Effects on air pollutant removal by plant absorption and adsorption

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Abstract

It is well known that plants aid the removal of air pollutants. On the other hand, there is little research on air purification capabilities of absorption and disintegration of the air pollutants by plants. This research observes the air purification effect of plants’ absorption capabilities of carbon dioxide (CO\textsubscript{2}) and nitrogen oxides (NO\textsubscript{X}) with the aim of quantifying air purification capabilities. CO\textsubscript{2} and NO\textsubscript{X} absorption rates were measured from the experiment and the characteristics and seasonal change of CO\textsubscript{2} and NO\textsubscript{X} absorption were measured.

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1. Introduction

Planting in and around buildings, especially outer walls, contributes to the reduction of environmental factors such as heat, wind and ambient noise [1]. The air-cleaning effects of plants, the carbon assimilation by photosynthesis of the plant itself and the minant disintegration by bacteria in soil have been reported previously [2,3]. However, there is little research on the purification of air pollutant substances through the use of plants in urban environments. This paper’s aim is the examination of the air purification capabilities through urban planting. CO\textsubscript{2} and NO\textsubscript{X} were selected as experimental gaseous contaminants, since CO\textsubscript{2} contributes to global warming, and for NO\textsubscript{X} there is still no satisfactory environmental standard in Japan [4,5]. Plants have both properties of absorption by photosynthesis and adsorption on leaves to remove NO\textsubscript{X} from ambient air. A measurement system using a chamber having an atmospheric environment was developed. Using the chamber, the removal effects of air pollution substances through seasonal variation, illumination intensity, etc. were investigated by measuring changes in contaminant concentrations, which are attributed to plants.

2. Outline for experiment and object materials

2.1. The object plant for measurement

It is expected that Conferta (Juniperus conferta palr) will become a common hanging and wall-mounted plant on buildings. For this reason, it was chosen with an Ivy from a vine plant for comparison purposes. Each plant has green plant parts on the ground and soil in a root ball for wall mounting. To enable measurement of the plants NO\textsubscript{X} sorption effect (absorption and desorption), the root ball and soil was wrapped in polyvinyl fluoride (PVF) sheeting. Measurement of the empty chamber was also undertaken to act as a reference point.
2.2. Measurement system

The chamber measurement system (0.5 m(W)×0.8 m(L) × 0.3 m(H), 0.12 m³) is shown in Fig. 1. The chamber consists of sheet glass in the southern area and the upper surface, and all other surfaces are finished in aluminum, which minimizes surface NOX absorption. A rectification board was set up inside the chamber to prevent short circuiting of air from the inlet to the outlet. Inside the chamber, humidity and temperature increase (which is caused by plant transpiration and sunlight) was prevented by a cooling system (50l/min, a pump, cooling pipe), which cooled and dehumidified the chamber’s air. High concentration pollution gas (CO₂ or NOx) and outdoor air introduction equipment (high-concentration bag, mini pump) were installed. Internal environmental elements (illumination intensity, temperature, humidity) were also measured.

A digital illuminometer (Tokyo Koden Ltd., ANA-F11) was used to measure illumination intensity. A CO₂ meter using the non-diffusion infrared absorption method (Gastec, CMCD-10, CMCD-11) was used to measure CO₂ concentrations. The NO-NO₂-NOX automatic analysis meter (Thermo Electron, MODEL42C), using the chemiluminescence method, was used for measuring NOX concentrations, and nitrous acid ion (NO²⁻) condensation water concentration, collected from the cooling system, was measured by ion chromatography (IC). A temperature- and humidity-measuring instrument (MODEL SK-L200TH) was installed inside the chamber.

3. Experiment of the effects of CO₂ removal

In this section, attention is paid to the CO₂ removal effect, aimed at seasonal quantification of one day’s carbon dioxide (CO₂) plant absorption/emission. Through measurement of the CO₂ absorption rate, illumination intensity, temperature and humidity, seasonal characteristics were developed. The one-day seasonal CO₂ absorption/emission model is based on the above, and was applied by using general environmental weather data from the Japan Meteorological Agency.

