PHYSICAL EFFECTS OF DUST ON LEAF PHYSIOLOGY OF CUCUMBER AND KIDNEY BEAN PLANTS

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Abstract
The physical effects of dust accumulating on leaf surfaces, on leaf physiology, such as photosynthesis, transpiration, stomatal conductance and leaf temperature of cucumber and kidney bean plants were investigated by the use of chemically inert dust. It was found that dust decreased stomatal conductance in the light, and increased it in the dark by plugging the stomata, when the stomata were open during dusting. When dust of smaller particles was applied, the effect was greater. However, the effect was negligible when the stomata were closed during dusting. The dust decreased the photosynthetic rate by shading the leaf surface. The dust of smaller particles had a greater shading effect. Moreover, it was found that the additional absorption of incident radiation by the dust increased the leaf temperature, and consequently changed the photosynthetic rate in accordance with its response curve to leaf temperature. The increase in leaf temperature also increased the transpiration rate.

INTRODUCTION
Various types of dust are emitted artificially and naturally into the atmosphere through industrial processes, road traffic, volcanic eruptions, dust storms, etc. Around such sources a large quantity of dust cover on vegetation has been frequently observed (e.g. Kennedy, 1980; Brabec et al., 1981; Yunus et al., 1985). Highly alkaline dust-like cement visibly injures plant leaves (e.g. Darley, 1966); even chemically inert dust physically affects photosynthesis and transpiration when it accumulates on leaf surfaces. Covering and plugging of stomata (Beasley, 1942; Ricks & Williams, 1974; Fluckiger et al., 1979), shading (Peirce, 1910; Thompson et al., 1984), increasing leaf temperature (Eller, 1977; Borka, 1984) and removal of cuticular wax (Eveling & Bataille, 1984; Eveling, 1986) were reported as physical effects of dust. However, almost all the previous studies only guessed the physical effects on photosynthesis in their discussions. There does not appear to be many related studies based on well-designed experiments.

This study aims to investigate the physical effects of dust accumulation on plant leaves, on leaf physiology, such as plugging of stomata, shading and increase in leaf temperature. Thus the rates of photosynthesis and transpiration, the stomatal conductance and the temperature of cucumber and kidney bean leaves covered with chemically inert dust were measured under various conditions.

MATERIALS AND METHODS
Plants and dust
Seeds of cucumber (Cucumis sativus L. cv. 'Suyo') and kidney bean (Phaseolus vulgaris L. cv. 'Kawachikurosoando') were sown in unglazed pots filled with vermiculite. After germination, cucumber and kidney bean seedlings were grown in a glasshouse maintained at 25/20 ± 2°C day/night air temperature, and were watered once a day with half strength Otsuka Chemical's culture solution containing 9 mM N, 1 mM P, 4 mM K, 2 mM Ca, 1 mM Mg, 24 μM Fe, 11 μM Mn and 21 μM B. The fourth leaf of 4-week-old cucumber and primary leaves of 2-week-old kidney beans were used for the experiments. Frequencies of stomata on the adaxial/abaxial leaf surfaces were 210/420 mm² in the cucumber and 60/400 mm² in the kidney bean.

The dusts used in the experiments were Kanto loam powders (KL) and carbon black (CB) manufactured under the Japanese industrial standard (JIS Z 8901). These dusts are chemically inert, and are usually used to test the performance of dust collectors. KL dusts are manufactured by burning and grinding volcanic ash-soil widely distributed in the Kanto district of Japan. These are light brown, and divided into three classes (coarse, fine and ultrafine) according to their particle size (Fig. 1). On the other hand, CB dust corresponds to soot. Its particle size ranges from 0.03 to 0.20 μm in diameter. The particle size of these dusts becomes smaller in the order, KL coarse, fine, ultrafine and CB.

Dust treatment
The fourth leaf of the cucumber and one of two primary leaves of the kidney bean were dusted in the chamber made of clear acrylics with 12 fluorescent lamps (Fig. 2). The other leaves were covered with a polyethylene film to prevent the dust from adhering. Before dusting, each plant was placed in an artificial-light cabinet, and the stomata were made open or closed by the control of light intensity. During dusting, light intensity was successively controlled by turning of the fluorescent lamps on or off to maintain the stomatal aperture. The photosynthetic photon flux density...
(PPFD) in the dust chamber was 350 μmol m⁻² s⁻¹ and 0 μmol m⁻² s⁻¹ when lamps were on and off, respectively. From the relation between stomatal conductance and PPFD (Fig. 3), we inferred that the stomata of the adaxial surfaces of cucumber and kidney bean leaves were almost fully opened or closed under each light condition.

