead of its diffusion [21].

In spring, PM_{10} on bare land was higher than that on wetland during the daytime, which was opposite to night and dawn, while for $PM_{2.5}$, its concentration on wetland exceeded that on the bare land on the whole (Figure 2b). This is because the average wind speed on wetland during the daytime is higher than that on bare land, which can help to the diffusion of larger particles in the air [40]. During the night, PM_{10} and $PM_{2.5}$ increased more rapidly on the wetland, especially under cloudy and moderately hazy weather (28th April, 30th April and 1st May). By analyzing and comparing the variations of PM_{10} and $PM_{2.5}$ concentrations from 0:00 to 7:00 of the three days, the average concentrations of PM_{10} and $PM_{2.5}$ on the wetland were 120.33 $\mu g \cdot m^{-3}$ and 157.23 $\mu g \cdot m^{-3}$ respectively higher than that on the bare land, with the ratios of 19.51% and 45.41%. The reason was that the air relative humidity under the cloudy and hazy weather lasts for 100% at night, which is to the disadvantage of the diffusion of atmospheric particulate matter and promotes the accumulation of fine particulate matter in forests on the contrary [41]. Therefore, the wetland under cloudy and hazy weather in spring will aggravate the accumulation of particulate matter, while it may reduce the concentration of particulate matter on sunny days.

In summer, according to Figure 2c, there is no obvious difference of PM_{10} concentration between the two land types except for the two days, 22th and 23th in July, which is similar to that of $PM_{2.5}$. High relative humidity in summer may be the main cause of insignificant difference between the two land types. On 22th and 23th July, the concentration of PM_{10} on wetland exceeded that on the bare land at night, both with greater change amplitudes, but during the daytime (9:00-18:00), it was lower than the bare land. However, $PM_{2.5}$ concentration on wetland was lower than that on bare land all day. This is due to the weather condition with cloud and thundershower of the two days, as a result, the relative humidity on wetland was higher at night, which was beneficial for the accumulation of coarse particulate matter, while during the daytime, it decreased with the increase of temperature. In addition, the plants grown in wetland and the waters could capture, absorb and dissolve the particulates particularly the fine particles [42]. Li [27] compared capturing and dissolving capacity of seven different plants including *Phragmites australis*, *Typha angustifolia*, *Scirpus tabernaemontani*, *Iris tectorum*, *Zizania aquatica*, E*eichhornia crassipes* and *Sagittaria sagittifolia* grown in wetland and calculated the amounts of particles captured and absorbed by plants. Liu [23] proved the concentrations of PM_{10} and $PM_{2.5}$ were lower over lake than bare land because of absorption of water.

In autumn, no significant difference of the concentration of PM_{10} was found between the bare land and wetland, while $PM_{2.5}$ concentration on the wetland was higher than that on the bare land all day (Figure 2d). Compared with meteorological factors on the bare land, humidity on the wetland was higher, besides, wind speed was slower, which could be 1.03 times and 0.42 times of the data on the bare land, respectively (Table 1). These meteorological conditions would be adverse to diffusion and deposition of mass particles [21,40]. And the $PM_{2.5}$ was more sensitive to meteorological conditions [23], as a result, the $PM_{2.5}$ concentration on wetland was higher than that on bare land. The result was consistent with the previous studies [12,23].

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On the whole, the average concentrations of PM_{10} and $PM_{2.5}$ on the wetland and bare land did not show significant regularity ($P > 0.05$) during the whole year [43]. It indicated the average concentrations of wetland and bare land have a large fluctuation during the whole monitoring period. The result was similar to Liu' study [23] which pointed out that the concentrations of $PM_{2.5}$ on lake and bare land were unstable.

