Phytoremediation of Formaldehyde by Plant Stems

Lijun Zuo
Southwest Jiaotong University
Dan Wu
Southwest Jiaotong University
Le Yu
Southwest Jiaotong University
Yanping Yuan (ypyuan@home.swjtu.edu.cn)
Southwest Jiaotong University https://orcid.org/0000-0001-8613-391X

Research Article

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Phytoremediation of formaldehyde by plant stems

Lijun Zuo[a], Dan Wu[b], Le Yu[a], Yanping Yuan[a, *]

[a]: School of mechanical engineering, Southwest Jiaotong University, 610031, Chengdu, China

[b]: School of architecture and design, Southwest Jiaotong University, 611756, Chengdu, China

[*]: Corresponding author. E-mail: ypyuan@home.swjtu.edu.cn; Telephone: 13880871068

Abstract

Decorative plants can efficiently purify formaldehyde and improve the quality of indoor air. The existing studies primarily revealed that the aerial and underground parts of plants' capacity to purify formaldehyde, while the performance of stems is unclear. A formaldehyde fumigation experiment was conducted on Pothos (*Epipremnum aureum*) and sacred lily (*Rohdea japonica*) in a sealed chamber. Results showed the stems could removal formaldehyde. The efficiency of removal by the stems of each plant was 0.089 $mg \cdot m^{-3} \cdot h^{-1}$ and 0.137 $mg \cdot m^{-3} \cdot h^{-1}$, respectively, the rate of purification was 40.0% and 61.6%, respectively. Both were related to plant species and the latter was affected by other factors like exposed area. To further explore the mechanism of phytoremediation, the correlation between the concentration of formaldehyde and CO_2 during the experiment was investigated. Results showed when leaves of plants were exposed to formaldehyde, the concentration of CO_2 increased with the decrease in concentration of formaldehyde, and the change in concentration of CO_2 could be used as an indicator of the degree of purification of formaldehyde by the plants.

Keywords: Indoor air quality; Phytoremediation; Formaldehyde purification; Stem remediation capacity; CO_2 concentration

1. Introduction

With the development of society and the transformation of lifestyles, indoor air quality is garnering increasing amounts of attention as people spend more than 80% of their time indoors each day (Jenkins et al., 1992; Tsai et al., 2012). Although the awareness of the human health impacts of exposure to air pollution growing rapidly (Caplin et al., 2019), indoor air quality is getting worse and worse. The deterioration can be accounted to the flourish of interior decoration (Wood et al., 2002), human activities like smoking (Masjedi et al., 2019) and the increase in building tightness caused by the energy crisis. Reasons above bring volatile organic compounds (VOCs) which are harmful to human health to indoors, and formaldehyde is one of the main components of indoor VOCs. Long-term exposure to a low concentration of formaldehyde can cause damage to the immune, nervous, developmental, and respiratory systems, and exposure to high concentrations of formaldehyde can even cause death (Suh et al., 2000). Among the many methods to purify indoor formaldehyde, phytoremediation technology has attracted increasing amounts of attention owing to its green, low cost, and environmentally friendly characteristics (Luengas et al., 2015).

Phytoremediation technology refers to the use of plants and their symbiotic microorganisms to purify pollutants in soil, water and air (Kim et al., 2018). Studies about phytoremediation technology remediate the contaminants in soil (Huang et al., 2004; Hunt et al., 2019) and water (Wang et al., 2020) are substantial, and this work focus on utilizing phytoremediation to purify pollutants in the air. In the early research on phytoremediation technology, Wolverton et al. exposed plants to a chamber filled with a high concentration of formaldehyde, controlled the humidity and light environment and proved that Pothos (*Epipremnum aureum*), *Syngonium podophyllum* Schott and spider plant (*Chlorophytum comosum*) could effectively remove formaldehyde (Wolverton et al., 1984). The existing research has generally indicated that the ways for plants to purify pollutants can be roughly divided into the purification of pollutants by the aerial part of plants, microorganisms in the soil, roots and the culture media (Cruz et al., 2014). The microorganisms, roots and culture medium are collectively referred to as the underground part of the plant.

The aerial part of plants can effectively remove VOCs. The purification of pollutants in the aerial part of plants is primarily through their adsorption by the cuticular wax of leaves, absorption by the stomata, and subsequent metabolic transformation (Treesubsuntorn et al., 2013). Both hydrophilic and hydrophobic pollutants can adhere

to the surface of the cuticular wax and penetrate into the plant when the concentration of pollutants on the leaf surface exceeds the equilibrium value (Kvesitadze et al., 2006). The adsorption of cuticular wax comprises 46% of the capacity of *Dracaena sanderiana* to remove benzene (Treesubsuntorn and Thiravetyan, 2012), and 20%, 23%, 25%, and 26% of the capacity of *Zamioculcas zamiifolia* Engl. to remove benzene, toluene, ethylbenzene, and xylene, respectively (Sriprapat and Thiravetyan, 2013). Formaldehyde can also enter the plant directly through the opened stomata, which play a significant role in the purification of pollutants in the aerial part. Kondo et al. (1995) found that the capability of plants to remove formaldehyde increased linearly with the increase in stomatal conductance. Tani et al. (2007) postulated that the absorption of pollutants by plants was regulated by the stomatal conductance owing to the high intercellular concentration of methyl isobutyl ketone when the amount of stomatal conductance was high.

The purification of pollutants by underground parts of plants occupies a significant position in phytoremediation. Microorganisms in the soil contribute substantially to the capacity of plants to improve indoor air quality (Orwell et al., 2006). The performance of the underground part to remove formaldehyde after sterilization is reduced by 90% (Kim et al., 2008). Currently, it is generally believed that when indoor air passes through potted plants and their substrates, pollutants are sucked into the substrate through diffusion and become a source of carbon nutrients for certain microbial communities (Wood et al., 2006). Studies have found that the capacity to remove pollutants was enhanced when the plants were repeatedly exposed to pollutants. Orwell et al. (2004) and Torpy et al. (2013) believed that this was caused by the stimulation of microorganisms in the soil. Plant roots and growing media also have the capability to remove pollutants. Plant roots can remove pollutants (Wild et al., 2005) and can also enhance the performance of microorganisms in the soil to remove them (Wenzel 2009). Zhan et al. found that the capacity of plant roots to remove pollutants depends on the root morphology, in which the content of lipids and the specific surface area were vital parameters (Zhan et al., 2013). Some researchers have studied the performance of different components of growth media to purify pollutants. Aydogan and Montoya (2011) noted that growth medium that contained activated carbon had a higher capacity to remove formaldehyde than the growth medium that contained expanded clay and growth stones. They concluded that a growth medium with high adsorption capacity and sufficient microbial sites could improve its performance to remove VOCs. Further

evidence for this hypothesis came from Irga et al. (2013), who found that potted plants differed in their capacity to remove benzene under soil culture and hydroponic conditions, indicating that the difference in the capability of growth media to provide microbial sites led to differences in the efficiency of benzene removal.

Regarding the difference in the performance of aerial and underground parts of plants to purify formaldehyde, Kim et al. (2008) believed that the aerial and underground parts had an equal capacity to remove formaldehyde under a light environment, while in dark conditions, the aerial parts basically could not purify formaldehyde. However, Schmitz et al. (2000) and Wang et al. (2014) postulated that even under light conditions, the capacity of aerial parts to purify formaldehyde was still limited, and the underground parts played a major role in the process of purifying formaldehyde.

Through the analysis of existing studies, it was found that the amount of formaldehyde purified per unit of leaf area was used to represent the performance of aerial parts to remove formaldehyde, and all of the purification capacity was attributed to the leaves, ignoring the role of stems in purifying formaldehyde.

To address the shortcomings described above, a formaldehyde fumigation experiment on plants in a closed glass chamber was conducted. The capability of stems to purify formaldehyde was studied by analyzing the change of formaldehyde concentration when stems exposed to formaldehyde. In order to further explore the formaldehyde purification mechanism and fill the gap that the change of CO_2 concentration in the chamber has not been examined, the relative correlation between formaldehyde concentration and CO_2 concentration was studied.