In the dust generator, dust was suspended in air pumped through a bottom inlet, and flowed into the dust chamber through a top inlet with air. The dust accumulated uniformly on the adaxial surface of the leaf which was held horizontally. Little dust, however, was observed on the abaxial surface after the treatment. The amount of dust accumulating on the leaf surface was controlled by dusting time, which was within 3 min, and the amount of dust per unit leaf area (dust load, g m⁻²) was estimated from the increase in the weight of a small piece (7.0 cm²) of clear adhesive tape (CAT) placed near the leaf, before and after a treatment. In a preliminary experiment, dust loads were also measured by weighing the dust washed from the leaf with chloroform. The dust loads by the two different methods agreed within 5% and were in the range 1–4 g m⁻² for all dusts and both plants. Thus, the easier method, with CAT, was used to obtain dust loads in this study. Moreover, a shading coefficient of dust (S) was calculated from the following equation

\[ S = 1 - \frac{T_d}{T_r} \]

where \( T_d \), \( T_r \) and \( T_r \) are transmittance of dust, CAT with dust and CAT without dust, respectively. These were measured with a quantum sensor (LI-190S, LI-COR) in the artificial-light cabinet in which the experiments were made.

**Gas exchange and leaf temperature measurements**

Unless otherwise specified, the experiments were made under the conditions of 25 ± 1°C for the cucumber and 20 ± 1°C for the kidney bean under the conditions of 70 ± 5% relative humidity (RH).

To study the direct effect of dust on the gas diffusion process through the stomatal opening, stomatal conductance for water vapor in the adaxial and abaxial surfaces of the dusted cucumber leaves were measured with a steady state porometer (LI-1600, LI-COR) in the artificial-light cabinet at the PPFD of 0, 550 and 1020 μmol m⁻² s⁻¹. The leaves were dusted with KLs at 1.2 g m⁻² when the stomata were open and closed. The experiment was replicated three times with two plants per dust each time.

The rates of net photosynthesis and transpiration were measured in the cabinet with an open gas exchange system, and were calculated based on the difference in CO₂ and water vapor concentrations between inlet and outlet air of the single leaf chamber made of clear acrylics with a stirring fan. The gas concentrations

![Fig. 1. Particle size accumulation curves of KL dusts.](image1)

![Fig. 2. Schematic diagram of dust generator and dust chamber.](image2)

![Fig. 3. Relationship between stomatal conductance of (a) cucumber and (b) kidney bean leaves, and PPFD. Measurement was made at 25 ± 1°C for cucumber and 20 ± 1°C for kidney bean under the conditions of 70 ± 5% RH. Points and vertical lines are means ± 1 SD (N = 6).](image3)
were measured with an infrared gas analyzer in a differential mode (ZALDA, Fuji Electric) and two electric hygrometers (SM-310, Shibaura Electronics). In the gas exchange system, the outside air was passed through water in a flask, placed in a thermostat, to control the humidity with an air pump, after it was stirred in a buffer tank to unify the CO₂ concentration. It was then introduced into the leaf chamber. The air flow rates were 20 l min⁻¹ for the cucumber and 6 l min⁻¹ for the kidney bean. The leaf temperature was measured with type T thermocouples contacted to the abaxial leaf surface in the leaf chamber.

In the following experiments, the dust was applied when stomata were closed. To study the shading effect on photosynthesis, the net photosynthetic rates of the cucumber and kidney bean leaves were measured twice a day, before and after a dust treatment. The measurement was made at the PPFD of 200, 400 and 700 μmol m⁻² s⁻¹. The experiment was replicated four times with a different plant for each dusting. The shading effect was estimated from the relative photosynthetic rate before and after a treatment.

The temperature of the cucumber leaves dusted with KL fine and CB were measured at six PPFD levels. The experiment was replicated three times with a different plant for each dusting. The short-wave radiant flux density (with LI-200, LI-COR) equivalent to the PPFD of 1300 pmol m⁻² s⁻¹ was 670 W m⁻² in the leaf chamber. Furthermore, the rates of net photosynthesis and transpiration of the cucumber leaves dusted with CB at 1.0 g m⁻² were measured at an air temperature of 15 to 40°C by 5°C steps, 70 ± 5% RH and 1300 pmol m⁻² s⁻¹. The experiment was replicated four times with a different plant each time.

Before each experiment, plants were watered well and were placed under each experimental condition for at least an hour. The measurement was made after the plants acclimated to the condition. The measured values of the leaves with and without dust were compared by using t-tests.

