Postprint: Effects of Simulated Rainfall on Dust Retention on Leaf Surfaces of Evergreen Plants

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Abstract

Through simulated rainfall experiments, under varying duration conditions at rainfall intensities of 15 mm/h and 30 mm/h, the effects of rainfall processes on leaf-surface particulate matter of different particle sizes were quantified from three aspects: dynamic changes, dust retention thresholds, and relationship establishment. The results indicate that the retention rate of particulate matter on leaf surfaces first decreases sharply with rainfall duration, then approaches a stable state. The impact on leaf surface dust is most pronounced during the initial rainfall period, with higher rainfall intensities resulting in shorter wash-off times. Both the thresholds for particulate matter retention amount and retention rate decrease with increasing rainfall intensity. The threshold for particulate matter retention amount follows the pattern of 10-100 m > 2.5-10 m > 0.2-2.5 m, consistent with pre-rainfall conditions. Particulate matter of all size fractions on Platycladus orientalis can be relatively effectively washed off by rainfall; for Buxus megistophylla, particulate matter of 10-100 m is more readily washed off by rainfall; Pinus tabuliformis exhibits a particulate matter retention rate threshold of 30%-50%, making it resistant to wash-off. There exists a good fitting relationship between rainfall amount and the retention rate of particulate matter on leaf surfaces; as rainfall amount increases, the retention rate decreases exponentially, with a relatively high rate of decrease within 10 mm of rainfall and a gentler curve beyond 10 mm.

Full Text

Impact of Simulated Rainfall on Leaf Surface Dust of Evergreen Plants

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Abstract

We utilized a simulated rainfall approach to quantify the influence of rainfall amount and duration at two intensities (15 mm/h and 30 mm/h) on the removal of particles of different diameters from leaf surfaces. We analyzed three aspects of the data: the dynamic change process, dust retention threshold, and the relationship between rainfall and leaf surface dust. The results showed that the retention rate of leaf surface dust first exhibited a sharp drop and then reached a steady state over time. The influence of rainfall on leaf surface dust was most obvious at the beginning. The duration of wash-off decreased as rainfall intensity increased. The threshold values for particle retention mass and rate decreased relative to increases in rainfall intensity. The threshold values of particle retention mass were 10–100 m > 2.5-10 m > 0.2–2.5 m, which were consistent with the state before rainfall. Most three-particle size fractions on *Platycladus orientalis* could be washed off quite effectively. Particles of 10–100 m on *Euonymus japonicus* were more likely to be washed off than the smaller particles. In addition, particles on *Pinus tabuliformis* were not easily washed off, with 30%–50% threshold values for retention rate. Rainfall and particle retention rate fit well and particle retention rate had decreased exponentially as rainfall intensity increased. With a 10 mm change in rainfall, there was a substantial decrease in particle retention rate, after which the decreasing curve became relatively gentle.

Keywords: leaf surface dust; simulated rainfall; particle size; evergreen plants; PM2.5

1. Introduction

Airborne particulate matter pollution is a widely concerning environmental issue. Air particulates are an important indicator for evaluating atmospheric pollution. These particles can remain suspended for long periods and travel long distances, posing significant health risks to humans. The disease risk associated with particulate matter is related to particle size, with smaller particles being more stable and less prone to natural settling compared to larger ones [2]. Plant removal of airborne particulates represents an important ecosystem service function. The dust retention capacity of plants is influenced by meteorological conditions and plant growth status, which can mitigate the hazards of atmospheric pollution and dust to human health [3]. Among meteorological factors, rainfall is particularly important as it can wash dust from plant surfaces and restore their dust retention capacity.

Previous studies have examined these processes. Schaubroeck et al. elucidated the input and output processes of leaf surface dust in *Pinus sylvestris* under rainfall influence, constructing a model for forest removal of airborne particulates through rainfall [4]. Wang et al.' s research on dynamic changes in leaf dust for typical weather conditions indicated that rainfall wash-off effects are closely related to plant and precipitation characteristics [5]. Wang et al.' s observations of particulate attachment density on coniferous leaves under spring weather changes found that particles are not easily washed off by moderate or higher intensity natural rainfall [6]. Beckett et al. found that precipitation cannot completely wash away particles retained on leaf surfaces [7]. Przybysz et al. discovered that 20 mm of simulated rainfall could remove 30%–40% of non-fine particles from *Pinus sylvestris* surfaces, with washed-off particles mainly being large-diameter [8]. However, natural rainfall experiments have poor controllability, making it difficult to quantitatively analyze precipitation characteristics' effects on leaf dust. Fang et al. studied wash-off characteristics of three northern tree species under simulated rainfall, finding no significant differences among species and no significant correlation between wash-off rate and leaf surface roughness [9].