2. Materials and methods

2.1 Plants

In this experiment, common indoor decorative plants, which were commonly used in the research of plant purification of formaldehyde and had obvious stems were selected. Pothos and sacred lily appeared to be the most suitable. Ten plants each of Pothos and sacred lily of the same age and similar growth were purchased from a market and pre-cultured for one month in an incubation chamber with a temperature of 22℃, a relative humidity of 60%, and a light intensity of 480 Lx. The plants were watered as needed. After the pre-cultivation, the parameters of each plant, such as height, crown width, and chlorophyll content were tested, and three plants with the most similar parameters were selected for the experiment. Two of them were used for the exposure experiment,

denoted as plant A and plant B. Another individual was used in the control experiment. The leaves were wiped with a clean soft towel to prevent dust and particles from affecting the capacity to adsorb and absorb formaldehyde before they were used in the experiment. The chlorophyll content of leaves was monitored before and after each experiment using a chlorophyll meter (SPAD-502 Plus, Konika-Minolta, Tokyo, Japan). After the experiment, the leaf area was measured using a leaf area meter (LI-3000C, LI-COR, Lincoln, NE, USA). Regarding the plant stem as a cylindrical shape, the surface area of the stem was determined approximately by measuring the diameter and length. The basic parameters of plants are shown in Table 1, and the treatment methods of plants are shown in Fig. 1.

Table 1 Basic parameters of plants

	Epipremnum aureum			*Rohdea japonica*		
	A	B	Control	A	B	Control
Age (year)	0.5	0.5	0.5	0.5	0.5	0.5
Crown width (cm)	35.3	33.7	36.4	27.5	25.5	24.9
Height (cm)	20.4	23.1	19.8	22.6	24.1	25.8
Leaf area (cm^2)	1,355.23	1,209.67	1,298.79	676.17	721.87	698.26
Stem area (cm^2)	268.47	249.56	240.18	110.06	95.30	89.68
Substrate	peat	peat	peat	peat	peat	peat
Substrate volume (L)	1.17	1.17	1.17	1.17	1.17	1.17

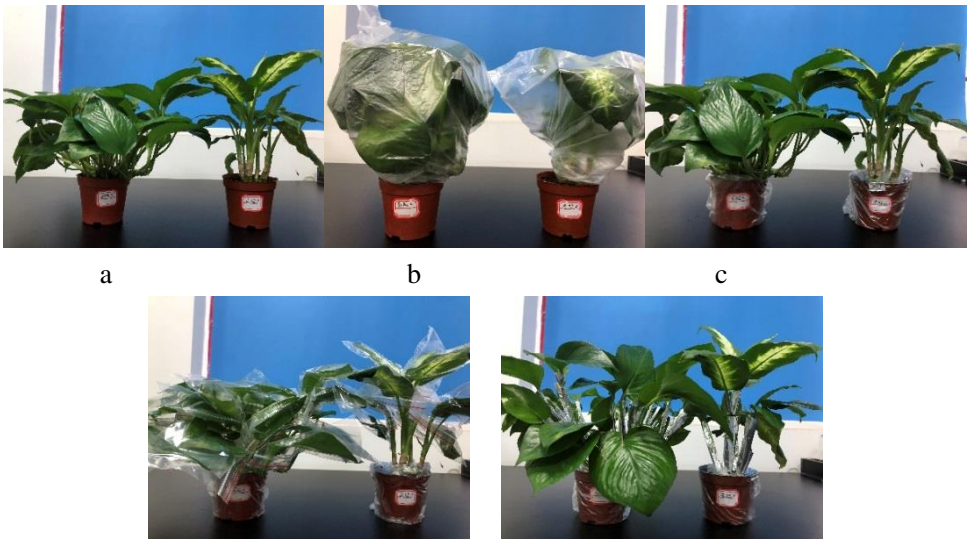

Fig. 1. Plant treatment method. a whole plant exposed to formaldehyde. b underground part exposed to formaldehyde. c aerial part exposed to formaldehyde. **d** stems exposed to formaldehyde. e leaves exposed to formaldehyde.

2.2 Glass chamber

In this experiment, a stainless steel glass chamber with a volume of 1 cubic meter (1 m long × 1 m wide × 1 m high) was selected as the fumigation chamber. A small electric fan was placed in the middle of top of the chamber, which was used to evenly mix the air. Four valves with a diameter of 1 cm were on the left and right sides 30 cm from the bottom of the chamber for air intake and sampling. The openable front of the chamber was the experimental material entrance. The adhesive glue of the glass chamber was sealed with aluminum foil to prevent it from releasing and absorbing formaldehyde, and the hatch interface was sealed with tape to avoid formaldehyde leakage after the hatch was closed. The electric fan was turned off 10 minutes after the end of the sample injection (the concentration of pollutants in the chamber had become stable (Hörmann et al., 2018)) to avoid unnecessary heat generation. The temperature in the chamber was controlled by air conditioning. Illumination was provided by three 24 W indoor LED lights, and full blackout curtains were used to prevent outdoor lighting from affecting the illuminance in the chamber.

2.3 Formaldehyde generator, gas sampling machine and spectrophotometer

A formaldehyde generator was selected, and a solution of 36%~38% diluted formalin solution was added to the generator as a source to generate formaldehyde. A rubber hose was used to connect the gas outlet of the generator to the first valve on left side of the glass chamber. A gas sampling machine was selected, and distilled water was used as the absorption liquid. The sampling machine, the absorption bottle, and the fourth valve on the right side of the glass chamber were correctly connected with a rubber hose, and the exhaust port of the sampling machine was connected back to the glass chamber to reduce the pressure changes in the chamber caused by sampling. A spectrophotometer (GENESYS180, Thermo Fisher Scientific, Braunschweig, Germany) was utilized to analyze the concentration of formaldehyde, which was measured in strict accordance with the national standard GB/T15516-1995 "Air Quality Determination of Formaldehyde-Acetylacetone Spectrophotometry" (GB/T15516-1995).

2.4 Other devices

A formaldehyde sensor was used to monitor the concentration of formaldehyde in the chamber. The temperature, humidity and CO_2 concentration in the glass chamber were measured with a CO_2 tester (MX1102, Onset HOBO, Bourne, MA, USA). The light

intensity in the glass chamber was measured with an illuminance meter (Tes1339R, Testo SE & Co. KGaA, Germany). The experimental system is shown in Fig. 2.

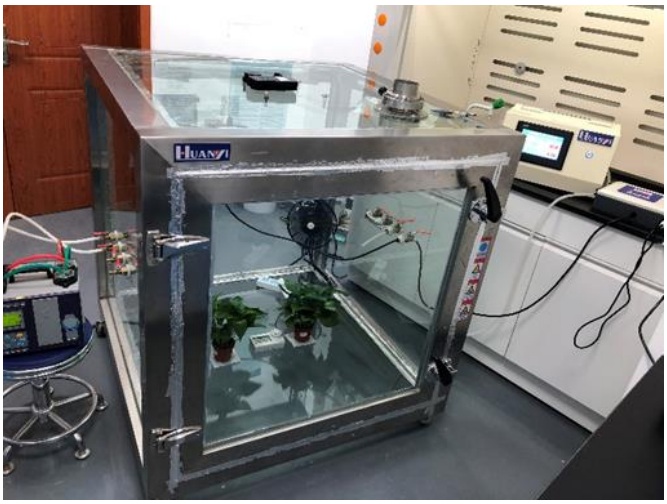

Fig. 2. Experimental system

2.5 Experimental methods

Before the formal experiment, all of the instruments except the plants were put into the glass chamber for a blank experiment to determine the change in concentration of formaldehyde in the glass chamber caused by the leakage/adsorption/absorption of the experimental system.

In the formal experiment, an air conditioner was used to control the temperature in glass chamber, and the LED lights were used to provide the illumination required for the experiment. All the equipment required was correctly connected. The plants were put in the chamber, and the door was closed with the interface sealed using aluminum foil when the temperature in the glass chamber reached the specified value. After that, the formaldehyde generator was started and turned off when the formaldehyde concentration sensor showed the specified value. After 10 minutes, the electric fan was turned off, and sampling was started. Sampling was performed every 1.5 hours, for a total of 6 samples. During the experiment, the HOBO CO_2 tester was used to continuously monitor the temperature, relative humidity and concentration of CO_2 in the glass chamber. Different parts of the plant were wrapped with aluminum foil, and the whole plant, the underground part, the aerial part, the stem, and the leaves were exposed to the environment of formaldehyde. At least three repeated experiments were conducted under each working condition. A control experiment was established; the plants were exposed to formaldehyde-free air under the same environmental parameters, and the chlorophyll content of the plants before and after exposure to the air with or

without formaldehyde was compared to determine the physiological effects of the exposure on the plants.

