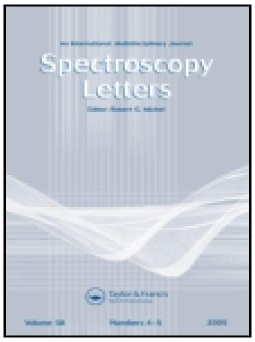

Spectroscopy Letters

An International Journal for Rapid Communication

ISSN: 0038-7010 (Print) 1532-2289 (Online) Journal homepage: http://www.tandfonline.com/loi/lstl20

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*Spectroscopy Letters*, 47:536–542, 2014

ISSN: 0038-7010 print/1532-2289 online
DOI: 10.1080/00387010.2013.820761

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# Estimation of Atmospheric Dust Deposition on Plant Leaves Based on Spectral Features

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**ABSTRACT** Urban atmospheric dust is a significant problem and becoming a considerable pollution source in many cities. This study was based on a comparison of spectral reflectance on the surfaces of dusty and clean leaves. A significant linear relationship ($r = 0.811$) correlation between the dust weight and near-infrared band region (700–1000 nm) was found through analysis of the spectral data. This relationship obtained from near-infrared band regions, based on the main effects and cluster and interval analysis, was more distinct and stable than that of blue, green, red, and middle-infrared band regions. Thus, the use of near-infrared band data is a reliable method to estimate the amount of dust deposition on plant leaves. A regression model ($R^2 = 64.3\%$) was constructed based on dust deposition on plant leaves and a near-infrared ratio. The model proved to be accurate as regards an estimation of dust weight, based on a comparison of residuals (normal distribution) and accuracy tests ($slope = 0.8437$). This model could provide a methodological basis for spatial dust distribution analysis and has the potential for evaluating air pollution levels.

**KEYWORDS** air pollution, interval analysis, near-infrared, spectrum, urban

## INTRODUCTION

Atmospheric dust is a common phenomenon in industrialized cities and has the potential for both negatively affecting plant growth and latently damaging the ecological system.[1] Urban atmospheric dust presents a significant problem particularly in the city of Beijing, China, which has a population of over 20 million. It is becoming the biggest pollution source.[2–5] Fast industrialization and urbanization in recent years has caused a rapid increase in the number of vehicles in and around Beijing, with the result that air pollution in Beijing has become increasingly severe.[6–8] Long-term observations such as those by Yang[9] and He[10] have shown a high level of air particulate matters and serious dust pollution. The Beijing city authority has now adopted various strategies to reduce such pollution. Such strategies include the expansion of plantation areas within the city, therefore technically and potentially benefitting the environment, ecology, and aesthetics.[11]

Over the last three decades, reflectance spectroscopy has been widely applied in the field of environment studies. Horler[12] found a high

Received 4 June 2013;
accepted 26 June 2013.

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correlation between chlorophyll concentration and the spectral feature in plant leaves. Miller[13] presented a regression model to evaluate chlorophyll content by using red edge. In addition to inversion chlorophyll, several studies using multiple linear regression models have revealed a high correlation between nitrogen concentration and spectral features in the leaves of plants.[14–18] However, since most of the current techniques used for assessing atmospheric dust require high-cost equipment and are time consuming, little research into the correlations between spectral reflectance features and atmospheric dust depositions has been conducted.[19]

This study focuses on the relationship between spectral reflectance features of plant leaf surfaces and various dust depositions. The aim of this study is to find a low-cost and rapid method to evaluate dust depositions on plant leaves. Such a procedure may provide a methodological basis for further exploring correlations between spectral reflectance features of plant leaves and atmospheric dust pollution, with an exploration of plant health as a by-product.

# MATERIALS AND METHODS

## Sampling Locations

This study was conducted in the city of Beijing, the capital of China. Beijing lies at east longitude 39.92°, north latitude 116.46°, and covers an area of 16,507.5 $km^2$. It is located at the northern edge of the North China Plain at the junction of the Inner Mongolia Plateau, Loess Plateau, and North China Plain.

Leaf samples were collected from 30 randomly selected sampling locations around the Beijing main road network. Figure 1 shows their geographical distribution. *Euonymus japonica*, one of the main plant species planted across the city by the Beijing city council, was used as the experimental plant. *E. japonica* leaves 1 meter in height were collected from each location, stored in zip-lock bags, and placed in an ice box prior to analysis.