### RESULTS AND DISCUSSION

**Direct effect of dust on stomatal conductance**

Table 1 shows the stomatal conductance of the adaxial surfaces of the cucumber leaves dusted with KLS. When the stomata were closed in dusting, the stomatal conductance of the dusted leaves was almost equal to that of control under every PPFD. When the stomata were in treatments, however, the conductance of the dusted leaves was significantly smaller (p < 0.05) than that of control at the PPFD of 550 and 1020 μmol m⁻² s⁻¹. The conductance reduced with particle size of applied dust, in the order KL coarse, fine and ultrafine. In contrast, the conductance of the leaves dusted with KL ultrfine and fine increased significantly (p < 0.05) in the dark. There were no differences in the stomatal conductance of the abaxial surface between the dusted and control leaves; this is not shown in Table 1. Since the stomatal conductance in the cucumber leaf was much larger on the abaxial surface than on the adaxial (Fig. 3), no significant differences in the conductance of the whole leaf were recognized between the dusted and control leaves: the whole-leaf stomatal conductance is the sum of the values on both the surfaces.

Stomata respond to light directly and indirectly (e.g. Mansfield et al., 1981; Sharkey & Raschke, 1981). The indirect response is mediated by changes in intercellular CO₂ concentration, which result from photosynthesis. At an irradiance below the light saturation point of photosynthesis, the shading can cause stomatal closing.

In Figs 3 and 4, responses of the stomatal conductance and net photosynthetic rates in the fourth leaf of the cucumber and in the primary leaves of the kidney bean to PPFD are shown, respectively. While the conductance of the abaxial surfaces of both the plants was almost equal, that of the adaxial surfaces of the cucumber leaves was about twice as large as that of the kidney bean. The stomatal conductance of the cucumber leaves increased almost linearly as PPFD increased, but the photosynthetic rates did not increase linearly with PPFD.

<table>
<thead>
<tr>
<th>Stomata during dusting</th>
<th>Dust</th>
<th>PPFD (μmol m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>KL ultrafine</td>
<td>26.5 ± 4.4* (146)</td>
</tr>
<tr>
<td></td>
<td>KL fine</td>
<td>25.3 ± 4.8* (139)</td>
</tr>
<tr>
<td></td>
<td>KL coarse</td>
<td>23.9 ± 4.6 (131)</td>
</tr>
<tr>
<td>Closed</td>
<td>KL ultrafine</td>
<td>19.0 ± 3.2 (104)</td>
</tr>
<tr>
<td></td>
<td>KL fine</td>
<td>17.7 ± 4.5 (97)</td>
</tr>
<tr>
<td></td>
<td>KL coarse</td>
<td>17.9 ± 4.7 (98)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>18.2 ± 4.8 (100)</td>
</tr>
</tbody>
</table>

*Percentage of control.

* and ** indicate significant differences between the treatment and the control at p < 0.05 and p < 0.01 by t-test, respectively.
up to about 350 μmol m⁻² s⁻¹, and the gradient became rapidly smaller above the PPFD on both the surfaces. The conductance of the kidney bean became constant above about 350 μmol m⁻² s⁻¹. The light-saturation points of photosynthesis of the cucumber and kidney bean were about 750 and 400 μmol m⁻² s⁻¹, respectively. In Table 1, shading coefficients of dust at 1.2 g m⁻² were 0.25, 0.20 and 0.15 for the treatments with KL ultrafine, fine and coarse, respectively. Thus the PPFDs incident on the leaf surface through the cover of KL ultrafine were calculated at 412 and 765 μmol m⁻² s⁻¹ under the conditions of 550 and 1020 μmol m⁻² s⁻¹ above the dust cover. The shading coefficient becomes larger when finer dust is applied (Hirano et al., 1990). Since shading coefficients of KL fine and coarse were smaller than that of KL ultrafine, the PPFDs, under covers of KL fine and coarse, were larger than that under KL ultrafine. Therefore, in Table 1, it can be said that the decrease in stomatal conductance at 1020 μmol m⁻² s⁻¹ was not caused by shading, because the PPFD under the dusts exceeded the saturation point of photosynthesis. At 550 μmol m⁻² s⁻¹, the direct shading effect of dust on stomatal conductance was small (Fig. 3), while the PPFD under the dusts was below the saturation point of photosynthesis.