2.6 Data analysis

The efficiency of removal (see formula 1) and the rate of purification (see formula 2) were used to analyze the formaldehyde purification performance.

$$\varphi = \frac{(c_0 - c_f) - (c_0 - c_i)}{h} \quad (mg \cdot m^{-3} \cdot h^{-1}) \qquad \text{(formula 1)}$$

$$\emptyset = \frac{(c_0 - c_f) - (c_0 - c_i)}{c_0} \quad (\%) \qquad \text{(formula 2)}$$

Where c_0 is the initial concentration of formaldehyde ($mg \cdot m^{-3}$); c_f is the formaldehyde concentration of the formal experiment ($mg \cdot m^{-3}$); c_i is the formaldehyde concentration of the blank experiment ($mg \cdot m^{-3}$), h is time (h).

3. Results and discussion

During the experiment, the environmental parameters in the glass chamber are shown in Table 2.

Table 2 Environmental parameters

Temperature (℃)	Initial relative humidity (%)	Light intensity (Lx)
21.8±1.0	56.5±4.1	475.7±22.4

Note: all data shown were mean ±S.D. for three independent replicates.

The chlorophyll content of the plants before and after exposure to the air with or without formaldehyde was analyzed using SPSS v. 22.0 (IBM, Inc., Armonk, NY, USA) with the significance level set at $p<0.05$. The average of the chlorophyll content of plants in repeated experiments was considered as the chlorophyll content of plants under each working condition. The chlorophyll content was compared to determine the physiological effects of the exposure on the plants. The chlorophyll content of each plant leaf is shown in Table 3 and the results showed that the exposure experiment had no effect on the normal growth of plants to some extent (two-tailed t-test, for Pothos, P=0.06 of plant A, P=0.073 of plant B and P=0.384 of control plant; for sacred lily, P=0.791 of plant A, P=0.472 of plant B and P=0.644 of control plant).

Table 3 Chlorophyll content of each plant leaf (SPAD)

		Before experiment			After experiment		
		A	B	Control	A	B	Control
Epipremnum aureum	Whole plant	49.5± 0.8	48.9± 0.3	46.6± 1.0	50.6± 0.5	49.4± 0.7	45.0± 2.6
	Underground part	50.9± 0.3	46.6±1	45.8± 0.4	51.9± 0.9	48.5± 1.2	46.9± 1.0
	Aerial part	50.3± 1.6	48.5± 0.3	46.4± 2.3	51.2± 2.5	49.2± 1.4	47.6± 2.8
	Stem	50.4± 1.7	47.9± 3.3	44.9± 1.7	53.7± 0.1	51.0± 0.4	46.9± 1.8
	Leaf	51.7± 0.5	49.5± 0.7	46.6± 1.3	52.5± 1.1	50.0± 0.9	46.4± 0.9
Rohdea japonica	Whole plant	62.2± 3.3	61.4± 2.0	55.7± 1.1	61.4± 2.8	62.7± 3.4	56.4± 1.0
	Underground part	64.2± 1.0	59.4± 1.0	51.6± 0.7	61.9± 2.0	56.3± 3.8	51.4± 0.8
	Aerial part	56.4± 5.9	58.7± 3.2	54.2± 2.9	60.2± 3.4	61.7± 2.4	55.2± 1.9
	Stem	53.1± 2.2	55.5± 3.4	53.8± 2.4	54.0± 1.9	59.2± 2.6	54.7± 0.7
	Leaf	53.5± 1.1	57.2± 2.1	56.6± 2.0	55.7± 1.2	58.1± 4.1	57.4± 2.1

Note: All data shown were mean ±S.D. for three independent replicates.

3.1 The formaldehyde purification capability of each part of the plants

When different parts of plants were exposed to the formaldehyde environment, the change in concentration of formaldehyde in the glass chamber is shown in Fig. 3.

The experimental results showed that both Pothos and sacred lily could effectively purify formaldehyde. The efficiency of removal of formaldehyde by Pothos was higher than that of sacred lily, reaching 0.221 $mg \cdot m^3 \cdot h^{-1}$ and 0.168 $mg \cdot m^3 \cdot h^{-1}$, respectively, which was basically consistent with the results of Xu et al. (2011) During the 7.5-hour experimental period, the rate of purification of formaldehyde of both plants could reach more than 75%. The efficiency of the removal of formaldehyde by the underground part and the aerial part of Pothos was 0.152 $mg \cdot m^3 \cdot h^{-1}$ and 0.163 $mg \cdot m^3 \cdot h^{-1}$, respectively, and the rate of purification of formaldehyde was 68.6% and 73.8%, respectively. The efficiency of the removal of formaldehyde by the underground part and the aerial part of sacred lily was 0.136 $mg \cdot m^3 \cdot h^{-1}$ and 0.131 $mg \cdot m^3 \cdot h^{-1}$, respectively, and the rate of purification of formaldehyde was 61.1% and 58.9%,

respectively. Unlike existing studies that generally concluded that the purification capacity of the underground part of plant was stronger than that of the aerial part, no obvious difference in the capability of different parts to purify formaldehyde was identified in this experiment. The ratio of volume of plants and glass chamber, environmental conditions, plant species, age of plants and other factors could be related to the differences. The stems and leaves of plants were separated from the aerial parts with pieces of aluminum foil. The experimental results showed that the performance of the aerial parts of plants to purify formaldehyde was not only dependent on the leaves, but the stems could also purify formaldehyde. The efficiency of the removal of formaldehyde by the Pothos stems and leaves was 0.089 $\mathrm{mg} \cdot m^3 \cdot h^{-1}$ and 0.165 $\mathrm{mg} \cdot m^3 \cdot h^{-1}$, respectively, and the rate of purification of formaldehyde was 40.0% and 74.4%, respectively. The efficiency of the removal of formaldehyde by the stems and leaves of sacred lily was 0.137 $\mathrm{mg} \cdot m^3 \cdot h^{-1}$ and 0.160 $\mathrm{mg} \cdot m^3 \cdot h^{-1}$, respectively, and the rate of purification of formaldehyde was 61.6% and 71.8%, respectively.

During the whole experiment, the efficiency of removal of the formaldehyde by different parts of the plants showed two different trends. The first was that the efficiency of removal gets highest in the initial period of time. This could be owing to the higher concentration of formaldehyde in the chamber during the initial period, which positively stimulated the capacity of plants to purify formaldehyde. The efficiency of removal by the whole plant, the underground part and the aerial part of Pothos, and the whole plant, the aerial part and the stem of sacred lily all showed this trend. The second was that the efficiency of removal was relatively low during the initial period of time, and as the experiment progressed, the efficiency of removal gradually reached its maximum value. The adaptation to formaldehyde environment as the experiment progressed could have accounted for this. The efficiency of removal of the leaves and stems of Pothos, and the underground parts and leaves of sacred lily all showed this trend. The first trend was similar to the change exhibited in the study of Kondo et al. (2005) and the second was the same as the change observed in the study of Kim et al (2011). The experimental results showed that the efficiency of removal of leaves was primarily affected by adaptability, and that of stems was related to species.