3.3. Effect of meteorological factors on PM_{10} and $PM_{2.5}$ concentrations

Correlation analysis between PM_{10} and $PM_{2.5}$ concentrations and meteorological factors on different land types was displayed in Table 2. A complicated relationship was found between the concentrations of PM_{10} and $PM_{2.5}$ and temperature. Specifically, PM_{10} and $PM_{2.5}$ concentrations were significantly negative correlated with temperature ($P < 0.01$) in winter and spring on two land types. However, in summer, only the correlation between the PM_{10} concentration and temperature on wetland was significant ($P < 0.01$), but for $PM_{2.5}$, it was insignificant, of which the reason may be that in summer, high temperature changed some constitutes of fine particles, moreover, according to a few previous studies [12,23,44], the small size of the particles seems to be more sensitive to meteorological factors. In addition, there was also no significant correlation between PM_{10} and $PM_{2.5}$ concentrations and temperature in autumn and the whole year on two land types except that of PM_{10} of the whole year on the wetland, which indicated the significantly positive correlation ($P < 0.05$). This is likely because that high temperature in a year could help to accelerate the photochemical reaction between precursors, further influence the formation of particles [39]. Therefore, the effects of temperature on particle concentrations are complex [8,9]. For instance, in summer, high temperature promotes the formation of particulate sulfate, but dissociates part of particulate nitrate [45–47], hence, it was hard to say the definite relationships between temperature and PM_{10} and $PM_{2.5}$ concentrations. In general, temperature plays a significant role in regulating PM_{10} and $PM_{2.5}$ concentrations by changing the humidity and wind speed, and it tends to have some effects on air disturbance and relative humidity [37]. In spring, the conditions of wetland were characterized lower temperature, high relative humidity and lower wind speed during night, therefore, the concentrations of PM_{10} and $PM_{2.5}$ were higher than that on bare land. As for significant correlations, the absolute value of R ranged from 0.100 to 0.495 for PM_{10}, and from 0.121 to 0.540 for $PM_{2.5}$ (Table 2), which were both lower than that between PM_{10} and $PM_{2.5}$ concentrations and humidity, wind speed respectively.

The relationships between concentrations of PM_{10} and $PM_{2.5}$ and humidity presented significantly positive correlations ($P < 0.01$) in different seasons within a year on two land types (Table 2). It was also proved by Liu et al., Zhu et al. and Qiu et al. in their researches [21,22,33]. For example, in this study, the daily concentrations of PM_{10} and $PM_{2.5}$ reached the highest value at night and dusk and the lowest near noon in general due to the higher humidity during night and dusk and lower humidity at noon. Moreover, cloudy and polluted weather conditions (28^{th} and 30^{th} in April, 1^{st} May) would come along with higher relative humidity (almost 100%), and under this situation, concentrations of PM_{10} and $PM_{2.5}$ on wetland were greater than that on bare land respectively which was same to the Liu' study [23]. High relative humidity is to the disadvantage of diffusion of PM_{10} and $PM_{2.5}$, besides, high relative humidity combined with high particle concentrations could accelerate the further formation of water-soluble ions [45,46]. The significant effect of humidity and wind speed on the pollution concentration has been proven by some previous studies [23,48]. The absolute value of R between concentrations of PM_{10} and $PM_{2.5}$ and humidity ranging from 0.402 to 0.797 for PM_{10}, with an average of 0.608, was higher than that between PM_{10} and $PM_{2.5}$ concentrations and other two meteorological factors. For $PM_{2.5}$, the average of R (0.598) was also the highest, which is similar to the result of Liu et al. [23]. Whereas, the relative humidity was found to bring less effects in the study of meteorological influence in four locations in Guangzhou, China [40], possibly due to the difference of climate in Beijing and Guangzhou.

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Table 2. Correlation coefficients between PM_{10} and $PM_{2.5}$ mass concentrations and meteorological factors on two different land surfaces during a year.

