

Phytoremediation of Formaldehyde from Indoor Environment by Ornamental Plants: An Approach to Promote Occupants Health

Abstract

Background: Formaldehyde is a common hazardous indoor air pollutant which recently raised public concerns due to its well-known carcinogenic effects on human. The aim of this study was to investigate a potted plant-soil system ability in formaldehyde removal from a poor ventilated indoor air to promote dwellers health. **Methods:** For this purpose, we used one of the common interior plants from the fern species (*Nephrolepis obliterated*), inside a Plexiglas chamber under controlled environment. Entire plant removal efficiency and potted soil/roots contribution were determined by continuously introducing different formaldehyde vapor concentrations to the chamber (0.6–11 mg/m³) each over a 48-h period. Sampling was conducted from inlet and outlet of the chamber every morning and evening over the study period, and the average of each stage was reported. **Results:** The results showed that the *N. obliterated* plant efficiently removed formaldehyde from the polluted air by 90%–100%, depending on the inlet concentrations, in a long time exposure. The contribution of the soil and roots for formaldehyde elimination was 26%. Evaluation of the plant growing characteristics showed that the fumigation did not affect the chlorophyll content, carotenoid, and average height of the plant; however, a decrease in the plant water content was observed. **Conclusions:** According to the results of this study, phytoremediation of volatile organic compound-contaminated indoor air by the ornamental potted plants is an effective method which can be economically applicable in buildings. The fern species tested here had high potential to improve interior environments where formaldehyde emission is a health concern.

Keywords: Formaldehyde, indoor air pollution, phytoremediation, potted plant

Introduction

Nowadays, indoor air pollution has become a major concern due to its known harmful effects on human health.^[1] With the onset of the energy crisis, changes in the building's design owing to energy-efficient strategy, a confined space for house and workplace is provided which reduce the air exchange rate (AER) and increase indoor air pollution.^[2-6] The environmental protection agency (EPA) of the United States has mentioned that indoor air pollutants can be found at a higher concentration than outdoor.^[7] However, monitoring and regulating of indoor air pollutants have been neglected behind the outdoor air pollutants.

One of the major indoor air pollutants is formaldehyde with a chemical formula of HCHO. It is one of the most well-known volatile organic compounds (VOCs) associated with indoor air pollution which is attracted public attention worldwide due to

its adverse health effects.^[3,8] Formaldehyde is a colorless gas with a strong odor which is soluble in water, as well as it can be smothering at room temperature.^[7] The main indoor sources of formaldehyde are from furniture and materials which widely used in the construction of inside the house such as fiberboard and laminated wood, carpets, curtains, rubber, oil-based paint, adhesive materials, cosmetics, electronic devices, and paper products.^[2,9,10] Furthermore, people are exposed to formaldehyde from combustion sources such as tobacco smoke, gas, petrol, and solid fuels.^[11] Typically, in newly built or refurbished residences the levels of formaldehyde are often so high compared to old buildings.^[12,13] Formaldehyde levels generally decrease with the product age,^[2,11,14] however, according to Wolverton, 10 years is too much time to breath this carcinogenic chemical into lungs.^[15]

The World Health Organization has reported that the health effects associated with acute exposure to indoor

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concentrations of formaldehyde include eye irritation, eye redness, frequent blinking, and irritation in the upper respiratory system.^[16] Furthermore, it has been reported that formaldehyde can cause long-term effects such as cancer, leukemia in children, premature birth, low birth weight, congenital anomalies, genotoxicity, and Alzheimer's disease. EPA considers formaldehyde as a probable human carcinogen (Group B1).^[2,7,17] It has been suggested that occupational exposure to formaldehyde may increase the risk of nasopharyngeal carcinoma. Thus, physician working in the operating theater remains alert to formaldehyde hazards among health-care workers.^[18]

At present, there are some techniques for eliminating formaldehyde from the indoor air such as biological methods, adsorption on activated carbon fibers, photocatalytic oxidation, and biofiltration; nevertheless, none of them are fully satisfactory due to low concentrations as well as the volatile characteristic of this chemical.^[19-22] Beside this, increasing the ventilation rate is difficult and not economical for public. Phytoremediation has attracted much consideration in recent decades probably due to its environmental, economic and social benefits. In addition, it is potential to help zero emission in both traditional and new buildings.^[23,24]