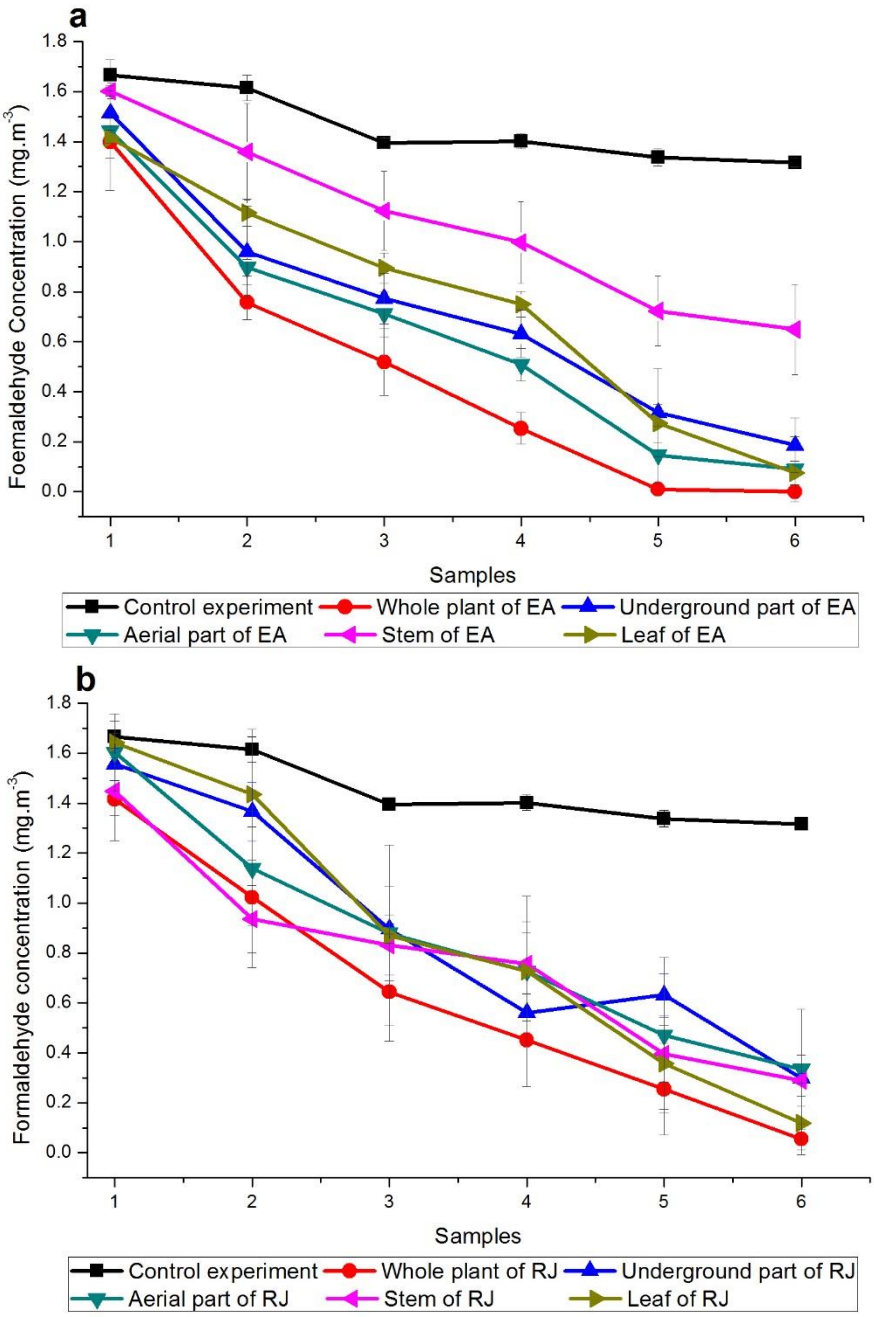

Fig. 3. Capacity of each part of the plants to purify formaldehyde (EA, Epipremnum aureum; RJ, Rohdea japonica). a Capacity of each part of *Epipremnum aureum* to purify formaldehyde. b Capacity of each part of *Rohdea japonica* to purify formaldehyde. Bars indicated formaldehyde concentration in samples performed every 1.5 hours. All data shown were mean±S.D. for three independent replicates.

3.2 The relative correlation of the capacity of the aerial part, stems and leaves of plants to purify formaldehyde

As Fig. 4 showed, the amount of formaldehyde purified by the aerial part, stems and leaves of Pothos were 1.225 $mg \cdot m^3$, 0.667 $mg \cdot m^3$, and 1.24 $mg \cdot m^3$, respectively,

and the amount of formaldehyde purified by the aerial part, stems and leaves of the sacred lily were 0.981 $mg \cdot m^3$, 1.027 $mg \cdot m^3$, and 1.197 $mg \cdot m^3$, respectively. The amount of formaldehyde purified in the aerial parts of plants was not equal to that in the leaves, nor is it equal to the sum of amount of formaldehyde purified in the stems and leaves. The amount of formaldehyde purified in the leaves of Pothos was approximately twice the amount of formaldehyde purified in the stems, coverage of stems by leaves might account to it. The amount of formaldehyde purified in the aerial parts of Pothos was larger than that of stems and little smaller than that of leaves. However, the amount of formaldehyde purified in the aerial parts of the sacred lily was less than that of the stems and leaves, and the leaves purifies the highest amount of formaldehyde. This showed that the stems and leaves of the sacred lily had a competitive relationship with the purification of formaldehyde. It was consistent with the research of Aydogan and Montoya (2011), in which the capability of the whole plant to purify was less than those of the aerial and underground parts. Generally, the stems could purify formaldehyde, and the capacity of the aerial parts of plants to purify formaldehyde was not equal to that of the leaves. The relative correlation between the aerial parts and leaves was related to plant species and factors, such as plant physiological status, formaldehyde concentration, and environmental parameters. The purification performance of stems was related to factors, such as plant species and the area exposed.

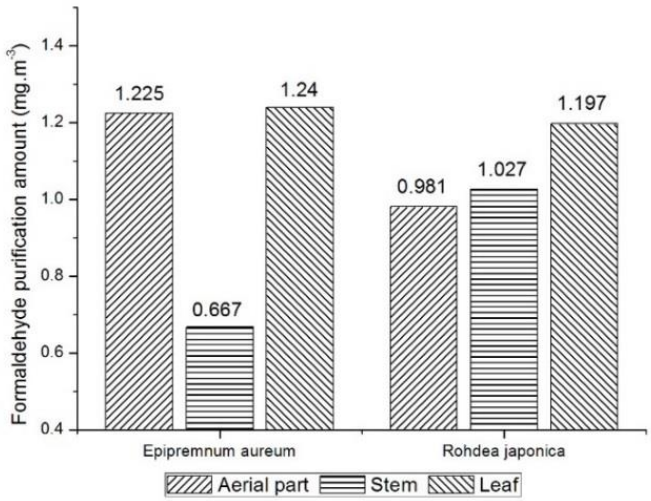

Fig. 4. Formaldehyde purification capacity of the aerial part, stems and leaves of plants. All data shown were mean for independent replicates.

3.3 Change in CO_2 concentration

The change in CO_2 concentration in the glass chamber during the experiment is shown in Fig. 5.

Plants could reduce the concentration of CO_2 in the environment through photosynthesis (Sevik et al., 2015). When CO_2 was the only pollutant, Mehmet Cetin and Hakan Sevik (2016) tested the capacity of five types of plants to purify CO_2, including *Ficus elastica*, *Yucca smalliana* fern., basil (*Ocimum basilicum*), Gloxinia (*Sinningia*), and croton (*Codiaeum variegatum* (L.) A. Juss.), in an airtight chamber, and the experimental results showed that these five plants could effectively reduce the internal concentration of CO_2. Moreover, Irga et al. (2013) showed that *Syngonium podophyllum* Schott could effectively reduce the CO_2 concentration in a glass chamber under both hydroponic and soil culture. When both formaldehyde and CO_2 were presented in the chamber, a slightly decrease could be found in the concentration of CO_2 in the control experiment, which might be caused by the adsorption by the chamber. However, it could be seen from Fig. 5a that when the underground part and the stem of Pothos and the sacred lily were exposed to the chamber, the CO_2 concentration was almost constant. Moreover, as shown in Fig. 5b, the CO_2 concentration in the chamber increased considerably when the whole plant, the aerial part, and the leaves of Pothos and the sacred lily were exposed to the chamber. The difference in trends of the change in CO_2 concentration could be related to whether the plant leaves were exposed to formaldehyde. The stomata on the leaves were the main channels for plant photosynthesis to absorb CO_2 and respiration to release CO_2. Formaldehyde directly entered the plant through the open stomata on the surface of its leaf or penetrated into the plant through the epidermis covered by the cuticular wax (Kvesitadze et al., 2006). Part of the formaldehyde that entered the plant was oxidized to CO_2 by methylotrophic bacteria (Yurimoto et al., 2015), entered the Calvin cycle to become the carbon source for photosynthesis, and was finally transformed into amino acids to become the nutrients needed for plant growth (Peterson et al., 2016). It was inferred from Fig. 5b that the entry of CO_2 from the oxidation of formaldehyde into the Calvin cycle reduced the capacity of plants to absorb CO_2 from the environment, and with the addition of respiration, the CO_2 concentration in the glass chamber showed an upward trend.