## Measuring Method

Each leaf was accurately weighed using an electronic analytic balance (1/10,000 g scale). The reflectance values of the leaves were measured by a spectrometer (Analytical Spectral Devices FieldSpec Pro, ASD 2001), a single-beam field spectroradiometer with a total of 2100 spectral bands and covering a range of 350–2500 nm.[20] The spectral measurements were repeated 10 times for each leaf plus its gathered dust. The mean values were taken to represent each leaf's spectral reflectance. Initially, the fresh leaves just collected were put in a small cooler temporarily and kept in a refrigerator until

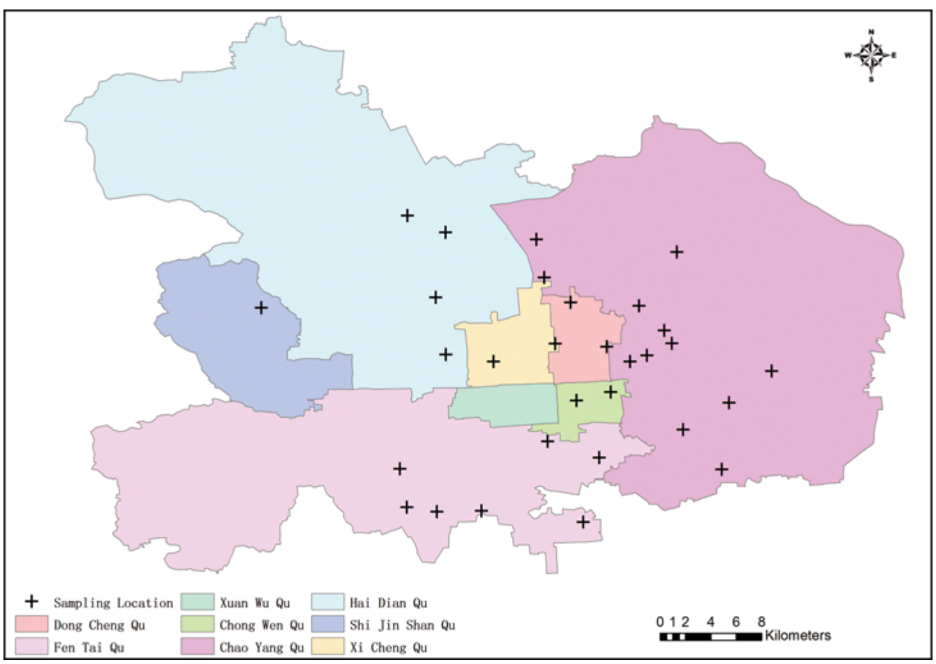


**FIGURE 1** Sampling point distributions across Beijing.

the weighting and spectral experiment. Then the dirty leaves were weighed and their reflectance measured by ASD. After cleaning by using ultra-pure water and dried by absorbent paper, the clean leaves were reweighed and the reflectance measured again.

# DATA ANALYSIS AND DISCUSSION OF RESULTS

## Comparative Analysis of Spectral Reflectance of Dust-Affected Leaves and Leaves Clear of Dust

Figure 2 presents the spectral reflectance comparison between dusty and clean leaves. The reflectance is the mean value of 30 samples. As shown in this figure, the dusty leaves had a higher reflectance in the visible band region. According to Chudnovsky,[19] the dust in the 400–700-nm had a 0.25 mean reflectance value, which led to the dusty leaves having a high reflectance value due to the dust-reflected energy. However, in the near-infrared bands, the reflectance of clean leaves is higher than that of the dusty ones. In this band region, the vegetation mainly depends on the foliar reflectance to reflect energy. The dusty leaves had lower reflectance values because the dust impedes foliar reflectance. In the middle-infrared region, the primary water absorption bands occurred at 1450 and 1940 nm. The higher reflectance values of dusty leaves resulted from a blocking effect caused by energy being absorbed by atmospheric moisture. The obvious differences in the spectral reflectance of the difference between the dusty and clean leaves provide a potential way to evaluate the dust weight on the plant leaves.