Numerous plants can remove formaldehyde from indoor air.^[2,25,26] Plant leaves uptakes formaldehyde through stomata and the cuticle, and younger leaves readily absorb the formaldehyde vapors.^[3,27] Besides, some researches have shown that soil microorganisms are capable of degrading pollutants and this degradation is suggested to be encouraged by root exudates.^[28-30] When Formaldehyde is absorbed, one part of it is oxidized into carbon dioxide in the Calvin cycle while the other is combined into the organism such as amino acids, lipids, free sugars, organic acids, and cell-wall components.^[3,10]

This study was conducted with the aim of determination of formaldehyde removal efficiency from indoor air by a potted plant using a pilot scale chamber made of Plexiglas. For this purpose, *Nephrolepis obliterated* plant (sword fern) from Lomariopsidaceae's family was used. This plant is hugely available throughout Iran and can be acclimatized with the indoor environment. In this work, formaldehyde was used as a common VOC contaminant in indoor, but these methods can be practical to other VOCs.^[31]

Methods

Test chamber and experimental setup

Experiments were conducted in a Plexiglas chamber with a volume of 375 L (84 cm length × 62 cm width × 72 cm height) which was made perfectly air-tight. A door was provided in front of the chamber which was sealed by adhesive foam-rubber insulation tape and adjustable metal clips. Two PC fan (Model: 350 XA, 2.03P4) fixed inside the chamber to provide complete mixing of fumigated air.

The temperature and relative humidity (RH) of the chamber were controlled by a digital thermometer [Figure 1]. The light intensity supposed to be natural indoor environment light which was measured around the chamber in five directions (west, east, north, south, and above the chamber) four times a day over experimental period using a YF-170 digital light meter (Tenmars Electronics Co., Ltd, Taiwan).

Figure 1 shows the experimental setup for this study. The system was consisted of three main parts including (I) the chamber for placement of plants to contact with air stream containing formaldehyde; (II) air pump connected to a flow meter and impingers system which supplies air, water vapor and formaldehyde gas mixture with desired concentration; and (III) sampling system from chamber inlet and outlet for analysis of formaldehyde concentration that include a vacuum pump, flow meter, dual impingers containing liquid absorbent. Stainless steel and silicon tubing were used to connect the system compartments.

Formaldehyde measurement

Formaldehyde vapor was introduced to the chamber by a gas bubbler containing 37% formaldehyde solution.^[2] Air was provided by a vacuum pump (Model: ACO-5504, 5w), and the air flows were measured by needle valve glass flow meter (CT Platon, France). In addition, air stream was passed through an activated carbon column to adsorb any potential contaminants. The formaldehyde concentration was measured according to the NIOSH-3500 method, a visible absorption spectrometry technique, using a DR5000 Spectrophotometer (DOC022.53.00654-HACH Lange, Co. USA). This is the most sensitive formaldehyde analysis method capable of detecting as low as 0.1 ppm which is best suited for the determination of formaldehyde in the environmental samples.^[32]

Plant materials

In this research, one of the fern species from Lomariopsidaceae's family, Kimberly Queen Fern (*N. obliterated*) was used. This species was selected because they are one of the common indoor plants used in Iran as well as they are economical and easily accessible. Pots of the plants were bought from commercial distributors (flower

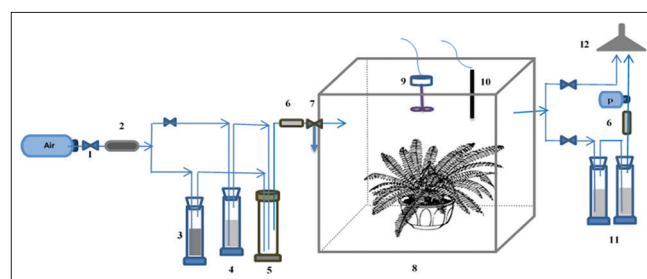


Figure 1: Schematic of the experimental setup: (1) air pump, (2) activated carbon column, (3) formaldehyde solution (37%) vessel, (4) humidifier vessel, (5) mixing vessel, (6) flow meter, (7) gas sampling port, (8) test chamber, (9) air mixing fan, (10) temperature and humidity sensor, (11) sampling impingers, (12) extraction

market) and kept under laboratory condition at least for a month for acclimatization and watered every 2 days.