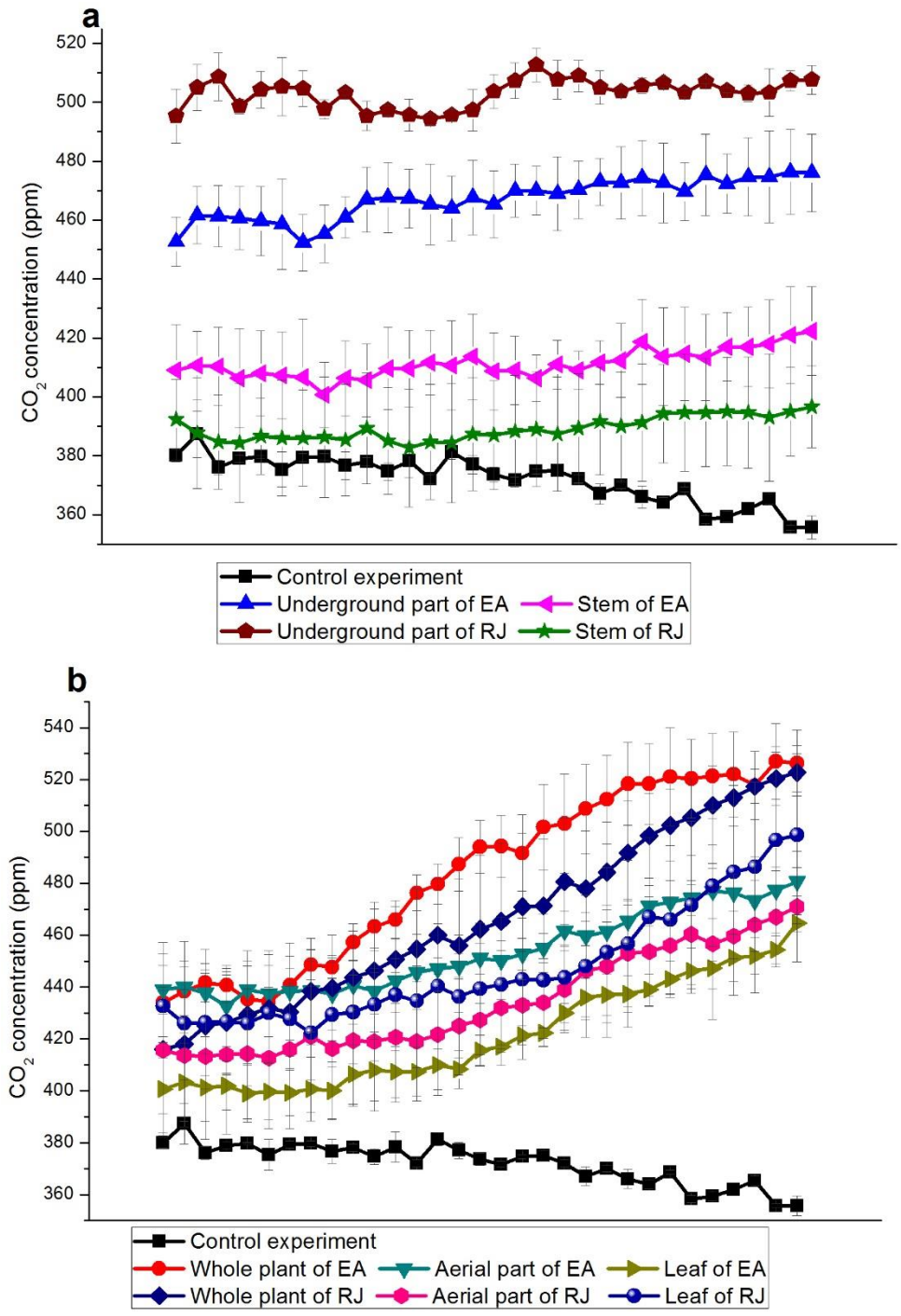

Fig. 5. Change in CO_2 concentration (EA, Epipremnum aureum; RJ, Rohdea japonica). a Without leaf exposed to formaldehyde. b With leaf exposed to formaldehyde. All data shown were mean ±S.D. for three independent replicates.

3.4 Correlation between the concentration of CO_2 and formaldehyde

When the whole plant, aerial parts and leaves of plants were exposed to an environment of formaldehyde, the correlation between CO_2 and formaldehyde concentrations is shown in Fig. 6.

When the plant leaves were exposed to an environment of formaldehyde, according

to the data fitting results, there was a quadratic function relationship between the concentration of CO_2 and formaldehyde(R^2>0.97), and as the concentration of formaldehyde decreased during the experiment, the CO_2 concentration gradually increased. So we postulate that in a similar research experiment on the capacity of plants to purify formaldehyde in glass chamber, the change in CO_2 concentration could be used to reflect the degree of the process of plant purification of formaldehyde.

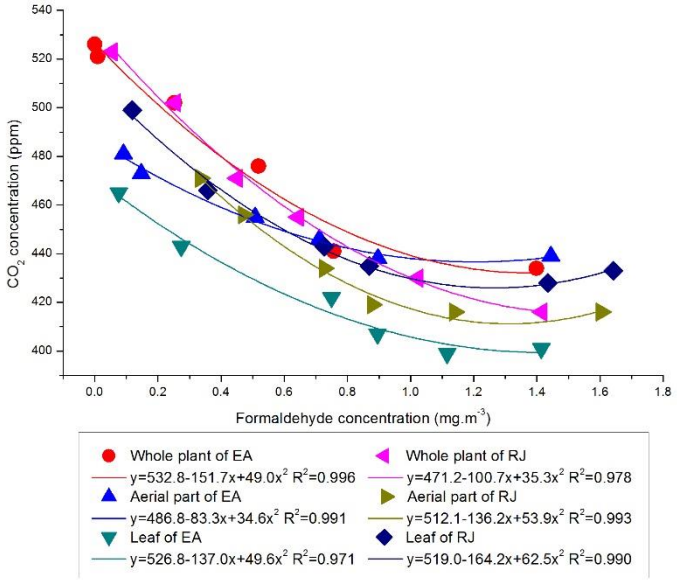

Fig. 6. Relationship between the concentration of CO_2 and formaldehyde (EA, Epipremnum aureum; RJ, Rohdea japonica). All data shown were mean ±S.D. for three independent replicates.

4. Conclusion

A fumigation experiment was conducted to verify the capability of plants stems to purify formaldehyde, and the correlation between the concentration of formaldehyde and CO_2 was investigated to further explore the mechanism of phytoremediation. The study reached the following conclusions:

(1) Both Pothos and sacred lily could effectively purify formaldehyde. The capacity of former to purify formaldehyde was stronger than that of the latter, and the efficiency of removal of formaldehyde was 0.221 $mg \cdot m^{-3} \cdot h^{-1}$ and 0.168 $mg \cdot m^{-3} \cdot h^{-1}$, respectively. The rate of purification of both could reach more than 75%.

(2) The stems of plants could remediate formaldehyde indeed. The efficiency of removal of formaldehyde of the stems of Pothos and sacred lily was 0.089 $mg \cdot m^{-3} \cdot h^{-1}$ and 0.137 $mg \cdot m^{-3} \cdot h^{-1}$, respectively, and the rate of the purification of formaldehyde was 40.0% and 61.6%, respectively. Both were related to plant species and the latter was affected by other factors like exposed area.

(3) The capability of aerial part of plant to purify formaldehyde was not equal to that of the leaves, nor the sum of the capacity of the stems and leaves to purify this compound. The relative correlation between the performance of aerial parts to purify formaldehyde and leaves was related to factors such as plant species.