In this way, the dust decreased stomatal conductance by an effect other than shading from light, while it increased the stomatal conductance in the dark. Thus, it is thought that the dust entering into the stomata caused such a decrease and increase in stomatal conductance. That is, the dust plugged the open stomata in the light period (Thompson et al., 1984; Krishnamurthy & Rajachidambaram, 1986), and prevented the stomata from closing (Beasley, 1942; Ricks & Williams, 1974; Fluckiger et al., 1979) in the dark. Hirano et al. (1992) found that stomatal conductance decreased in the light even after washing off the volcanic ash accumulating on a cucumber leaf surface, and thought that it was caused by the ash plugging the stomata. Dust may affect stomatal conductance by covering the stomatal opening, even if there is no dust in the stomata. However, except for the case of cement dust which covers a leaf surface like a crust (Singh & Rao, 1981), it seems that the covering effect can be neglected, because stomatal conductance did not change when the stomata were closed during dusting (Table 1).

**Shading effect of dust on photosynthetic rate**

Before and after dusting, the net photosynthetic rates of leaves were compared (Fig. 5). The photosynthetic rate after dusting was indicated as a value relative to that before dusting. On both the cucumber and the kidney

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**Fig. 5.** Relationship between dust loads and net photosynthetic rate of (a) cucumber and (b) kidney bean leaves at the PPFD of 200, 400 and 700 μmol m⁻² s⁻¹; the leaves were dusted when the stomata were closed. The photosynthetic rates are indicated in the relative values before and after each dust treatment. Measurements were made at 25 ± 1°C for cucumber and 20 ± 1°C for kidney bean under the conditions of 70 ± 5% RH.
bean, the photosynthetic rate decreased accordingly as the dust load increased, but the relationships depended on the particle size of the dusts. When the finer dust accumulated, the relative photosynthetic rate was smaller. Moreover, it was smaller at lower PPFD. The relationship between the relative photosynthetic rate and the shading coefficient, however, was equal for all dusts at the three PPFD levels when Fig. 5 was modified with the shading coefficient. From this result, it was thought that the decrease in the photosynthetic rate of the dusted leaves was induced by shading. In general, the photosynthetic rate increases as light intensity increases, but reaches a plateau at a light-saturation point. If the light intensity incident on the leaf surface through the dust cover is higher than the light-saturation point, dust will not decrease the photosynthetic rate by shading. Since the light saturation point of the kidney bean leaf was about 400 µmol m\(^{-2}\) s\(^{-1}\) (Fig. 4), the shading effect on the photosynthesis was small at 700 µmol m\(^{-2}\) s\(^{-1}\). Although the shading coefficient was 0.4, the photosynthesis was almost saturated. On the other hand, since the saturation point of the cucumber leaf was about 750 µmol m\(^{-2}\) s\(^{-1}\), which was much higher than that of the kidney bean, the photosynthetic rate was sensitive to shading.

In this experiment, the effects of the dust on the photosynthesis except shading, such as plugging of the stomata and increasing of the leaf temperature, were negligible, because the dust was applied when the stomata were closed, and the leaf temperatures of both the plants were within the optimum ranges of the photosynthetic rates. The leaf temperatures of the cucumber and kidney bean were 25–30 and 20–25°C, respectively, which depended on light intensity.

**Effect of increased leaf temperature on photosynthesis and transpiration**

Figure 6 shows the temperature difference between the cucumber leaves with and without dust. The results obtained with the three classes of KL dust resembled each other well. With both KL fine and CB dusts, the leaf temperature difference increased as the light intensity or the dust load increased. However, dark-colored CB dust increased leaf temperature much more than light-colored KL dust. The leaf temperature differences at 1300 µmol m\(^{-2}\) s\(^{-1}\) of PPFD, which was equivalent to 670 Wm\(^{-2}\) of short-wave radiant flux density, were 3°C for CB and 0-6°C for KL fine at 1.3 g mm\(^{-2}\); the former being above five times as large as the latter. In this experiment, the maximum shading coefficient was 0.42, which was measured with KL fine at 2.9 g m\(^{-2}\).

Thus the shading has little effect on stomatal conductance and so transpiration rate at 1300 µmol m\(^{-2}\) s\(^{-1}\). Moreover, since dust was applied when the stomata were closed, the stomata were not plugged (Table 1). Therefore, the additional absorption of incident radiation by the dust cover caused the increase in leaf temperature (Eller, 1977; Borka, 1984).