3.1. Effects of CO₂ removal

From a high-concentration bag made from vinyl chloride, CO₂ was introduced into the chamber during the first several minutes, and raised to a high concentration, 3500–4000 ppm. The concentration level decreased over a 60 min period from the experiment’s start through plant absorption, after which time, the purification capability of the plant was examined from the change in the chamber’s CO₂ concentration at the elapsed time.

3.2. Examination of the absorption and emission of CO₂

From the chamber’s CO₂ concentration change, CO₂ purification capabilities were evaluated using the concentration attenuation curve (from the CO₂ purification capability experiment result), in the chamber for t = 15–60 min after peak concentration from the substance absorption/emission in minute intervals for both day and night time. The CO₂ absorption velocity x was obtained by using formula (1). By assuming that CO₂ absorption rate x was proportional to concentration, the amount of CO₂ absorption by photosynthesis, could be calculated and the amount d of the emission by dark reaction with formula (2).

\[
x = \frac{C_o q \Delta t - C_{(t)} q \Delta t - V(C_{(t)} - C_{(t-\Delta t)})}{C_{(t)} S \Delta t},
\]

\[
d = \frac{-C_o q \Delta t + C_{(t)} q \Delta t + V(C_{(t)} - C_{(t-\Delta t)})}{S \Delta t},
\]

where \(C_o\) is the CO₂ concentration in the chamber (mg/m³), \(C_o\) the outdoor air CO₂ concentration (mg/m³), \(S\) the surface area of leaf (m²), \(q\) the ventilation rate (m³/h), \(V\) the chamber capacity (m³), \(x\) the CO₂ absorption velocity (m/min) and \(d\) the amount of CO₂ emission (mg/min/m²).

(The leaf area was calculated from photographs taken by a digital camera at each period. In the root ball, the soil experiment results were the same as that of the empty chamber test.)

The relationship between CO₂ absorption velocity \(x\) and illumination intensity is shown in Fig. 2. The correlation with illuminance is high in summer at high absorption velocity level, and there is little influence of the illuminate in winter. Moreover, when
the illuminance was set to 60–80 klx or higher, CO₂ absorption velocity \( \alpha \) showed a pattern of leveling off.

The relationship with temperature is shown in Fig. 3. Although \( \alpha \) for spring, summer and autumn increased with a rise in temperature to nearly 40 °C, it fell when the temperature rose above this figure. Since temperatures above 40 °C are uncommon in Japan, it can be said that \( \alpha \) increases with temperature. Moreover, CO₂ absorption velocity \( \alpha \) in winter was a small value and constant.

Fig. 4 shows the change in absorption and discharge of CO₂ that is taken from one day’s measurement of concentrations in the chamber. From the result of changes in absorption and emission of CO₂ taken from a day’s measurement of chamber concentration, the daytime concentrations fell to 200 ppm by photosynthesis, lower than the outdoor air concentration. The conversion of emissions from absorption was experienced frequently. Concentration rose at night through dark reaction.

The average amount of night emission \( d \) was 2.95 mg/m²/min in spring, 14.93 in early summer, 11.28 in late summer, 11.55 in autumn, and 2.55 in winter. There was high emission in early summer, late summer, and autumn.

One day’s CO₂ absorption/emission was predicted. Table 1 shows the calculated conditions. From consideration of the foregoing paragraph, \( \alpha \) in summer was proportional to the illuminance and was respectively set as the fixed value in autumn and winter. Setting the illuminance for 9:00–14:00 in summer to 30 klx ([a bright day] of the total design sky illuminance), in each period, and using the average CO₂ concentration and temperature, \( d \) (night) was fixed during each period. Consequently, the amount of one day’s CO₂ absorption was 145.6 mg CO₂/day in summer, 44.7 in autumn and 27.5 in winter (Table 1).

3.3. Examination into the CO₂ removal effect

Using formula (3) based on the weather data, illuminance, temperature and CO₂ concentration, one day’s CO₂ absorption/emission from one stock of Confera under all season conditions were obtained.