(4) When plant leaves were exposed to an environment of formaldehyde, the formaldehyde absorbed by the plant was converted into CO_2 in the plant, which weakened its capacity to absorb CO_2 from the environment. With the additional presence of respiration, the concentration of CO_2 in the glass chamber increased. The increase in CO_2 concentration positively correlated with the amount of plant formaldehyde purified, and this change could be used to reflect the progress of the process of purification of formaldehyde by the plant.

Declarations

- **Ethics approval and consent to participate**

Not applicable.

- **Consent for publication**

Not applicable.

- **Availability of data and materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

- **Competing interests**

The authors declare that they have no competing interests.

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- **Authors' contributions**

LJZ contributed to investigation, methodology, data curation and writing-original draft. DW contributed to investigation, methodology and writing - review & editing. LY contributed to writing-original draft, data curation and investigation. YPY contributed to conceptualization, supervision and project administration. All authors read and approved the final manuscript.

- **Acknowledgements**

Not applicable.

- **Authors' information (optional)**

Not applicable.

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Figures

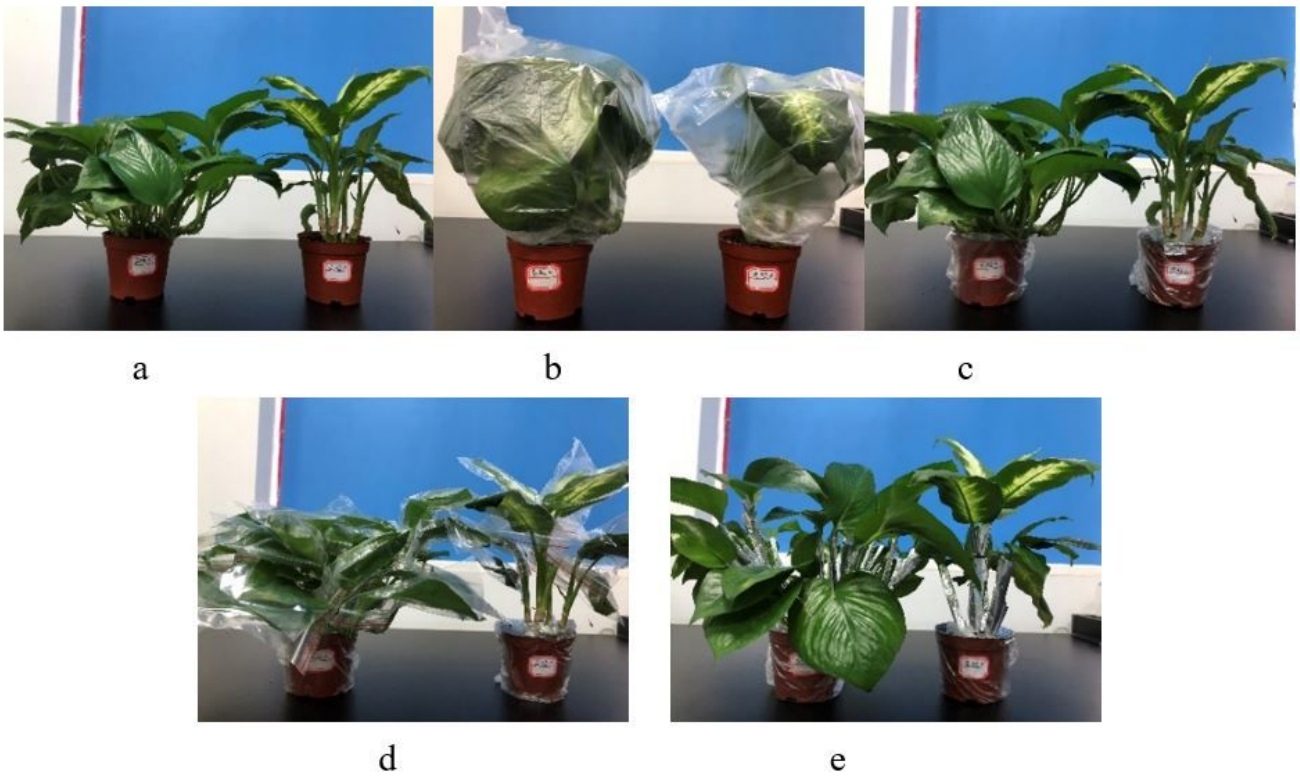

Figure 1

Plant treatment method. a whole plant exposed to formaldehyde. b underground part exposed to formaldehyde. c aerial part exposed to formaldehyde. d stems exposed to formaldehyde. e leaves exposed to formaldehyde.