Experimental procedures

To investigate formaldehyde removal potential of the plants, experimental procedures were designed and carried out in four stages: (I) “empty chamber tests” without potted plants with a known amount of formaldehyde inlet to determine any combined chamber losses due to (e.g. leakage, absorption and chemical reactions); (II) “whole plant absorption tests” including soil and areal part of the plant by introducing different formaldehyde concentrations to the chamber; (III) “darkness test” to distinct light intensity effects on formaldehyde removal efficiency of the plants; and (IV) soil absorption test (including roots).

Empty chamber losses were assessed before the other above-mentioned experiments. The chamber’s combined loss was tested with inlet formaldehyde concentration ranges of 4.5–7 mg/m³ under two different RH of 40% and 80% for 6 days. Then, two pots of the plants with an average height of 48.4 cm areal part and 17 cm of root part (pot and soil) were placed inside the chamber, to provide sufficient leaf area for optimum air purification. The plants were continuously exposed to formaldehyde vapors with inlet concentrations ranging from 0.5 to 12.0 mg/m³.^[3] The tests for each concentration were carried out 2 days. Among the exposure periods, sampling from inlet and outlet of the chamber was performed every early morning and late evening (4 times for each inlet concentration), and the averages of them were reported. It should be noted that the plant rested for 24 h before starting the next concentration test.

Darkness tests were taken place by covering whole the chamber (entire plants [EPs] inside it) with a black cloth. This test was also carried out for 2 days but only for one of the inlet concentration which laid the median of tested concentrations range (e.g., 4.7 mg m⁻³). Hereafter, aboveground part of the two other plants with the same pot and areal sizes of those used in the previous tests was surgically removed and the pots containing only soil and roots were put back into the chamber, and then experiments were repeated for an inlet concentration of 5.23 mg/m³ for 2 days.^[3,27] A new set of plants were used in this stage of experiments to avoid confounding errors as a result of prior formaldehyde exposure.

Plant morphology and physiology

Key characteristics of the plants including morphology and physiology (plant height, leaf area, dry weight, fresh wet weight, chlorophyll content and carotenoid) were evaluated before and after fumigation to assess the effects of formaldehyde on these features as plant growing indices. Chlorophyll content and carotenoid were determined according to Lichtenthaler and Wellburn method.^[33] For determination of the individual leaf area, the leaves were counted and categorized as large, medium, and small. Six samples were taken from each category, and their area was

measured by a leaf area meter (ΔT Area meter MK2). The average surface area for each category was multiplied by the number of the leaves counted in each category, and the total surface area of each plant was calculated.^[2] Furthermore, plant height was measured before and at the end of the experiments. The fresh wet weight of the leaves was determined by the analytical scale and reported in mg/cm² of leaf area. Thereafter, the leaves dry weight was measured by drying them in the oven under 80°C for 24 h, weighing out by an analytical scale and reporting in mg/cm² of leaf area.

Data analysis

The concentration of formaldehyde in the air flowing to the chamber (C_T) was calculated using the following formula:

$$C_T = (C_2 \cdot Q_2) / (Q_1 + Q_2)$$

Where C_2 is formaldehyde concentration in the air bubbled from the impinger containing formaldehyde solution, Q_1 is the air flow needs for dilution and Q_2 is the air flow passing through the formaldehyde solution [Figure 1]. The removal efficiency was calculated using the formaldehyde concentrations entering and leaving the chamber as follow:

$$RE = \left(1 - \frac{C_{out}}{C_{in}} \right) \times 100$$

The elimination capacity (EC), the amount of formaldehyde vapor removed per unit surface area of plant leaf (mg/m²/h), was calculated as follow:

$$EC = Q(C_{in} - C_{out}) / S_L$$

Where C_{in} and C_{out} are the inlet and the outlet concentrations of formaldehyde (mg/m³), respectively, Q is the inlet polluted air flow (m³/h) to the chamber and S_L is total leaf area (m²). Finally, the statistical analyses, drawing the graphs and tables were carried out under Excel software.

Results

Averages of temperature inside and outside the reactor during the experiments were 26.99°C ± 0.84°C and 26.84°C ± 0.81°C, and those for RH were 78.94%±2.25% and 18.885 ± 1.54%, respectively. Background light approaching to the chamber coordinates during daytime was measured and their averages at the measuring time and for whole the study period were calculated. The light intensity was 1795.56 ± 259.29 Lux. There was a difference between the RH inside and the outside the chamber. For the temperature and light intensity, the difference was negligible.