During winter when deciduous plants shed leaves, evergreen plants are important for air purification. However, their dust retention capacity is limited. After new leaves become saturated with adsorbed particles, they primarily serve as storage media, requiring rainfall wash-off to remove particles and restore dust retention capacity. Yet, the effects of rainfall processes on different particle sizes under varying rainfall intensities and durations remain unclear. Quantifying the relationship between rainfall and leaf surface dust turnover is scientifically important for revealing rainfall' s impact on plant dust retention. Therefore, through simulated rainfall experiments, this study examined dynamic changes and retention thresholds of different particle sizes on leaf surfaces of three evergreen species under different rainfall intensities and durations, and established relationships between rainfall amount and retention rates for different particle sizes. This research enriches data on rainfall' s effects on plant dust retention and provides a theoretical foundation for better selection of dust-retaining tree species.

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2. Experimental Design

Simulated rainfall experiments were conducted in the rainfall simulation hall at Beijing Forestry University' s Jiufeng Experimental Forest Farm. The study utilized the hall' s precipitation and control systems, with each rainfall zone measuring 8 m × 8 m. Different rainfall conditions were automatically controlled via computer console. The rainfall process was simulated using rotary downward-spray and superposition nozzles.

The artificial rainfall simulator was model QYJY-503C, with 12 independent rainfall zones and a distribution uniformity exceeding 0.8. Based on preliminary experiments, rainfall intensities were selected as 15 mm/h and 30 mm/h, with a maximum rainfall amount of 15 mm.

3. Experimental Materials

Three common evergreen species from Beijing were selected: the arborvitae *Platycladus orientalis* and Chinese pine *Pinus tabuliformis* as evergreen trees, and Japanese spindle *Euonymus japonicus* as an evergreen shrub. Experimental samples were potted saplings with heights of 80 cm. Sampling locations were open areas of the rainfall hall where dust could accumulate to saturation levels, which typically required 15–24 days.

Once rainfall stabilized, potted plants were placed in the rainfall zone. Leaf samples were collected at time intervals after rainfall washing, with six replicates per sample type. Plants of the same species had similar growth conditions.

4. Analytical Methods

Particulate matter quantity was expressed as dust retention per unit leaf area, measured using the washing-weighing method [12]. Collected leaves were placed in beakers, rinsed with ultrapure water, and ultrasonically cleaned. After leaf removal, the suspension was vacuum-filtered. According to China' s ambient air quality standards, airborne particles with aerodynamic diameter less than 100 m are called Total Suspended Particulates (TSP), those less than 10 m are inhalable particles (PM10), and those less than 2.5 m are respirable particles (PM2.5).

Different pore size filters were used sequentially to retain three particle size fractions: 10–100 m, 2.5–10 m, and 0.2–2.5 m. Filter membranes were balanced in a constant temperature and humidity chamber for 30 minutes and weighed with a 0.01 mg precision balance before and after filtration. Cleaned leaves were scanned with a scanner, and leaf area was determined using ImageJ software by scanning twice and averaging.

The calculation equation for dust retention per unit leaf area in this experiment was:

$$P = \frac{M}{S}$$

where P is dust retention per unit leaf area (g/cm^2), M is the mass difference of filter membrane before and after filtration (g), and S is the sampled leaf area (cm^2).

The experiment was conducted under indoor windless conditions, without considering secondary suspension. Wet deposition not contacting leaves in artificial rainfall was minimal, and wet deposition on leaf surfaces was considered zero.

Leaf dust includes wax layer retention and surface deposition, with rainfall primarily affecting surface dust. Only leaf surface dust before and after rainfall was measured.

The dynamic equilibrium equation for leaf surface particles in this experiment was:

$$W_N = \frac{P_N}{P_0} \times 100\%$$

where W_N is the retention rate of leaf dust at different rainfall periods, P_0 is dry deposition per unit leaf area before rainfall, and P_N is remaining dust per unit leaf area after rainfall duration N (where $N > 0$).