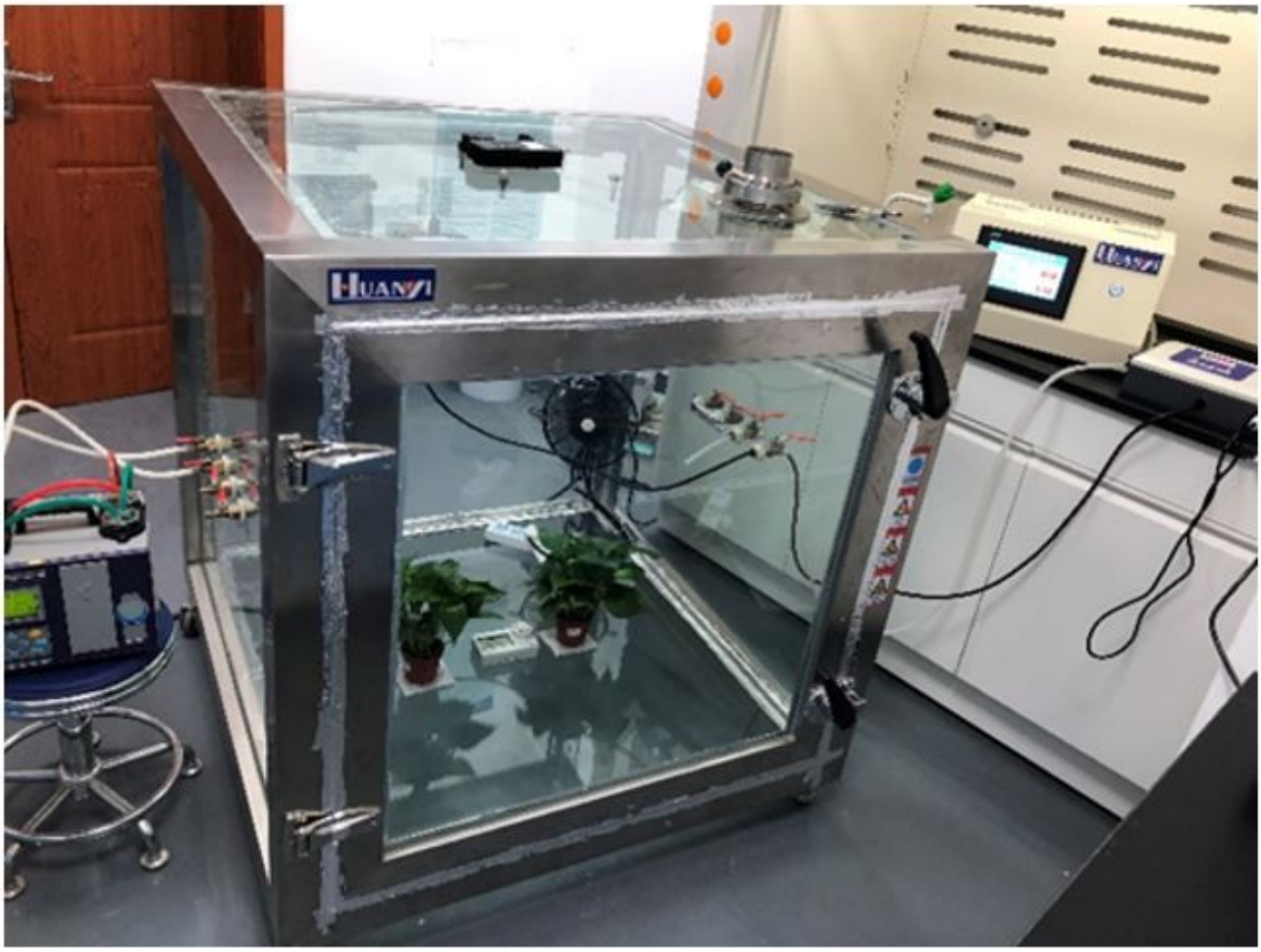

Figure 2

Experimental system

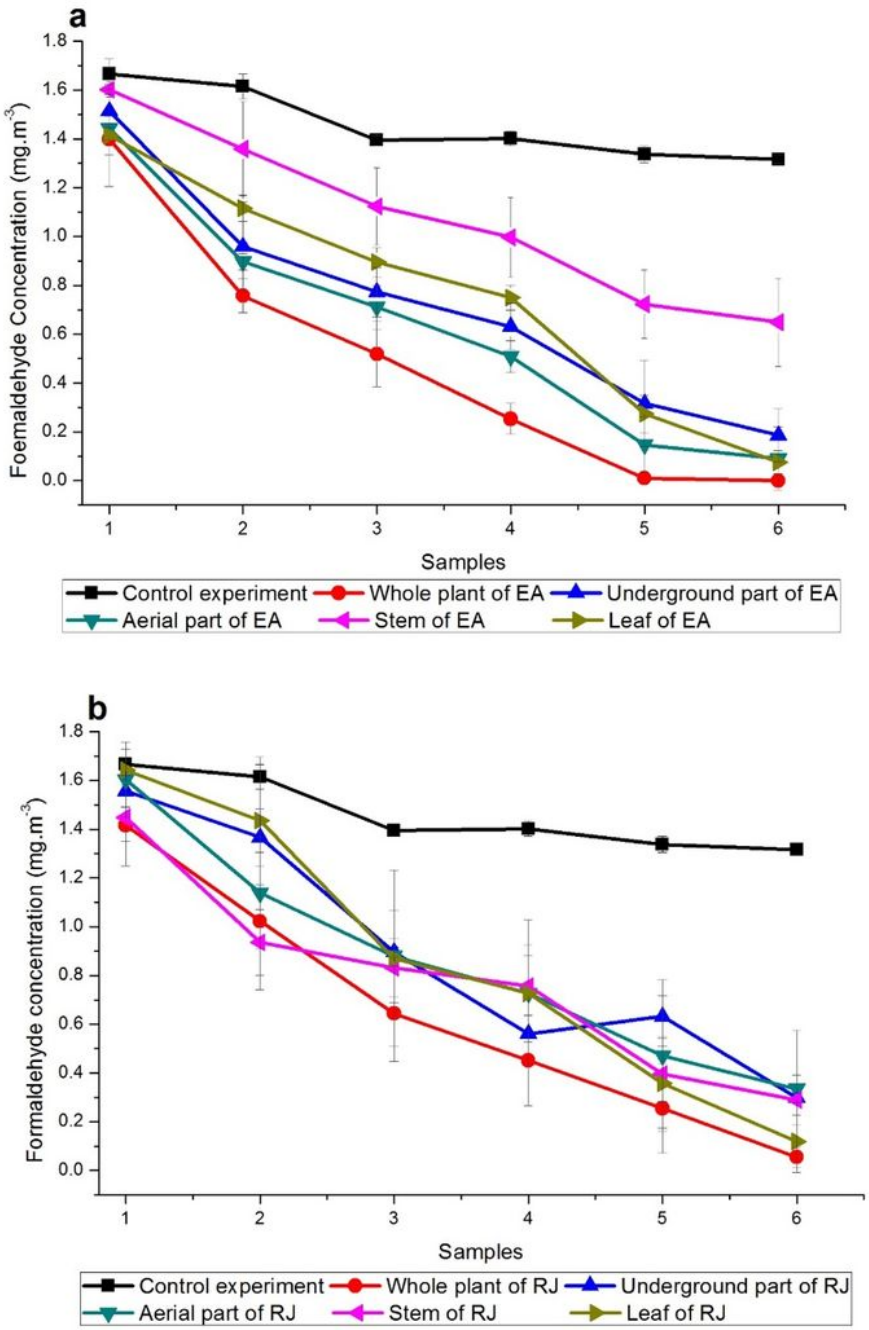

Figure 3

Capacity of each part of the plants to purify formaldehyde (EA, Epipremnum aureum; RJ, Rohdea japonica). a Capacity of each part of Epipremnum aureum to purify formaldehyde. b Capacity of each part of Rohdea japonica to purify formaldehyde. Bars indicated formaldehyde concentration in samples performed every 1.5 hours. All data shown were mean±S.D. for three independent replicates.

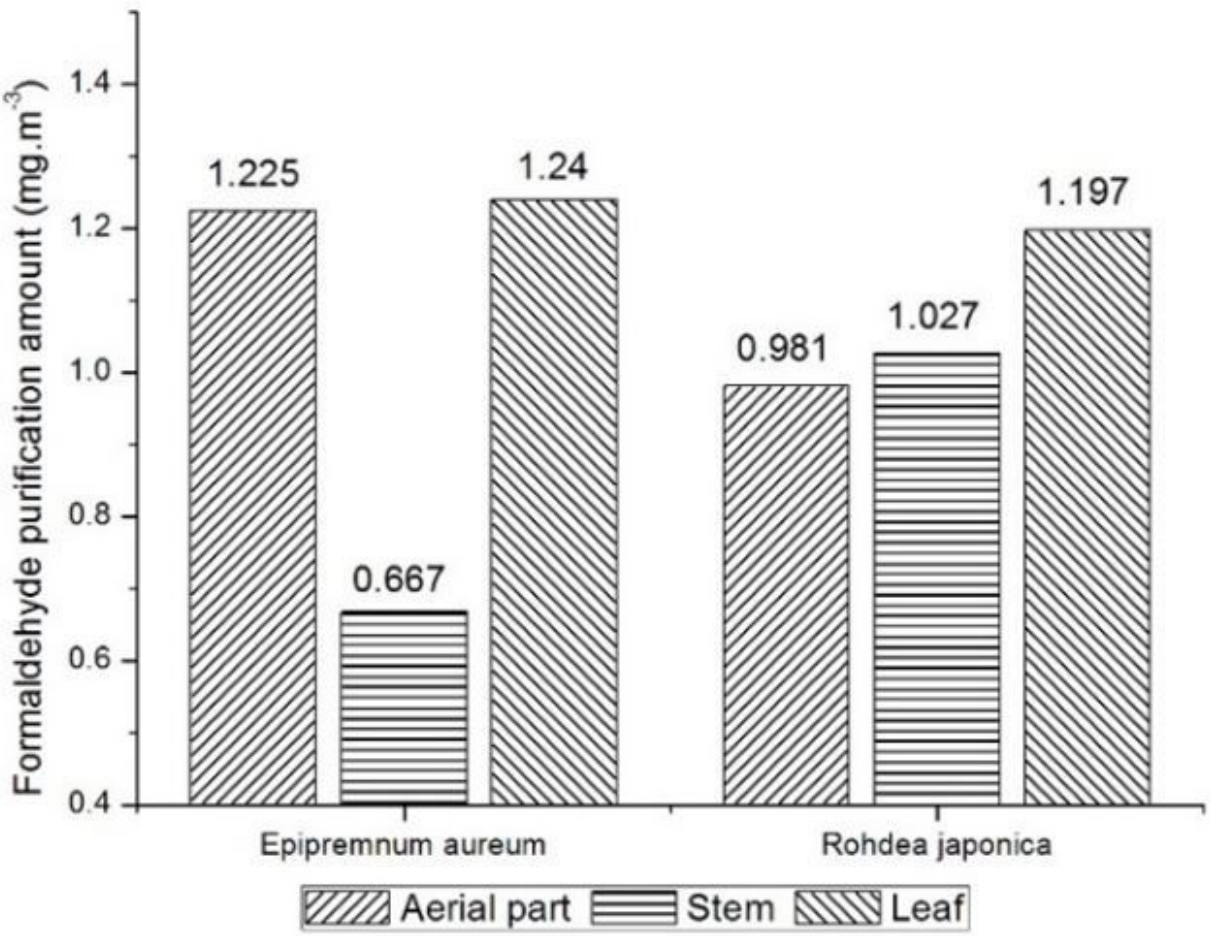

Figure 4

Formaldehyde purification capacity of the aerial part, stems and leaves of plants. All data shown were mean for independent replicates.