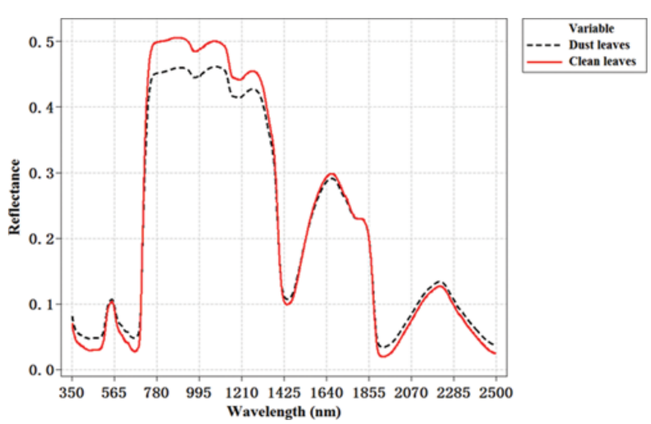


**FIGURE 2** **Comparisons of spectra reflectance between clean and dust leaves.**

## Correlation Analysis

As shown in Table 1, Pearson correlation coefficients between dustfall weight and green and middle-infrared peak ratio are 0.053 ($p = 0.780$) and 0.37 ($p = 0.044$), respectively. This indicates that they have no significant correlation. According to Table 2, Pearson correlation coefficients between dust weight and three wave troughs are 0.034 ($p = 0.857$), −0.001 ($p = 0.996$), and 0.068 ($p = 0.721$). Thus, they also have no significant correlation. The Pearson correlation coefficient between dustfall weight and near-infrared band region in Table 1, however, was 0.811 ($p = 0.00$), indicating a significantly positive linear correlation.

## Main Effects and Cluster Variables Analysis for Spectrum Peak and Wave Trough Affected by the Dust

Comparing the clean and dusty leaf spectra, we recorded the position-changing value of the peak and wave trough. For example, in the 500–600-nm bands of sample 1, the peak position dusty leaf band number is 550 and the peak position clean leaf band number is 552, so the changing value is 2, which was recorded. The main effect analysis for dustfall weight from 30 samples is shown in Fig. 3. It can be seen that in the peak change values of 500–600, 1600–1800, and 2100–2300 nm and the wave trough change values of 1400–1600 and 1900–2000 nm, the blue line is nearly horizontal (parallel to the x-axis); thus, no major effect was evident. Each factor level affects the response (the response is the dustfall weight) in the same way, and the response mean is the same across all factor levels. However, in the peak 700–1400 nm and wave trough 600–700 nm of the near-infrared and red band region, the blue line

**TABLE 1** **Pearson Correlation Coefficients Between Dustfall Weight and Three Wave Crests**

| Spectrum | Correlation coefficients | p value |
|---|---|---|
| Green | 0.053 | 0.780 |
| Near-infrared | 0.811 | 0.000 |
| Middle-infrared | 0.370 | 0.044 |

**TABLE 2** Pearson Correlation Coefficients Between Dust Weights and Three Spectrum Troughs

| Spectrum | Correlation coefficients | p value |
|---|---|---|
| Red | 0.034 | 0.857 |
| Middle-infrared (1438) | −0.001 | 0.996 |
| Middle-infrared (1925) | 0.068 | 0.721 |

is not horizontal, and an apparent difference in the vertical position of the plotted points is evident. This illustrated that the peak 700–1400 um and wave trough 600–700 nm had a significant main effect for the dustfall weight.

Between the clean and dusty leaves, the peak and wave trough ratio may be affected by the dustfall weight. Four peak ratio values and three wave trough ratio values were used as seven variables and cluster variable analysis was used to find a relationship between them. During the procedure, single linkage was used to calculate intercluster distances in cases when a cluster has multiple variables. Single linkage shows that the distance between two clusters is the minimum distance between a variable in one cluster and a variable in the other. The cluster variables analysis result is shown in Fig. 4 and reveals that the peak ratio of 700–1400 nm is a standalone cluster with a similarity of 78.03, and the other peak and wave ratio can be clustered into one group with a similarity of 85.35. The result indicates that 700–1400 nm affected by the dustfall weight did not share common characteristics with other band regions. The influence of the dustfall for the 700–1400-nm near-infrared band may have a specific relationship, which is apparently different from that of others.