The retention threshold is defined as the minimum value of particle retention under rainfall influence, characterized by no significant difference from values at adjacent time points. The retention amount threshold in this paper was taken as the dust retention per unit leaf area at rainfall cessation, while the retention rate threshold was taken as the retention rate at rainfall cessation, without considering the wax layer.

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5. Results

5.1 Dynamic Changes in Leaf Dust Under Rainfall

Figure 1 [Figure 1: see original paper] shows the change process of leaf surface particle retention rate with rainfall amount under different rainfall intensities and durations for three evergreen species. At 15 mm/h rainfall intensity, retention rates for *E. japonicus* and *P. orientalis* decreased significantly within 10 minutes, with the largest decrease occurring during the entire rainfall process, after which they plateaued. *P. tabuliformis* retention rate remained essentially unchanged within 10 minutes, then followed a pattern similar to the other two species between 40–60 minutes.

At 30 mm/h rainfall intensity, *E. japonicus* and *P. orientalis* showed similar patterns to those at 15 mm/h, but the decreasing trend was more pronounced within 5 minutes. *P. tabuliformis* retention rate decreased rapidly within 5 minutes, then stabilized after 5–20 minutes. This indicates that higher rainfall intensity reduces particle retention rates and advances the time to reach retention thresholds.

5.2 Retention Thresholds of Leaf Dust Under Rainfall

Figure 2 [Figure 2: see original paper] shows retention amount thresholds for different particle sizes on leaf surfaces of three evergreen species. Retention amount thresholds from largest to smallest were: 10–100 m (24.68 ± 5.17 g/cm^2), 2.5–

10 m (16.20 ± 4.84 g/cm²), and 0.2-2.5 m (9.77 ± 3.14 g/cm²) (Mean ± SD, n = 6). This pattern was consistent with the maximum dust retention by particle size before rainfall.

Under different rainfall intensities, leaf surface retention amount thresholds for *E. japonicus* and *P. orientalis* showed no significant differences among the three particle size fractions. For *P. tabuliformis*, retention amount thresholds for particles >10 m differed significantly between rainfall intensities (ANOVA, $P < 0.05$), while thresholds for particles <10 m showed no significant differences.

Table 1 presents multiple comparison results for leaf surface dust retention rate thresholds under different rainfall intensities. Contrary to retention amount thresholds, retention rate thresholds by particle size showed: 10–100 m < 2.5–10 m < 0.2–2.5 m. Different particle size retention rate thresholds varied among species. *P. tabuliformis* had significantly lower retention rate thresholds for particles >10 m compared to particles <2.5 m. *P. orientalis* showed no significant differences among particle sizes. *E. japonicus* had significantly higher retention rate thresholds for 2.5–10 m particles at 15 mm/h intensity, but only *P. tabuliformis* across all size fractions and *P. orientalis* for 2.5–10 m particles showed significant differences between intensities. This indicates rainfall has weaker wash-off capacity for particles on *P. tabuliformis* surfaces, while particles on *E. japonicus* and *P. orientalis*, especially 10–100 m particles, are more easily washed off, allowing greater recovery of dust retention potential.

5.3 Relationship Between Rainfall Amount and Leaf Dust

In actual rainfall, intensity is not constant. Therefore, data from both rainfall intensities at different durations were combined to establish relationships between rainfall amount and retention rates for three particle size fractions. Fitting results showed good exponential relationships between rainfall amount and leaf surface particle retention rate ($P < 0.001$). As rainfall amount increased, particle retention rate decreased exponentially.

Figure 3 [Figure 3: see original paper] and Table 2 show the fitting relationships and equation coefficients. The curves became relatively gentle after 10 mm of rainfall, indicating that leaf surface dust is more affected during early rainfall stages, with a larger decrease rate in particle retention within the first 10 mm of rainfall, gradually reaching the retention threshold under rainfall influence after 10 mm. Retention rates were greatly affected by rainfall amount.