When \( \alpha \) was proportional to illumination intensity up to a certain value or higher, it showed a fixed value pattern, \( \alpha \) was set to the maximum value and from this, formula (4) was used.
Moreover, formula (5) was used with the assumption that \( d \) is fixed in early summer and late summer, because of low temperature and as other seasons are dependant on temperature as per Fig. 5.

\[
a = \sum_{\text{day}} a C + d t',
\]

\[
a = a_1 \text{Eth} + a_2,
\]

\[
d = b_1 T + b_2,
\]

\[
\text{Eth} = f(I_{\text{th}}, h),
\]

where, \( a \) is the amount of CO\(_2\) absorption (mg/m\(^2\)/min), \( a \) the CO\(_2\) absorption velocity (m/min), \( d \) the amount of night discharge (mg/m\(^2\)/min), \( t \) the time of night (min), \( a_1, a_2, b_1, b_2 \) are the constants, \( T \) the temperature (°C), Eth the global illumination (klx), Ith the all sky illumination (kW/m\(^2\)), and \( h \) the solar altitude (rad).

Quantitative results of one day’s CO\(_2\) absorption/emission on a fine day (from one stock of Conferta with approx 800 cm\(^2\) leaf area) was 1022.1 mg CO\(_2\)/day in spring, 1901.1 in early summer, 145.4 in late summer, 252.2 in autumn, and 168.0 in winter.

Compared to the measured one day’s chamber results, the value increased by approximately 400 times in early summer. In the experiment, daytime chamber CO\(_2\) concentrations fell remarkably, and absorption was controlled by the rise in internal temperature; it is considered that the CO\(_2\) absorption/emission in one-day was a small value.

### 4. Experimentation of NO\(_X\) removal effects

By using a high-concentration bag of NO\(_X\), the concentration in the chamber during the first several minutes was raised to a little higher concentration level of 1000 ppm than that of atmospheric levels.

The concentration of NO\(_X\) decreased continuously during the experiment attributed to the plant. Then the purification capability of the plant was examined from the change in the chamber’s NO\(_X\) concentration as a function of time. PVF bag (Max 30 l) having little NO\(_X\) adsorption was used as an NO\(_X\) high-concentration bag and the bag was filled with mixed gas (the standard gas (NO\(_2\): 4.7 ppm) and zero gas which had been passed through a clean gas scrubber).

#### 4.1. NO\(_X\) purification capability experiment and evaluation method

The high-concentration bag was connected for 6 min before the commencement of the experiment. The chamber's NO\(_X\) concentration was raised, and zero gas was introduced from the zero gas bag. In order to take into account the dissolved NO\(_X\) in the cooling system condensation water, the amount of condensation water was measured in each experiment and the NO\(_X\) ion concentration was obtained by using ion chromatography.

The reduction patterns of NO\(_X\) concentration in the case of Conferta and Ivy were higher than those of “nothing” and “soil”.

The calculated value of the NO\(_X\) concentration was based on the NO\(_X\) purification capability experiment results with the assumption of adsorption/desorption of NO\(_X\) within the chamber and the dissolution in condensation water. Then the amount of NO\(_X\) reduction was calculated from the difference in the NO\(_X\) concentration obtained by the calculated value at time \( t = 60 \) min and the experimental data. From the substance of absorption/emission, the calculated value used formula (7) at the time of a concentration rise.

### Table 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>( x ) (m/min)</th>
<th>( d ) (mg/m(^2)/min)</th>
<th>Leaf surface area (m(^2))</th>
<th>Time of daytime</th>
<th>CO(_2) conc. (ppm)</th>
<th>Result (mg CO(_2)/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>0.0012 \times \text{Illuminance (klx)}</td>
<td>11.0</td>
<td>687</td>
<td>6:30–16:30</td>
<td>340.9</td>
<td>145.6</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.017</td>
<td>6.5</td>
<td>763</td>
<td>6:45–16:15</td>
<td>337.1</td>
<td>27.5</td>
</tr>
<tr>
<td>Winter</td>
<td>0.005</td>
<td>1.8</td>
<td>796</td>
<td>7:00–16:00</td>
<td>427.9</td>
<td>44.7</td>
</tr>
</tbody>
</table>