## Interval Plots Analysis for the Spectra Ratio

An interval plots analysis for the spectra ratio value between clean and dusty leaves was conducted in the blue, green, red, near-infrared, and middle-infrared bands region (Fig. 5). From the result, a 95% confidence interval extends from 0.643481 to 0.745842 for the blue band, from 0.861215 to 0.947696 for the green band, from 0.66953 to 0.76789 for the red band, from 1.07409 to 1.10097 for the near-infrared band, and from 0.94063 to 0.987317 for the middle-infrared band. These results indicate that the near-infrared band had the smallest span. By comparing the interval represented by a vertical line, it was found that the near-infrared band also had the shortest interval. This illustrates that the variability in the near-infrared bands was small, and the dustfall influence is less than that on the other four band regions.

## Dustfall Weight Inversion

Our results described above offer a feasible way to estimate the plant leaves' dust deposition into dust amount by the wave ratios obtained from near-infrared bands. Thus, a regression model is further established to estimate the dust weight by the

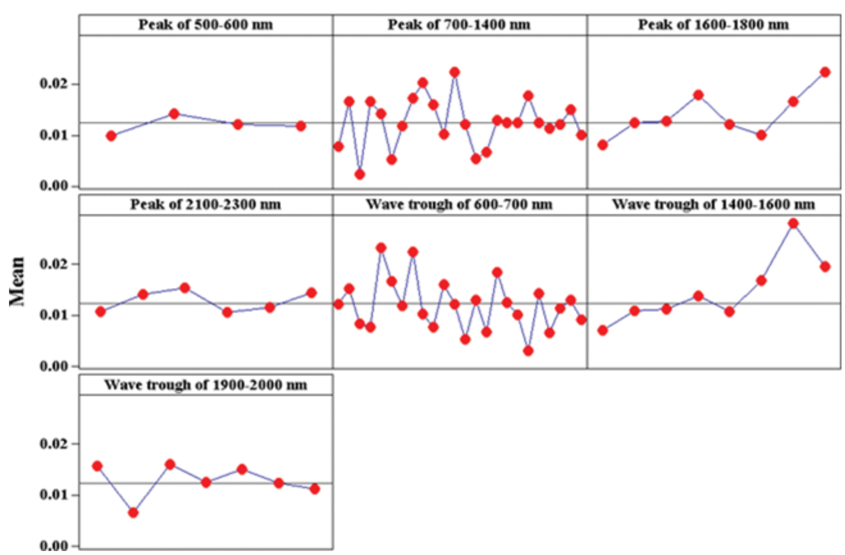


**FIGURE 3** Main effects plot for dustfall weight.

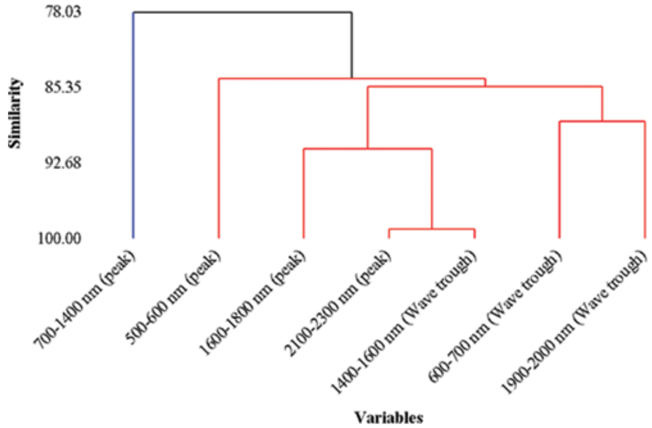


**FIGURE 4** Cluster variables analysis result.

near-infrared band ratio from the 700–1400 nm band region. It was discovered that the 814 nm band ratio to estimate dust weight better fits the data (Fig. 6). The regression model equation is given below:

$$\text{Dustfall (g)} = -0.1254 + 0.1245 \text{ Ratio (814 nm)}, \quad R^2 = 0.643$$

The equation clearly shows that the 814 nm ratio value between clean and dusty leaves positively correlates with the weight of dust deposition. As shown in Fig. 7, the residuals form a straight line, demonstrating normal distribution, and the established model has a good fit for the data.