Table 1 represents the average outlet (C_{out}) formaldehyde concentrations achieved during the experiment with *N. obliterata* plant under various inlet formaldehyde concentrations (C_{in}). Total reduction of formaldehyde by the EP, and by root and soil with and without considering chamber combined losses were also examined. The empty chamber’s combined losses tested with inlet formaldehyde

concentration ranges of 5.01–6.11 mg/m³ under two different RH of 40% and 80% were 5.11% and 14.04%, respectively. Thus, in spite of reporting whole removal efficiency, the loss of 14% was deducted from all the results achieved during the experiments and reported as net removal efficiency. Due to a limitation in flow rate for keeping the chamber AER near to 1 time per hour (1 n/h), it was impossible to reduce the chamber RH down to 75%, so we tried to carry out the experiments under an RH of 80% ±5%. EP removal efficiency was examined with ascending inlet formaldehyde concentrations ranging from 0.6 to 11.2 mg/m³, each for 2 days and the averages of the results were reported [Table 1].

Formaldehyde removal efficiency by potted *N. obliterata* plant-soil system with and without chamber combined losses, as affected by different inlet formaldehyde concentrations are shown in Figure 2a. About 81%–100% of formaldehyde was removed from the polluted air flown into the chamber. The EP net removal efficiencies were calculated by subtracting the chamber combined losses from the whole removal percentages. Figure 2b shows the formaldehyde EC of the EP without and with considering the chamber losses.

Additional experiments were conducted under a thoroughly dark environment to compare the removal efficiency under light versus dark conditions. The plant was exposed to a formaldehyde concentration of 4.7 mg/m³ for 2 days in a dark environment. The effluent concentrations were measured in the morning and evening of each day, and the average of the results was reported in Table 1.

The results of plant growing characteristics and their percentage changes after contact with the pollutant were represented in Table 2. The most important effects of formaldehyde on the plant were a reduction in the plant wet weight and water content which were reduced by 27%

and 5%, respectively. However, the tested concentration of formaldehyde could not abort the plant growth, whereas the chlorophyll content, carotenoid level, and average height of the plants were increased by 9.58%, 21.79%, and 6.46%, respectively, during the fumigation.

Discussion

The results of this study showed that *N. obliterata* plant-soil system considerably removed formaldehyde vapors from the polluted air during continues long time fumigation. As shown in Figure 2, about 90%–100% of formaldehyde was removed from the polluted air flown into the chamber with an inlet concentration range of 0.63–9.73 mg/m³. However, increasing the inlet concentration to 11.09 mg/m³ within 48 h the removal efficiency was decreased. This shows that the plant could not tolerate with concentrations higher than about 10 mg/m³. By increasing the inlet formaldehyde concentration and by extending the exposure time the EC was increased. This increase in the elimination rate might be occurred by attribution of plant and soil surface, roots, degradation by microorganisms or bacterial adaption and uptake by the stomas of plant.^[27,33,34] It has been suggested that when formaldehyde enters the plant through the leaves is firstly detoxified by oxidation then transformed into CO₂ and built into the plant material via the Calvin cycle.^[35] Depletion of formaldehyde like other VOCs in the chamber which results in slower diffusion rate into the plant is likely to be happened.^[27] However, a breakpoint was attained with an inlet concentration of 9.7 mg/m³. Whereas experiments with an inlet concentration of 11.09 mg/m³, the EC was not promoted.

In a similar study but with different plants, Xu *et al.* reported formaldehyde removal efficiencies of about 95% for spider plant-soil system, 53% for *Aloe vera*-soil system, and 84% for golden pothos-soil system with an inlet concentration range of 1–11 mg/m³ and at the light

Table 1: Average reduction of formaldehyde vapors achieved by air and root part of *Nephrolepis obliterate* with and without combined chamber losses