Fig. 5. Correlation of amount of night discharge and temperature.
(0 ≤ t ≤ 6), and used formula (8) at the time of the concentration attenuation (6 ≤ t ≤ 60).

\[ C(t) = C(0)e^{-\frac{Q}{V}t} + (1 - e^{-\frac{Q}{V}t}) (fC_o + (1 - f)Ch), \]

\[ C(t) = C(0)e^{-\frac{Q}{V}(t-6)} + (1 - e^{-\frac{Q}{V}(t-6)})fC_o, \]

where \( C \) is the \( NO_X \) concentration (ppb), \( C_o \) the outdoor air \( NO_X \) concentration (ppb), \( f \) the rate of natural inflow (dimensionless), \( Q \) the ventilation rate at the time of a concentration rise (l/min), \( q \) the ventilation rate at the time of concentration attenuation (l/min), \( V \) the chamber capacity (l).

From the quantity of condensation water which was collected from the cooling system, the value of \( NO_X \) which melted into \( NO_2 \) and \( NO_3 \) ions was analyzed and calculated. The amount of nitrogen equivalent to the atmospheric \( NO_X \) and condensation water was produced in a \( NO_X \) adsorption index.

### 4.2. Influence by soil and the plant

The difference between the theoretical prediction and the experimental result at \( t = 60 \) is shown in Table 2 for all chamber conditions. Although the variation is large, when attention is paid only to the chamber’s concentration and its averages (compared with the case of “nothing” and “soil”), there is large reduction of \( NO_X \) concentration in the case of Conferta and Ivy. It is therefore thought that it contributed to the reduced concentration in the air as the whole system contained the plants.

Absorption/emission amount of \( NO_X \) which took into consideration the amount of \( NO_X \) ion in the condensation water, chamber soil are shown in Fig. 6. When the chamber wall surface adsorption in the order of several µg is taken into consideration, \( NO_X \) will be emitted from the soil. Whenever the illuminance was high, the emission was observed. Moreover, when the plant was placed into the chamber, the \( NO_X \) quantity in the condensed water was taken into account. The emission was found to be higher than the adsorption, as can be seen in Fig. 7. In the daytime case when illumination intensity is high, emission is also high. On the other hand, the measuring data at nighttime shows absorption. The moisture in the soil containing the

### Table 2

<table>
<thead>
<tr>
<th>Case</th>
<th>Empty</th>
<th>Soil</th>
<th>Conferta</th>
<th>Ivy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NO_X ) sorption (µg N)</td>
<td>2.94</td>
<td>3.25</td>
<td>4.42</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Fig. 6. \( NO_X \) sorption in the case of soil with illumination intensity; subtracting \( NO_X \) content in condensed water from \( NO_X \) sorption in the case of soil.

Fig. 7. \( NO_X \) sorption in the case of plant with illumination intensity; subtracting \( NO_X \) content in condensed water from \( NO_X \) sorption fits the case of plant measurement.

### 4.3. Trial calculation of the amount of \( NO_X \) which sticks to the leaf’s surface through leaf-washing examination

In order to check the amount of plant \( NO_X \) adsorption, the amount of \( NO_X \) ion contained in the water flushed from the leaf surface (Conferta) was measured by using ion chromatography. After flushing the leaf (Conferta), it was soaked and exposed to pure water for approx. 1 h, one leaf was dipped in pure water for 3 min and the other ultrasonically washed in pure water for 1 min. Since \( NO_2 \) and \( NO_3 \) ions were not detected through ion chromatography when each pure water sample was analyzed, \( NO_X \) adhered to the leaf should have been washed by carrying out washing of the plant’s surface with pure water for 1 h.