Type	Season	Particulate	Parameters	Climate factors		
				Temperature	Humidity	Wind speed
Wetland	Winter	PM_{10}	R	-0.495**	0.700**	-0.553**
			P Value	0.000	0.000	0.000
		$PM_{2.5}$	R	-0.540**	0.729**	-0.541**
			P Value	0.000	0.000	0.000
	Spring	PM_{10}	R	-0.391**	0.797**	-0.442**
			P Value	0.000	0.000	0.000
		$PM_{2.5}$	R	-0.400**	0.816**	-0.454**
			P Value	0.000	0.000	0.000
	Summer	PM_{10}	R	-0.239**	0.526**	-0.149
			P Value	0.006	0.000	0.088
		$PM_{2.5}$	R	-0.115	0.412**	-0.087
			P Value	0.188	0.000	0.319
	Autumn	PM_{10}	R	-0.068	0.594**	-0.446**
			P Value	0.511	0.000	0.000
		$PM_{2.5}$	R	-0.109	0.595**	-0.404**
			P Value	0.286	0.000	0.000
	year	PM_{10}	R	0.100*	0.555**	-0.238**
			P Value	0.031	0.000	0.000
		$PM_{2.5}$	R	-0.003	0.544**	-0.260**
			P Value	0.941	0.000	0.000
Bare land	Winter	PM_{10}	R	-0.369**	0.506**	-0.385**
			P Value	0.000	0.000	0.000
		$PM_{2.5}$	R	-0.407**	0.472**	-0.355**
			P Value	0.000	0.000	0.000
	Spring	PM_{10}	R	-0.340**	0.813**	-0.347**
			P Value	0.000	0.000	0.000
		$PM_{2.5}$	R	-0.229**	0.801**	-0.220*
			P Value	0.009	0.000	0.012
	Summer	PM_{10}	R	-0.131	0.457**	-0.393**
			P Value	0.133	0.000	0.000
		$PM_{2.5}$	R	-0.134	0.467**	-0.392**
			P Value	0.123	0.000	0.000
	Autumn	PM_{10}	R	-0.081	0.725**	-0.535**
			P Value	0.432	0.000	0.000
		$PM_{2.5}$	R	0.006	0.632**	-0.431**
			P Value	0.952	0.000	0.000
	year	PM_{10}	R	0.076	0.402**	-0.385**
			P Value	0.103	0.000	0.000
		$PM_{2.5}$	R	0.121**	0.511**	-0.329**
			P Value	0.009	0.000	0.000

Note: R means Person correlation coefficients; * Correlation is significant at the 0.05 level (two-tailed). Similarly thereafter; ** Correlation is significant at the 0.01 level (two-tailed).

There was a significantly negative correlation observed between PM_{10} and $PM_{2.5}$ concentrations and wind speed ($P < 0.05$) except in summer on the wetland, during that time, there was no significant correlation between the both (Table 2). This is because wind speed in summer is the lowest (0.06 ± 0.01) among different seasons on the wetland, and low wind speed may have smaller effect on the diffusion of PM_{10} and $PM_{2.5}$ [35]. The relatively slow wind speed favor accumulation of particles

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resulting in elevated pollution concentrations [17]. Humidity and wind speed influence the concentration by affecting the dry deposition velocity and resuspension [47–49]. For example, in spring, during the daytime, PM_{10} concentration on the wetland was lower than that on the bare land, however, there is an opposite case during night. Maybe the causes for this were due to higher average wind velocity during day of wetland which was conducive to diffusion of particles. But wind velocity would slow down at night which caused higher concentration of PM_{10}.

3.4. Removal efficiencies of PM_{10} and $PM_{2.5}$

Figure 4 showed the removal efficiencies of PM_{10} and $PM_{2.5}$ on the wetland and bare land during daytime and night in different seasons. In winter and spring, the removal efficiencies of PM_{10} and $PM_{2.5}$ on two land types were significantly higher during daytime than that during night ($P < 0.05$) and they were also higher on the wetland and lower on the bare land, except the values during night in winter. By contrast, in summer and autumn, the removal efficiencies of PM_{10} and $PM_{2.5}$ during night were significantly higher than that during daytime, in addition, they were higher on the bare land and lower on the wetland. Although there was no significant difference between the removal efficiencies of PM_{10} and $PM_{2.5}$, on the whole, the removal efficiency of PM_{10} was greater than that of $PM_{2.5}$, which did conform with the results of Wu et al. and Yang et al. [50,51]. On the wetland, the removal efficiency of PM_{10} followed the order of spring > winter > autumn > summer, similar to that of $PM_{2.5}$, which was consistent with result of Yang et al. [51], whereas PM_{10} and $PM_{2.5}$ removal efficiencies on the bare land ranked as autumn > summer > winter > spring.