Type of test	Inlet concentration (mg/m ³)	With combined chamber losses			Without combined chamber losses			Leaf surface area (m ²)
		C out (mg/m ³)	Hole RE (%)	Whole EC (mg/m ² /h)	C out (mg/m ³)	Net RE (%)	Net EC (mg/m ² /h)	
Chamber loss at 40% RH	6.11±1.53	5.80±1.46	5.11±0.13	-	5.80	5.11	-	-
Chamber loss at 80% RH	5.01±1.93	4.28±1.59	14.04±1.38	-	4.28	14.04	-	-
Average entire plant	0.63±0.02	0.0±0	100.0±0	0.07±0.002	0.09	86.00	0.06	3.826
	1.31±0.04	0.04±0.02	97.29±1.23	0.14±0.008	0.22	83.00	0.12	3.826
	2.48±0.04	0.13±0.02	94.97±0.52	0.26±0.003	0.47	81.00	0.22	3.826
	3.40±0.16	0.19±0.01	94.39±0.56	0.35±0.026	0.67	80.00	0.30	3.826
	4.70±0.06	0.37±0.02	92.11±0.54	0.47±0.013	1.03	78.00	0.40	3.826
	7.09±0.04	0.69±0.03	90.26±0.36	0.70±0.002	1.68	76.00	0.59	3.826
	9.73±0.14	0.79±0.03	91.87±0.42	0.98±0.03	2.16	78.00	0.83	3.826
	11.09±0.07	2.09±0.04	81.14±0.47	0.99±0.02	3.65	67.00	0.82	3.826
Effect of darkness	4.70±0.06	0.80±0.05	82.97±0.83	0.43±0.001	1.46	69.00	0.36	3.826
Root zone, pot and soil	5.13±1.62	2.91±0.91	40.43±1.43	31.25±1.18	3.85	26.39	20.40	0.028*

*Pot soil surface area (m²). EC=Elimination capacity, RE=Removal efficiency, C=Carried, RH=Relative humidity

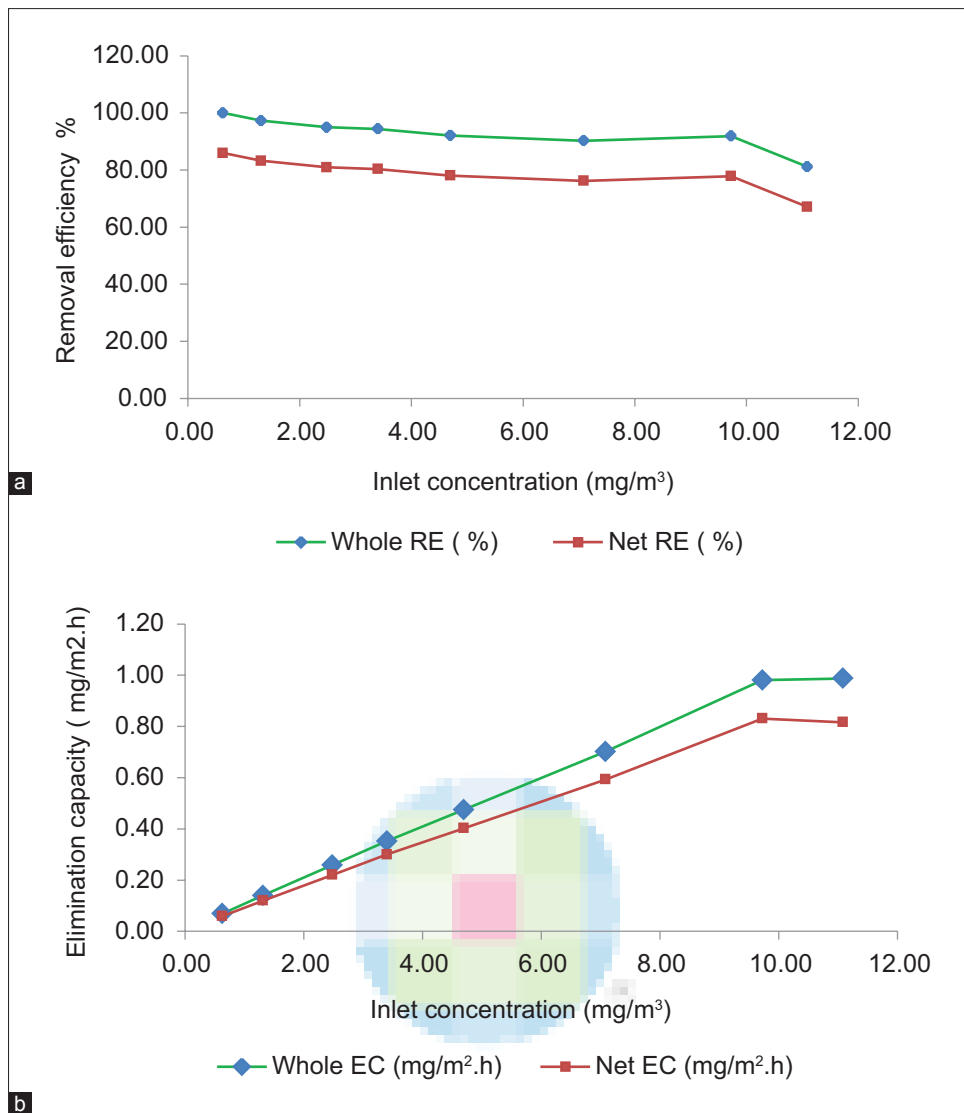


Figure 2: Formaldehyde removal efficiency (a) and elimination capacity (b) by potted *Nephrolepis obliterate* plant-soil system with (whole) and without (net) combined chamber losses, as affected by inlet formaldehyde concentrations