The effect of the increased leaf temperature by dust cover on the rates of photosynthesis and transpiration were studied (Table 2). The rates of the dusted cucumber leaves were measured simultaneously at air temper-

![Fig. 6. Relationship between difference in leaf temperature (T_{d-T_c}) and PPFD. T_d and T_c were temperatures of the cucumber leaves with and without dust, respectively. The leaves were dusted with KL and CB dusts when the stomata were closed. Points are means of three measurements. Measurements were made at 25 ± 1°C and 70 ± 5% RH.](image)

**Table 2. Photosynthesis, transpiration and temperature of the cucumber leaves dusted with CB at 1.0 g m\(^{-2}\) when the stomata were closed.** Data are means ± 1 SD (N = 4). Measurement was made at 1300 µmol m\(^{-2}\) s\(^{-1}\) of PPFD (=670 Wm\(^{-2}\) of short-wave radiant flux density) and at 70 ± 5% RH.

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf temperature</td>
<td>Dusted</td>
<td>25.2 ± 0.2**</td>
<td>28.8 ± 0.1**</td>
<td>32.3 ± 0.2**</td>
<td>35.6 ± 0.3**</td>
<td>39.1 ± 0.2**</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>21.5 ± 0.2</td>
<td>25.3 ± 0.2</td>
<td>29.2 ± 0.2</td>
<td>33.0 ± 0.2</td>
<td>36.9 ± 0.3</td>
</tr>
<tr>
<td>Photosynthetic rate</td>
<td>Dusted</td>
<td>18.7 ± 1.1*</td>
<td>19.6 ± 1.3</td>
<td>19.8 ± 1.3</td>
<td>19.1 ± 1.2</td>
<td>17.4 ± 1.1</td>
</tr>
<tr>
<td>(µmol m(^{-2}) s(^{-1}))</td>
<td>Control</td>
<td>16.4 ± 1.2</td>
<td>18.1 ± 1.2</td>
<td>19.4 ± 1.3</td>
<td>19.7 ± 1.3</td>
<td>18.8 ± 1.4</td>
</tr>
<tr>
<td>Transpiration rate</td>
<td>Dusted</td>
<td>2.78 ± 0.38</td>
<td>3.24 ± 0.37</td>
<td>3.78 ± 0.40*</td>
<td>4.09 ± 0.45*</td>
<td>4.47 ± 0.49*</td>
</tr>
<tr>
<td>(mmol m(^{-2}) s(^{-1}))</td>
<td>Control</td>
<td>2.16 ± 0.35</td>
<td>2.55 ± 0.34</td>
<td>2.93 ± 0.36</td>
<td>3.32 ± 0.39</td>
<td>3.55 ± 0.37</td>
</tr>
</tbody>
</table>

* and ** indicate significant differences between the treatment and the control at p<0.05 and p<0.01 by t-test, respectively.
CONCLUSIONS

It was found that the dust accumulating on leaf surfaces influenced the stomatal conductance, photosynthesis and transpiration by shading, plugging of the stomata and increasing the leaf temperature. These effects were investigated separately in this study, but their compound effect remains an important problem.

Around large dust sources, such as factories without dust collectors, highways with heavy traffic and active volcanoes, plant leaves become contaminated by dust. For example, it was reported that 5 to 70 g m⁻² of dust, with a particle size between KL fine and ultrafine accumulated on plant leaves situated near to a power plant (Brabec, 1981); 1 to 2 g m⁻² of dust, with a size similar to KL coarse accumulated on leaves near to a motorway (Thompson et al., 1984) and about 50 g m⁻² of ash, with a size similar to KL coarse accumulated on plant leaves near to a volcano (Hirano et al., 1992). In this study, dust was applied only to the adaxial leaf surface. However, it was reported that plants of many species were contaminated by dust not only on the adaxial leaf surface but also the abaxial (Pyatt, 1973). It was also reported that the percentage of stomata containing dust in their openings reached a 50% maximum on an abaxial leaf surface of Quercus petraea, by scanning electron microscopy (Ricks & Williams, 1974). While the dust load on the abaxial surface is smaller than that on the adaxial surface, it is inferred that the former influences the stomatal conductance more significantly than the latter. This is because plants of many species, especially trees, have stomata only on their abaxial leaf surfaces, and the stomatal conductance of the abaxial surface is much larger than that of the adaxial surface, in general (Fig. 3). Such a decrease in stomatal conductance induces a decrease in CO₂ uptake in the light. On the other hand, dust in stomata prevents the stomata from closing. This may be a serious problem when plants are exposed to concentrated gaseous air pollutants (e.g. SO₂, O₃) or water stress, because the uptake of gaseous air pollutants and water loss increases (Ricks & Williams, 1974; Fluckiger et al., 1979).

The results obtained here suggest that plants around large dust sources are susceptible to chronic decrease in photosynthesis and consequently in growth, in particular when both the adaxial and abaxial leaf surfaces are contaminated by dust.

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