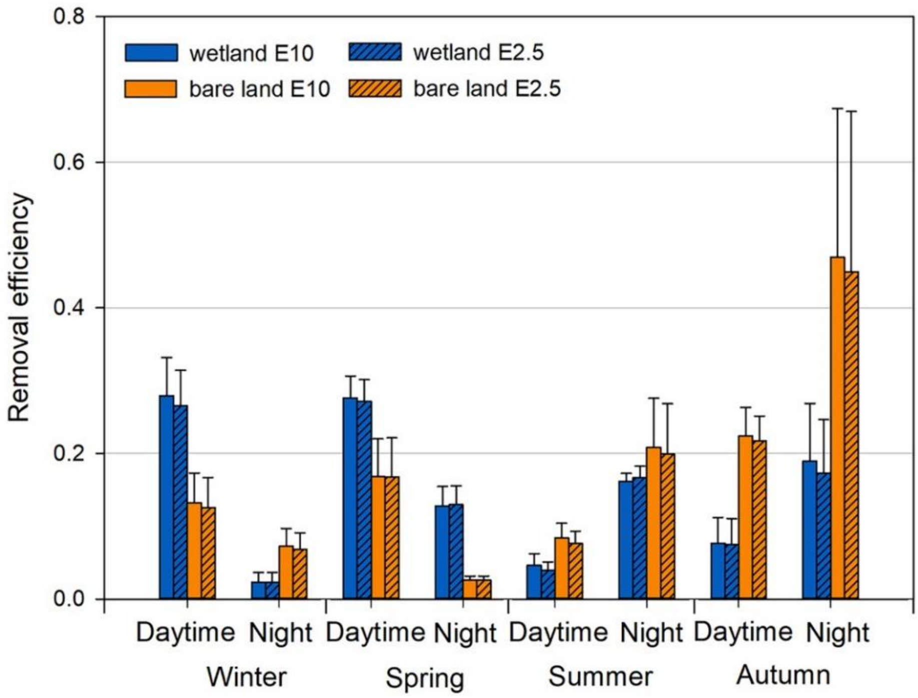

Figure 4 Removal efficiencies of PM_{10} and $PM_{2.5}$ on the wetland and bare land in different seasons

According to the equation (1), the removal efficiency depends on the deposition and the mass particles average concentration [11,28,29]. However, deposition tends to be affected by the deposition velocity, which has a close positive relationship with the wind speed [51–53]. The removal efficiency was also influenced by anthropogenic and other meteorological factors, such as the temperature, relative humidity and irradiance [50,53]. There was a negative relationship between the temperature and dry deposition of PM_{10} and $PM_{2.5}$: with the decrease of the temperature, the dry deposition increased, whereas the relative humidity had a positive effect on the dry deposition [23,42]. Diversely, Yang et al. showed the influences of the temperature and relative humidity on dry deposition were uncertain [51].

In this study, the wind speed in winter and spring on the wetland was higher than that in summer and autumn, which is contrast to the circumstance on the bare land, where the wind speed in summer and autumn exceeded that in other two seasons (Table 1). And there is the lower temperature and higher humidity in winter and spring on the wetland compared with other two seasons. As a result, the removal efficiencies of PM_{10} and $PM_{2.5}$ in winter and spring on the wetland were higher than that of other two seasons, which is opposite to the situation on the bare land. But there is an exception during night in winter, where the removal efficiencies of PM_{10} and $PM_{2.5}$ on the wetland were lower than that on the bare land. This was because the higher concentrations of PM_{10} and $PM_{2.5}$ on the bare land led to higher dry deposition and accordingly the removal efficiencies increased [50]. Surprisingly, we found the removal efficiencies of PM_{10} and $PM_{2.5}$ in summer were lower than those in other seasons. Nevertheless, in summer, the plants grown in wetland have ability to absorb and capture particles, moreover, some water-soluble ions could dissolve the particles into water [45–47]. So in theory, the removal efficiency should be higher than other seasons. As for this phenomenon, we discovered the wind speed in summer was too slow and almost close to zero, which led to the lower removal efficiency.