Then, after washing Conferta and conducting the \( NO_X \) purification experiment for 1 h, \( NO_X \) ion concentrations were measured with about 40% of the leaf
Table 3
Equation of NO\textsubscript{x} sorption

\[ u\text{NO}_x C_{(t)} = C_{00} e^{-Q_{t}/V} + \left(1 - e^{-Q_{t}/V}\right) \left\{ C_{00}(1 - f) + C_{\text{unit}} + \frac{M}{Q}\right\}  \]  \hspace{1cm} (9)

\[ \frac{\left(C_{(t+\Delta t)} - C_{(t)}\right) - \left(u\text{NO}_x C_{(t+\Delta t)} - C_{(t)}\right)}{\Delta t} = \frac{U_{(t+\Delta t)}}{\Delta t} = \eta \]  \hspace{1cm} (10)

\(V\) chamber volume (m\(^3\))

\(C\) chamber NO\textsubscript{x} concentration (µg/m\(^3\))

\(u\text{NO}_x\) calculated chamber NO\textsubscript{x} concentration (µg/m\(^3\))

\(f\) rate of infiltration (dimensionless)

\(C_{00}\) zero gas NO\textsubscript{x} concentration (µg/m\(^3\))

\(C_{\text{unit}}\) outdoor NO\textsubscript{x} concentration (µg/m\(^3\))

\(Q\) air flow rate (m\(^3\)/min)

\(a\) sorption area (m\(^2\))

\(M\) desorption from chamber (µg/min)

\(\sigma\) Absolute humidity (g/m\(^3\))

\(\text{Av}_{\text{NO}} C_{(cero-4a-0)}\) 60 min average NO\textsubscript{x} concentration before measurement

\[ k_{\text{NO}_x} = \frac{u\text{NO}_x}{C_{(t)}} = \frac{U_{\text{NO}_x}}{C_{(t)}\Delta t} \]  \hspace{1cm} (12)

\[ k_{\text{CO}_2} = \frac{C_{\text{unit}}\Delta t - C_{(t)}\Delta t - V(C_{(t+\Delta t)} - C_{(t)})}{C_{(t)}\Delta t} \]  \hspace{1cm} (13)

\(k\) sorption(adsorption) velocity (m/min)

\(u\text{NO}_x\) sorption(adsorption) flux (µg/m\(^2\)/min)

\(\Delta t\) time interval (min)

\(C\) concentration (µg/m\(^3\))

\(C_{\text{NO}_x}\) concentration in the atmosphere and NO\textsubscript{x} concentration in the condensed water

\(\Delta t\) time interval (min)

\(\eta\) sorption area (m\(^2\))/sorption amount per min (µg/min)

\(k_{\text{NO}_x}\) NO\textsubscript{x} absorption velocity of plant (m/min)

\(K_{\text{CO}_2}\) CO\textsubscript{2} absorption velocity of plant (m/min)

\[ \eta_{\text{NO}_x} = \frac{k_{\text{NO}_x}}{k_{\text{CO}_2}} \frac{C_{\text{NO}_x}}{C_{\text{CO}_2}} \frac{K_{\text{NO}_x}}{K_{\text{CO}_2}} = (\text{const.}) \]  \hspace{1cm} (14)

After three NO\textsubscript{x} purification experiments, the amounts of adsorption on the leaf’s surface were 42.5 µg N, 31.2 and 22.7, respectively. Compared with the reduced amount of NO\textsubscript{x} concentration in the atmosphere and the amount of NO\textsubscript{x} dissolved in the condensed water, the difference in value was in the order of one.

4.4. Calculating the amount of nitrogen oxide removal by planting

Formula (9) is based on the mass balance of decreased amount of concentration through chamber ventilation, and, the calculation formula of the amount of NO\textsubscript{x} sorption is shown in formula (10). From the measured results, by comparing the attenuated concentration differences which are based on the actual measured chamber concentration, the NO\textsubscript{x} sorption per unit time (mg/min) and NO\textsubscript{x} sorption flux (mg/m\(^2\) min) were calculated. The value of the NO\textsubscript{x} removal capability did not take into account of the dissolution in the condensed water. Each measured NO\textsubscript{x} removal capability considered the condensed water’s NO\textsubscript{x} dissolution and was divided into absorption and emission.