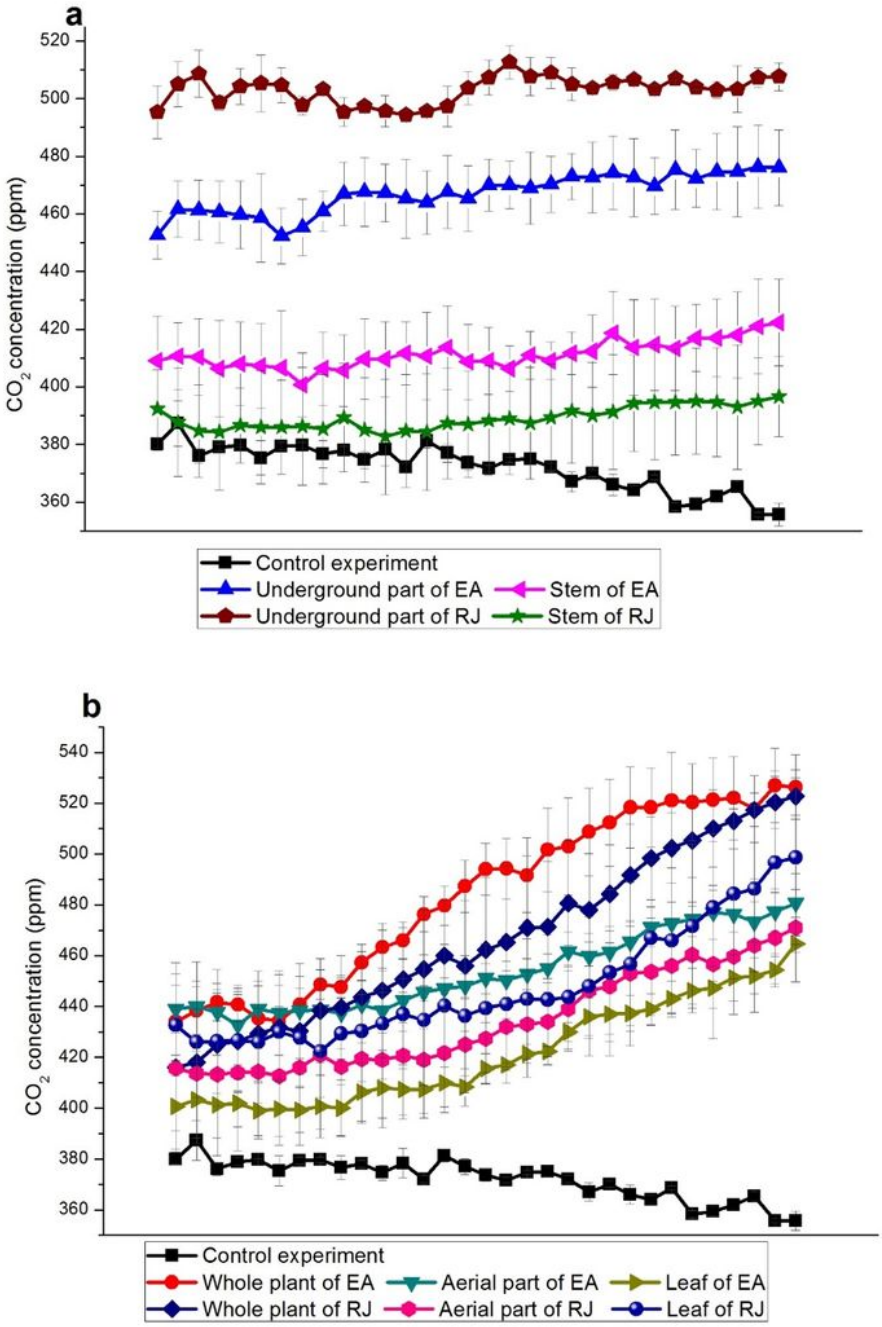

Figure 5

Change in CO2 concentration (EA, Epipremnum aureum; RJ, Rohdea japonica). a Without leaf exposed to formaldehyde. b With leaf exposed to formaldehyde. All data shown were mean ±S.D. for three independent replicates.

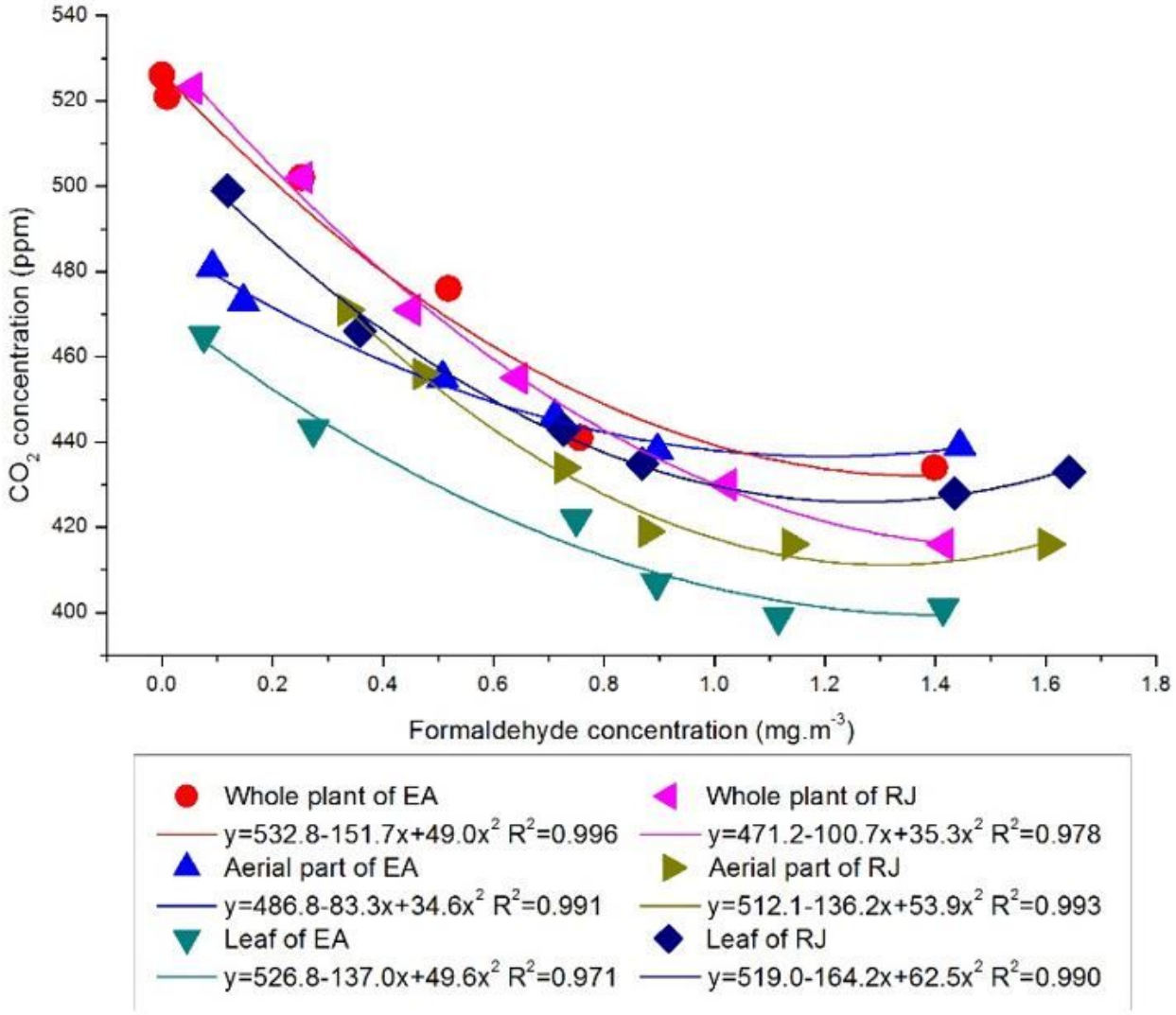

Figure 6

Relationship between the concentration of CO2 and formaldehyde (EA, Epipremnum aureum; RJ, Rohdea japonica). All data shown were mean ±S.D. for three independent replicates.