4. Conclusions

This study indicated that the daily change trends of the concentrations of PM_{10} and $PM_{2.5}$ in each season on the wetland and bare land were approximately similar, with the highest value at night and dusk and the lowest near noon. The average concentration of PM_{10} reached the higher value in winter and spring both on the two land types, and the $PM_{2.5}$ concentration on the wetland also came up to the higher value in winter and spring, whereas, on the bare land, it was higher in spring and summer. As for the relationships between meteorological factors and concentrations of PM_{10} and $PM_{2.5}$, relative humidity and wind speed are significantly correlated with the PM_{10} and $PM_{2.5}$ concentrations on wetland and bare land ($P < 0.05$). The removal efficiency of PM_{10} was greater than that of $PM_{2.5}$. Strong wind speed, lower temperature and higher relative humidity could facilitate the dry deposition and accordingly increase the removal efficiency.

The results of this study show the importance of removing PM_{10} and $PM_{2.5}$ from the atmosphere further improving the air quality in Beijing through effective approaches and management. Given the irregular variation of PM_{10} and $PM_{2.5}$, various factors affecting the concentrations of PM_{10} and $PM_{2.5}$ and complicated mechanism in the process of removing atmospheric particles, further researches about the changes of chemical constitutes and characteristics of particles in the study area should be conducted; how to further reduce the particle concentrations through improving the microclimate in wetland ecosystems was valuable to be discussed; and other factors and their synergistic effects affecting the dry deposition and removal efficiency of particles are still needed to explore in the future.