Table 2: Morphology and physiology changes of *Nephrolepis obliterate* during the experiments

Parameter	Unit	Before test	After test	Changes (%)
Plant average height	cm	48.38	51.50	6.46 increase
Total leaf area	cm ²	37332	39179	4.95 increase
Pot soil surface	cm ²	283.50	283.50	Constant
Total pot soil and rote volume	Liter	7.72	7.72	Constant
Leaf fresh weight	mg/cm ²	18.15	13.13	27.65 decrease
Leaf dry weight	mg/cm ²	3.31	2.89	12.58 decrease
Water content of fresh leaf	%	81.77	77.98	4.64 decrease
Chlorophyll content	mg/g	2.44	3.71	9.58 increase
Carotenoids	mg/g	5.62	7.21	21.79 increase

intensity of 240 μmol/m²/s in daytime.^[3] It has been reported that the EC by which formaldehyde is removed increases on repeated exposure which is in accordance with

our results.^[6,21,33] According to Table 1, contributions of the potted soil along with roots in the formaldehyde removal accounted for 26.39% of the total removal by EP. The capacity of potted soils for removal of formaldehyde in the present study was considerably similar to those has been already reported in the literature.^[3,34,36] This achievement may be attributed to the abundance of soil microbial activity stimulated by root exudate which acts as nutrient for the soil microorganisms.^[37] Furthermore, formaldehyde removal capacity increases by the increasing of exposed surface of potted plant.^[3]

The results also showed that similar to other studies with the same inlet formaldehyde concentration, removal efficiency under natural daylight was higher than the dark environment. Furthermore, under the same condition but in the days with higher light intensity the formaldehyde removal was higher.^[3,27] Both the stomata and cuticle in the plant leaves could be the pathways for VOC removal.

However, it is probably upon on the properties of the VOCs. Formaldehyde is a hydrophilic VOC, therefore could not diffuse through cuticle easily because it consists of lipid.^[38,39] It was, therefore, concluded that formaldehyde was taken up through the stomata as stomata are open in light and closed in darkness.^[40,41] Another explanation can be the increase in the photosynthesis and metabolism rate in daytime leads to more formaldehyde removal compared to night time.^[42,43]

It has been reported in some studies that the removal rate in the first ours is higher and decreases by the passage of time.^[44] However, this is only accurate in the batch system not in continues flow system which we applied in our study. This could be an explanation for lower removal efficiency by the EP in higher inlet concentrations after prolonged exposure in our study compared to studies which showed good formaldehyde removal efficiency at high inlet concentration for this species plant-soil system after the shorter exposure period.^[10] Increasing of the plant growing characteristics here in our study represented that formaldehyde with an inlet concentration up to 11 mg/m³ could not stop the plant growth during the fumigation tests. This is likely to be ascribed to the high resistant of the plant against formaldehyde.

Conclusions

Formaldehyde is mainly released to the indoor environment from building materials, home furnishings, and tobacco smoking. The potted *N. obliterated* plant-soil system examined in this study was talented to the removal of formaldehyde from polluted air in a long time exposure. Although the EP had more contribution in the removal of formaldehyde, the influence of potted soil and roots was considerable which can be attributed to the pollutant absorption and metabolism by the microorganisms in the soils. Formaldehyde EC by the plant increased with elevating the inlet concentrations and reached a plateau with concentrations upper than 11 mg/m³. EP showed more removal in day time rather than night time and darkness. Examination of the plant morphology and physiology showed that *N. obliterated* is very resistant to the formaldehyde, whereas long-term exposure could not stop the plant's growth. It is evident from our results that, phytoremediation is one of the most effective, economically and environmental friendly indoor air purification methods which can help improve physical and psychological health.

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Conflicts of interest

There are no conflicts of interest.

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