In order to verify the reliability of the model, we used experimental data of eight samples (actual test values) to compare with the data estimated from the model (inversion values). The results are shown in Fig. 8. The slope between the estimation and the real values was 0.8437, indicating that the inversion

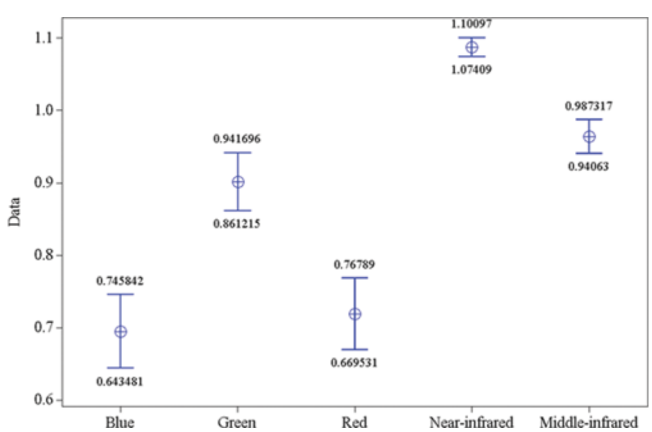


**FIGURE 5** Interval plots of blue, green, red, near-infrared, middle-infrared.

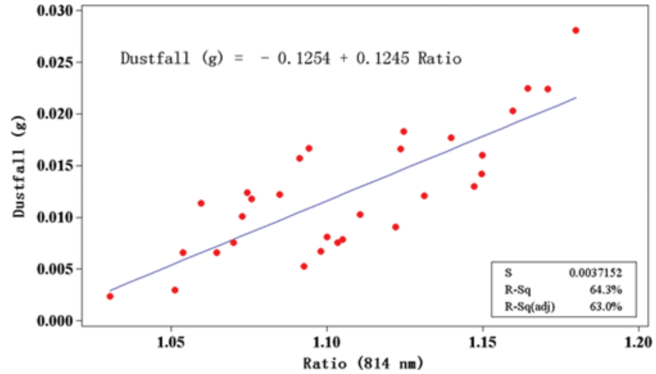


**FIGURE 6** Regression model for dustfall weight.

model has a good precision, and therefore its estimating results are reliable.

## Potential Applications

The regression model of dustfall weight can rapidly estimate dust deposition weight on plant leaves. The method can be applied without the need to forward plant leaves to laboratories as it can be carried out onsite.

The evaluation of the dust weight can provide a spatial indication of air pollution strength across a city and offer a basis from which contributions can be made toward the management of the quality of the environment. As shown in Fig. 9a, the different sizes of the blue circles represent the different weights of the dustfall. Figure 9a displays an example of visualization expression, which effortlessly presents clear comparisons of dustfall weight in various locations. The dust weight data can also be used to create an interpolation map to estimate dustfall across the whole city region. Figure 9b shows the