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References

1. Park, S.H.; Ko, D.W. Investigating the Effects of the Built Environment on $PM_{2.5}$ and PM_{10}: A Case Study of Seoul Metropolitan City, South Korea. *Sustainability* **2018**, *10*(12), 4552. https://doi.org/10.3390/su10124552
2. Beckett, K.P.; Freer-Smith, P.H.; Taylor, G. Urban woodlands: their role in reducing the effects of particulate pollution. *Environ.* Pollut. 1998, 99(3), 347–360. https://doi.org/10.1016/S0269-7491(98)00016-5
3. Tiwari, S.; Srivastava, A.K.; Singh, A.K.; Singh, S. Identification of aerosol types over Indo-Gangetic Basin: Implications to optical properties and associated radiative forcing. *Environ. Sci. Pollut. Res*. **2015**, *22*, 12246–12260. https://doi.org/10.1007/s11356-015-4495-6
4. Lipfert, F.W. An assessment of air pollution exposure information for health studies. *Atmosphere* **2015**, *6*, 1736–1752. https://doi.org/10.3390/atmos6111736
5. Yang, F.M.; Ma, Y.L.; He, K.B. A brief introduction to $PM_{2.5}$ and related research. *World Environ.* **2000**, *4*, 32–34.
6. Wang, L.L.; Wang, Y.S.; Wang, Y.H.; Sun, Y.; Ji, D.S.; Ren, Y.F. Relationship between different synoptic weather patterns and concentration of NOX, O^3 and PM2.5/10 in beijing during summer and autumn. *China Environ. Sci*. **2010**, *30*, 924–930. https://doi.org/10.1111/j.1445-5994.1996.tb02957.x
7. Yarnal, B. Synoptic climatology in environmental analysis, a primer. *J. Prev. Med. Inf.* **1993**, *347*, 170–180.
8. Li, H.; Duan, F.; He, K.; Ma, Y.; Kimoto, T.; Huang, T. Size-dependent characterization of atmospheric particles during winter in beijing. *Atmosphere* **2016**, *7*(3), 36. https://doi.org/10.3390/atmos7030036
9. Wu, J.; Xu, C.; Wang, Q.; Cheng, W. Potential sources and formations of the $pm_{2.5}$ pollution in urban hangzhou. *Atmosphere* **2016**, *7*(8), 100. https://doi.org/10.3390/atmos7080100
10. Beckett, K.P.; Freer-Smith, P.; Taylor, G. Effective tree species for local air quality management. *J. Arboric.* **2000**, *26*(1), 12–19.
11. Nowak, D.J.; Crane, D.E.; Stevens, J.C. Air pollution removal by urban trees and shrubs in the United states. *Urban For. Urban Green*. **2006**, *4*, 115–123. https://doi.org/10.1016/j.ufug.2006.01.007
12. Petroff, A.; Mailliat, A.; Amielh, M.; Anselmet, F. Aerosol dry deposition on vegetative canopies. Part I: review of present knowledge. *Atmos. Environ.* **2008**, *42*(16), 3625–3653. https://doi.org/10.1016/j.atmosenv.2007.09.043
13. Wang, Y.C. Carbon sequestration and foliar dust retention by woody plants in the greenbelts along two major Taiwan highways. *Ann. Appl. Biol*. **2011**, *159*(2), 244–251. https://doi.org/10.1111/j.1744-7348.2011.00494.x
14. Dzierżanowski, K.; Popek, R.; Gawrońska, H.; Sæbø, A.; Gawroński, S.W. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *Int. J. Phytoremediation*. **2011**, *13*(10), 1037–1046. https://doi.org/10.1080/15226514.2011.552929
15. Wang, X.F. Determination of concentrations of elements in the atmospheric aerosol of the urban and rural areas of Beijing in winter. *Biol. Trace. Elem. Res.* **1999**, *71*(1), 203–208. https://doi.org/10.1007/BF02784206
16. Edwards, R. Smog blights babies in the womb. *New. Sci*. **1996**, *152*(2052), 4.
17. Chen, J.G.; Yu, X.X.; Sun, F.B.; Lun, X.L.; Fu, Y.; Jia, G.D.; Zhang, Z.M.; Liu, X.H.; Mo. L.; Bi, H.X. The concentrations and reduction of airborne particulate matter (pm10, pm2.5, pm1) at shelterbelt site in beijing. *Atmosphere* **2015**, *6*(5), 650-676. https://doi.org/10.3390/atmos6050650
18. Nieuwstadt, F. The Turbulent Structure of the Stable, Noctural Boundary Layer. *J. Atmos. Sci*. **1984**, *41*, 2202–2216.
19. Hao, Y.B.; Cui, X.Y.; Wang, Y.F.; Mei, X.R.; Kang, X.M. Predominance of precipitation and temperature controls on ecosystem CO2 exchange in Zoige alpine wetlands of southwest China. *Wetlands* **2011**, *31*, 413–422. https://doi.org/10.1007/s13157-011-0151-1
20. Kang, X.M.; Wang, Y.F.; Chen, H.; Tian, J.Q.; Rui, Y.C.; Zhong, L.; Paul, K.; Hao, Y.B.; Xiao, X.M. Modeling carbon fluxes using multi temporal MODIS imagery and CO_2 eddy flux tower data in Zoige alpine wetland, south-west China. *Wetlands* **2014**, *34*, 603–618. https://doi.org/10.1007/s13157-014-0529-y
21. Qiu, D.D.; Liu, J.K.; Zhu, L.J.; Mo, L.C.; Zhang, Z.M. Particulate matter assessment of a wetland in Beijing. *J. Environ. sci*. **2015**, *36*(10), 93–101. https://doi.org/10.1016/j.jes.2015.04.016
22. Liu, J.K.; Zhu, L.J.; Wang, H.H.; Yang, Y.L.; Liu, J.T.; Qiu, D.D.; Ma, W.; Zhang, Z.M.; Liu, J.L. Dry deposition of particulate matter at an urban forest, wetland and lake surface in Beijing. *Atmos. Environ.* **2016**, *125*(PartA), 178–187. https://doi.org/10.1016/j.atmosenv.2015.11.023