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6. Discussion

6.1 Rainfall Effects on Leaf Dust

Studying rainfall' s impact on leaf surface dust is crucial for revealing plant removal of PM2.5 and other airborne particles. Results demonstrate that both rainfall intensity and duration significantly affect dynamic changes and retention thresholds of leaf surface dust. Except for *P. tabuliformis*, where leaf dust remained stable during early rainfall, retention rates of leaf surface particles under rainfall showed sharp initial decreases that gradually weakened before stabilizing. This indicates rainfall’ s most obvious impact occurs at the beginning. Water-soluble particles in leaf dust dissolve in water during early rainfall stages [6]. Measurements showed water-soluble ions accounted for 19.8% of *P. tabuliformis* leaf dust, with higher proportions in atmosphere than on leaves because high humidity extends ion lifetime and facilitates secondary ion formation [13]. Currently, few analyses exist on water-soluble ion proportions in leaf dust, though Beijing atmospheric PM2.5/PM10 contains over 30% water-soluble ions [13]. However, leaf surface particles are difficult to collect with particle sizers, and changes in water-soluble ion proportions across particle sizes remain unclear.

6.2 Species Differences in Wash-off Characteristics

At 15 mm/h intensity, *P. tabuliformis* leaf surface particles were not easily washed off, while *E. japonicus* and *P. orientalis* surfaces more readily reached saturated water-holding capacity, causing particle-laden runoff. At 30 mm/h intensity, species differences became significant [9], indicating precipitation characteristics affect wash-off results. Rainfall of 2.5–2.67 mm cannot completely wash leaf surface dust clean, consistent with deep-cleaning experiments on *E. japonicus* [11]. Rainfall wash-off effects on *P. tabuliformis* are weaker than on other species, related to its small chamber edge structures that can deeply embed small particles [14]. *P. orientalis* leaf surfaces have ridge-like protrusions forming grooves, and rainfall’ s effect on different particle sizes is smaller than *E. japonicus* chambers, opposite to atmospheric particle adsorption results [14], suggesting leaf surface microstructure differentially affects particle adsorption and wash-off retention. *P. tabuliformis* has sticky secretions making particles difficult to wash off, consistent with previous findings [6]. Additionally, this study found *P. tabuliformis* retention rates significantly decreased with increased rainfall intensity, especially for 10–100 m particles.

6.3 Limitations of Simulated Rainfall Experiments

This study demonstrates good fitting relationships between rainfall amount and leaf surface particle retention rates, quantifying rainfall effects on different particle sizes in greater detail and supplementing limitations in outdoor and previous simulation experiments [5,9]. Simulated experiments are affected by multiple factors, including maximum dust retention before rainfall, differences between potted and field plants, and measurement errors, all causing some experimental variation. Future simulations should consider corrections for these interfering factors in addition to rainfall intensity and duration effects. Simulated rainfall kinetic energy has a linear relationship with rainfall intensity, allowing similarity between simulated and natural rainfall through intensity control [15]. This simulation required less rainfall to wash leaf dust than natural rainfall experiments [5-6] because natural rainfall experiments typically use smaller intensities, while this simulation used moderate to heavy rainfall. Differences from equipment limitations require future technological improvements. Additionally, wet deposition in natural rainfall is an input pathway for leaf surface particles [16], and how this affects leaf dust results needs further study.

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7. Conclusions

1. Rainfall intensity and duration significantly affect dynamic changes in leaf surface dust. Retention rates decrease sharply initially, then gradually weaken after the early rainfall stage. When rainfall intensity increases, particle wash-off time decreases.

2. Particle retention amount decreases with increasing rainfall intensity, with significant differences except for *P. tabuliformis*. Retention amount thresholds by particle size show 10-100 m > 2.5-10 m > 0.2-2.5 m, consistent with maximum dust retention before rainfall.

3. Particle retention rates decrease with increasing rainfall intensity, with significant differences for *P. tabuliformis* and *P. orientalis* at 2.5-10 m. Species retention rate thresholds show: *E. japonicus* and *P. orientalis* particles at 10-30%, *P. tabuliformis* at 30-50%. Larger particles are more easily washed off, while 0-10 m particles are not easily washed off (10-15% for *E. japonicus*, 20-35% for *P. orientalis*).

4. Rainfall amount and particle retention rate have good fitting relationships. Particle retention rates decrease exponentially with increasing rainfall amount, decreasing rapidly within 10 mm of rainfall, after which the decreasing curve becomes gentle.

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Note: Figure translations are in progress. See original paper for figures.