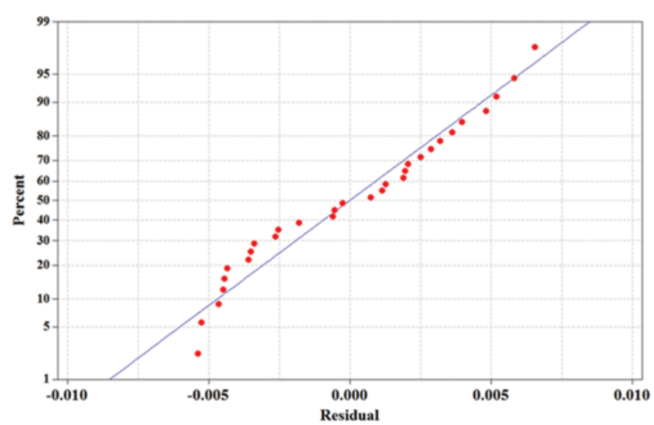


**FIGURE 7** Normal plots of residuals.

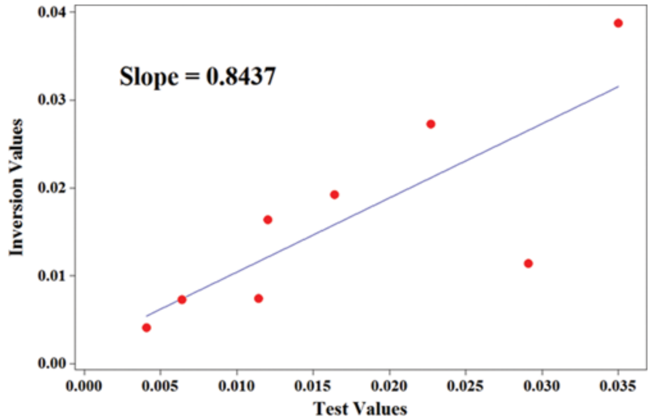


**FIGURE 8** Correlation between inversion and test values.

dust weight condition in Beijing by interpolation images. The red and blue colors represent respective high and low dust weight values. This image predicts the whole experimental region by the known point data and has potential importance for further spatial analyses. Also presented is the ability to rapidly estimate dust deposition weight on plant leaves, a detail that is helpful in the study of the correlation between dust pollution and plant health and maybe even in the correlation between plant and human health existing under the same circumstances. The deposition of atmospheric dust on the plant leaves affects the epidermal, geometry, structural, and cuticular features.[21] Therefore, quantifying relationships between dust weights and plants is useful, and this newly presented model can offer the means of acquiring such relationship solutions.

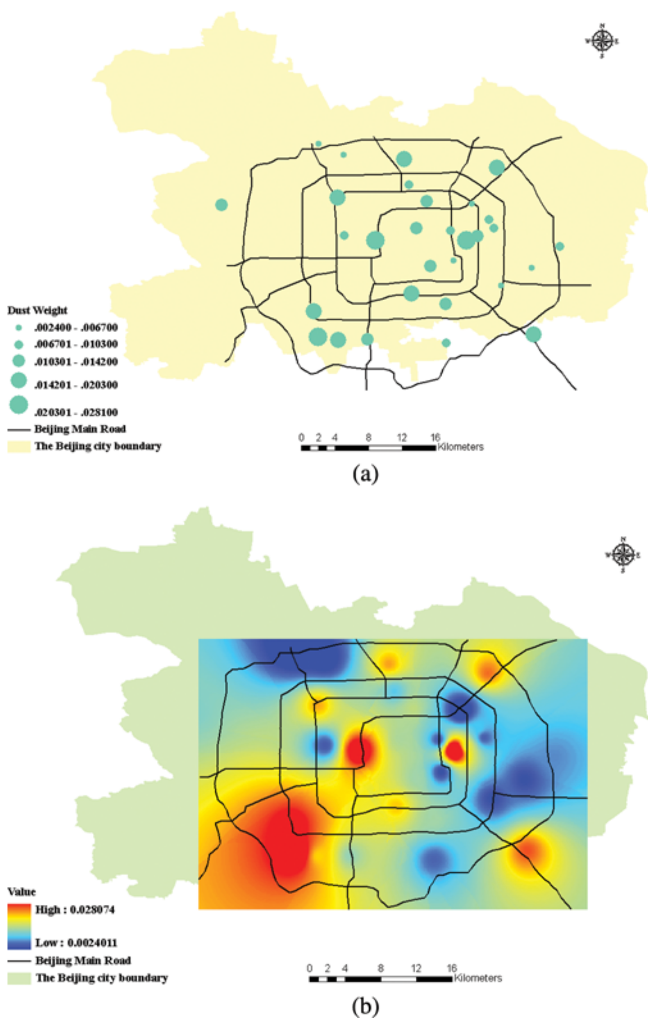


**FIGURE 9** Possible applications (a) Spatial distribution of the dustfall, (b) Interpolation image of the dustfall.

## CONCLUSIONS

An analysis of the relation between dustfall weights and spectra features based on the selected 30 examples in Beijing was conducted in this study. This work demonstrated that leaf dust had a linear relationship ($r = 0.811$) with the near-infrared band and there was no significant correlations with the spectrum in other bands. A comparison of blue, green, red, and middle-infrared band regions reveals that this relationship from main effects and cluster and interval analysis is more reliable. In the 700–1400 nm near-infrared band region, the 814 nm band ratio corresponding to the dust deposition weight can be used to construct a good model to fit the data ($R^2 = 64.3\%$). This model can form an effective and efficient method to estimate the dust weight on the plant leaves. This regression dust weight model has the potential as a useful tool for both estimating atmospheric pollution and for further studies on the effect of dust pollution on plant health.

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