23. Liu, J.K.; Mo, L.C.; Zhu, L.J.; Yang, Y.L.; Liu, J.T.; Qiu, D.D.; Zhang, Z.M.; Liu, J.L. Removal efficiency of particulate matters at different underlying surfaces in Beijing. *Environ. Sci. Pollu. Res*. **2016**, *23*(1), 1–10. https://doi.org/10.1007/s11356-015-5252-6
24. Hao, L.S.; Min, J.Z.; Duan, Y.; Wang, J.H.; Wang, J.H.; Wu, Z.H.; Shi, L.X. Observational research on distribution of aerosols observational research on distribution of aerosols over the Hengshui Lake Area. *J. Nanjing Institute of Meteorol*. **2008**, *31*(1), 109–115.
25. Sun, R.; Chen, A.; Chen, L; Lu, Y.H. Cooling effects of wetlands in an urban region: The case of Beijing. *Ecol. Indic.* **2012**, *20*, 57–64. https://doi.org/10.1016/j.ecolind.2012.02.006
26. Dockery, D.W.; Pope, C.A.; Xu, X.; Spengler, J.D.; Ware, J.H.; Fay, M.E. An association between air pollution and mortality in six US cities. *N. Engl. J. Med.* **1993**, *329*(24), 1753–1759. https://doi.org/10.1056/NEJM199312093292401
27. Li, C.Y.; Cui, L.J.; Zhang, X.D.; Zhu, Y.N.; Li, W.; Lei, Y.R.; Kang, X.M. Particulate matter adsorption capacity of 7 species of wetland plants in Beijing. *Ecol. Environ. Sci.* **2016**, *25*(12), 1967–1973.
28. Escobedo, F.J.; Nowak, D.J. Spatial heterogeneity and air pollution removal by an urban forest. *Landsc. Urban Plan.* **2009**, *90*, 102–110. https://doi.org/10.1016/j.landurbplan.2008.10.021
29. Tallis, M.; Taylor, G.; Sinnett, D. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London under current and future environments. *Landsc. Urban Plan.* **2011**, *103*, 129–138. https://doi.org/10.1016/j.landurbplan.2011.07.003
30. Freer-Smith, P.; El-Khatib, A.; Taylor, G. Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas with european and north american species. *Water Air Soil Pollut.* **2004**, *155*, 173–187.
31. Pullman, M. Conifer PM2.5 deposition and re-suspension in wind and rain events. *Cornell University*, **2009**, Ithaca.
32. Beckett, K.P.; Freer-Smith, P.H.; Taylor, G. Particulate pollution capture by urban trees: effect of species and wind speed. *Glob. Chang. Biol.* **2006**, *6*, 995–1003. https://doi.org/10.1046/j.1365-2486.2000.00376.x
33. Zhu, L.; Liu, J.; Cong, L.; Ma, W.; Ma, W.; Zhang, Z. Spatiotemporal characteristics of particulate matter and dry deposition flux in the Cuihu wetland of Beijing. *PloS one* **2016**, *11*(7), e0158616. https://doi.org/10.1371/journal.pone.0158616
34. Xiuli, G.; Yiyong, W.; Xiao, N.; Xiaomei, Y. Differences in air temperature and relative humidity between a marsh wetland and its surrounding dry farmland. *J. Northeast For. University* **2011**, *39*(11), 93–96.
35. Wu, D.; Zhang, F.; Ge, X.; Yang, M.; Xia, J.; Liu, G.; Li, F. Chemical and Light Extinction Characteristics of Atmospheric Aerosols in Suburban Nanjing, China. *Atmosphere* **2017**, *8*(8), 149. https://doi.org/10.3390/atmos8080149
36. Whitlow, T. H.; Hall, A.; Zhang, K. M.; Anguita, J. Impact of local traffic exclusion on near-road air quality: findings from the New York City "Summer Streets" campaign. *Environ. Pollut.* **2011**, *159*(8–9), 2016–2027. https://doi.org/10.1016/j.envpol.2011.02.033
37. Nguyen, T.; Yu, X.; Zhang, Z.; Liu, M.; Liu, X. Relationship between types of urban forest and PM2. 5 capture at three growth stages of leaves. *J. Environ. Sci.* **2015**, *27*, 33–41. http://dx.doi.org/10.1016/j.jes.2014.04.019
38. Witkowska, A.; Lewandowska, A. U.; Saniewska, D.; Falkowska, L. M. Effect of agriculture and vegetation on carbonaceous aerosol concentrations (PM2. 5 and PM10) in Puszcza Borecka National Nature Reserve (Poland). *Air Qual. Atmos. Hlth.* **2016**, *9*(7), 761–773. https://doi.org/10.1007/s11869-015-0378-8
39. Wang, J.; Ogawa, S. Effects of meteorological conditions on PM2. 5 concentrations in Nagasaki, Japan. *Int. j. environ. Res. public hlth*. **2015**, *12*(8), 9089–9101. https://doi.org/10.3390/ijerph120809089
40. Chen, L.; Peng, S.; Liu, J.; Hou, Q. Dry deposition velocity of total suspended particles and meteorological influence in four locations in Guangzhou, China. *J. Environ. Sci.* **2012**, *24*(4), 632–639. https://doi.org/10.1016/S1001-0742(11)60805-X
41. Katata, G.; Kajino, M.; Matsuda, K.; Takahashi, A.; Nakaya, K. A numerical study of the effects of aerosol hygroscopic properties to dry deposition on a broad-leaved forest. *Atmos. Environ.* **2014**, *97*, 501–510. http://dx.doi.org/10.1016/j.atmosenv.2013.11.028
42. Liu, J.; Zhai, J.; Zhu, L.; Yang, Y.; Liu, J.; Zhang, Z. Particle removal by vegetation: comparison in a forest and a wetland. *Environ. Sci. Pollut. Res.* **2017**, *24*(2), 1597–1607. https://doi.org/10.1007/s11356-016-7790-y