The attenuated concentration experiment was conducted in a neutral state with an empty chamber to consider NO\textsubscript{x} adsorption–desorption characteristics of the measurement system. From the measured results, the relationship between the NO\textsubscript{x} adsorption amount per unit time and NO\textsubscript{x} concentration in the measurement system were used as the chamber function of absolute humidity and concentration history. This function is expressed by the regression formula (11) in Table 3, and takes into consideration the measured results. The calculation formula of NO\textsubscript{x} sorption and CO\textsubscript{2} absorption velocities are shown in formula (12) and (13). The relationship between a plant’s NO\textsubscript{x} absorption and CO\textsubscript{2}
absorption velocities has a proportionality relationship shown in formula (14).

4.5. Evaluation of the nitrogen oxide removal effect by planting

The NO\textsubscript{x} sorption velocity result and CO\textsubscript{2} absorption velocity (actual measurement) is shown in Fig. 8, a clear relationship is not seen in the results. This shows that the NO\textsubscript{x} removal is not NO\textsubscript{x} absorption by photosynthesis but the surface adsorption contributes greatly to the NO\textsubscript{x} purification capabilities of the planting.

In the examination immediately after the end of the concentration attenuation experiment, the amount of NO\textsubscript{x} adsorption on a leaf was measured. After the experiment, NO\textsubscript{x} was dissolved by dipping some leaves in pure water (50 ml for 5 min), and the quantity of the NO\textsubscript{2}\textsuperscript{+} ion in the pure water was measured by using ion chromatography. There was no detection up to 20 min but 0.0707 mg/l was detected at 40 min. From the detection of NO\textsubscript{2}\textsuperscript{+} ion in the pure water exposed to leaves for 40 min, it shows that NO\textsubscript{x} was sticking to the leaf’s surface.

From correlation with the NO\textsubscript{x} absorption/emission and the outside environment factor, temperature and illuminant intensity on the NO\textsubscript{x} removal effect was evaluated. Since the amount of temperature and illuminance influence each other, it is difficult to clarify which has contributed the most to the amount of NO\textsubscript{x} sorption. From this result, the following considerations were performed. The relationship between the amount of temperature, illuminance, and the NO\textsubscript{x} absorption/emission is shown below.

The relationship between circumference temperature and illuminance vs. the NO\textsubscript{x} absorption/emission is shown in Fig. 9. For temperature, both the plant and soil part showed reduction patterns of NO\textsubscript{x} absorption/emission and decreased in line with the temperature rise as shown. In illuminance, although there is a pattern for the NO\textsubscript{x} absorption/emission to decrease with an increase in illuminance, the variation is shown as a value of NO\textsubscript{x} absorption/emission in the low illuminance region. It shows that NO\textsubscript{x} removal mechanism is based on the physical adsorption on the leaf, therefore the removal effect by plants should be considered for not only absorption but also adsorption.

5. Summary

From the chamber experiment, plants’ CO\textsubscript{2} absorption and emission characteristics show there was a little amount of CO\textsubscript{2} absorption in winter. Photosynthesis was actively performed in spring and summer (especially late summer) and it became clear that there was a large amount of CO\textsubscript{2} absorption.

The amount of absorption largely influences the CO\textsubscript{2} absorption in a chamber experiment during the daytime, and the emission amount is influenced largely at night by temperature.

As a result of quantifying one day’s CO\textsubscript{2} absorption/emission in the general environment, there was a large amount of absorption in spring and early summer. It is clear that there is a decrease of less than 1/3 from early summer to late summer. Moreover, regarding the amount of emission, it was high in early summer, late summer, and autumn, and about 3 times higher in spring and winter.

To verify the NO\textsubscript{x} plant removal effect, Conferta was used in the experiment, however, the influence of the dissolution in the condensed water containing the NO\textsubscript{x} emitted from the soil was large.

The amount of plant NO\textsubscript{x} sorption decrease is influenced by a rise in the surrounding temperature, illuminance. Therefore, the removal effect by plants should be considered for not only absorption but also adsorption.

References