43. Zhao, H.; Zheng, Y.; Li, C. Spatiotemporal Distribution of $PM_{2.5}$ and O_3 and Their Interaction During the Summer and Winter Seasons in Beijing, China. *Sustainability* **2018**, *10*(12), 4519. https://doi.org/10.3390/su10124519
44. Ruijgrok, W.; Tieben, H.; Eisinga, P. The dry deposition of particles to a forest canopy: a comparison of model and experimental results. *Atmos. Environ.* **1997**, *31*(3), 399–415. https://doi.org/10.1016/s1352-2310(96)00089-1
45. Tofful, L.; Perrino, C. Chemical composition of indoor and outdoor $PM_{2.5}$ in three schools in the city of Rome. *Atmosphere* **2015**, *6*(10), 1422–1443. https://doi.org/10.3390/atmos6101422
46. Wu, R.D.; Zhou, X.H.; Wang, LP.; Wang, Z.; Zhou, Y.; Zhang, J.; Wang, W.X. $Pm_{2.5}$ characteristics in qingdao and across coastal cities in china. *Atmosphere* **2017**, *8*(4). https://doi.org/10.3390/atmos8040077
47. Qi, L.; Chen, M.D.; Ge, X.L.; Zhang, Y.F.; Guo, B.F. Seasonal variations and sources of 17 aerosol metal elements in suburban nanjing, china. *Atmosphere* **2016**, *7*(12), 153.
48. Matsuda, K.; Watanabe, I.; Wingpud, V.; Theramongkol, P.; Ohizumi, T. Deposition velocity of O_3 and SO_2 in the dry and wet season above a tropical forest in northern Thailand. *Atmos. Environ.* **2006**, *40*, 7557–7564. https://doi.org/10.1016/j.atmosenv.2006.07.003
49. Wesely, M.L.; Cook, D.R.; Hart, R.L. Measurement and parameterization of particulate sulfur dry deposition over grass. *J. Geophys. Res.* **1985**, *90*, 2131–2143. https://doi.org/10.1029/JD090iD01p02131
50. Wu, Y.N.; Liu, J.K.; Zhai, J.X.; Cong, L.; Wang, Y.; Ma, W.M.; Zhang, Z.M.; Li, C.Y. Comparison of dry and wet deposition of particulate matter in near-surface waters during summer. *PloS one* **2018**, *13*(6), e0199241. https://doi.org/10.1371/journal.pone.0199241
51. Yang, T.Y.; Wang, Y.; Wu, Y.N.; Zhai, J.X.; Cong, L.; Yan, G.X.; Zhang, Z.M.; Li, C.Y. Effect of the wetland environment on particulate matter and dry deposition. *Environ. Technol.* **2018**, 1–11. https://doi.org/10.1080/09593330.2018.1520307
52. Croxford, B.; Penn, A.; Hillier, B. Spatial distribution of urban pollution: civilizing urban traffic. *Sci Total Environ.* **1996**, *189*, 3–9. https://doi.org/10.1016/0048-9697(96)05184-4
53. Baumgardner, D.; Varela, S.; Escobedo, F.J.; Chacalo, A.; Ochoa, C. The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis. *Environ. Pollut.* **2012**, *163*, 174–183. https://doi.org/10.1016/j.envpol.2011.12.016