



Removal of Trimethylamine from Indoor Air Using Potted Plants under Light and Dark Conditions

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ABSTRACT

A phytoremediation was evaluated as a solution for mitigating the fishy odor, or trimethylamine (TMA), that occurs in the seafood industry, including fresh markets. A synthetic TMA chemical was used to generate the fishy odor, and eight types of potted plants—*Prickly pear cactus*, *Dracaena sanderiana* Sander, *Dieffenbachia camilla*, *Tradescantia spathacea*, *Peperomia magnoliifolia*, *Chlorophytum comosum*, *Cereus hexagonus* (L.) Mill., and *Scindapsus aureus*—were selected as candidates for removing TMA in light and dark conditions. The results showed that *S. aureus* had the highest TMA removal efficiency in light conditions after 72 h (> 95%). However, it had very low efficiency under dark conditions, suggesting that *S. aureus* should be placed in locations with all-day light sources. On the other hand, cactus types (*C. hexagonus* (L.) Mill. and *Prickly pear cactus*) are highly efficient at removing TMA in both light and dark conditions after 72 h (> 90%) and may therefore be more suitable for real-world environments containing both light and dark conditions.

Keywords: Fishy odor; Phytoremediation; Trimethylamine; Potted plant; Light conditions.

INTRODUCTION

Trimethylamine (TMA, $N(CH_3)_3$) is a gaseous organic compound at room temperature (Chung and Lee, 2009). It is a colorless gas with a fishy odor at low concentrations and can change to ammonia-like odor at higher concentrations (OSHA, 1994; Kim *et al.*, 2011; Boraphech and Thiravetyan, 2015). Degradation of plants and animal residuals by microorganisms, especially rotting marine animals, produce TMA (Zhu *et al.*, 1997; Chien *et al.*, 2000; Chang *et al.*, 2004; Chung and Lee, 2009). The offensive odor can affect human's health when they live in unpleasant smell area for a long period. The major adverse health impacts from inhalation exposures are breathing difficulty, irritation of upper respiratory tract, coughing, and even death (Chien *et al.*, 2000). Exposure dose is one of the factors, which affects

human health (Geraets *et al.*, 2014). The National Institute for Occupational Safety and Health (NIOSH) recommended that 10 ppm is a recommended exposure limit (REL) for TMA (NIOSH, 1981). TMA is one of air pollution problem because it causes unpleasant smell at low concentrations (Wolverton *et al.*, 1989; Ding *et al.*, 2007; Sintermann *et al.*, 2014). Hence, mitigation of odor problem can help to improve human's life. There are many methods to eliminate or reduce the odor problem, such as absorption, biofiltration, and phytoremediation. Phytoremediation is a good alternative method to solve this problem (Ding *et al.*, 2007) because this method is not expensive, environmentally friendly, highly efficient, and acceptable (Wolverton *et al.*, 1989; Wolverton, 1996; Nobel, 1999; Wood *et al.*, 2001).

Since the 1990s, purification of offensive odor chemicals using houseplants has been studied by National Aeronautics and Space Administration, or NASA (Oyabu *et al.*, 2003). After NASA's experiments, purification of these chemicals using houseplants has emerged as a well-known method. Wolverton *et al.* (1993) mentioned that these offensive odor chemicals, such as formaldehyde, xylene, and ammonia, in an indoor environment were removed by plant and soil microorganisms. Oyabu *et al.* (2001) also reported that toluene, formaldehyde, and xylene were cleaned from ambient air by plants. Moreover, purification of contamination in soils, sludge, sediments, surface water,

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or ground water can be done by a phytoremediation process (U.S. EPA, 1999). Phytoremediation is a natural process which consists of several mechanisms such as phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, biosorption, phytostabilization, phytovolatilization, phytodegradation, and phytostimulation (Torok *et al.*, 2015). The treatment efficiency of each mechanism depends on the properties, and physical, chemical, and biological characteristics of each pollutant (U.S. EPA, 1999; Turker *et al.*, 2013; Torok *et al.*, 2015).

Plants play the major role in phytoremediation process. Normally, plants are living things which produce their food by photosynthesis process. Green plants transform solar energy to chemical energy through this process. Therefore, the photosynthesis is a main process for plants, which can be affected by various kinds of light sources (Taiz and Zeiger, 1998). The sunlight and lamps can be the representative of light sources. Moreover, the different wavelengths of light sources can be applied for plants (Morh and Browese, 1995). Light-emitting diode (LED) lamp is a good alternative of light source (Nhut *et al.*, 2003; Chung *et al.*, 2010; Yurio *et al.*, 2011; Lin *et al.*, 2013). It is probable that under LED conditions, plants will increase the purification efficiency of odor chemicals (Chen *et al.*, 2014).

Several research studies have reported the removal of odor chemicals and volatile pollutants (Drozdova *et al.*, 2001; Yang *et al.*, 2009; Turkey *et al.*, 2013; Torok *et al.*, 2015). However, few researchers have studied TMA. Therefore, the aim of this research was to remove TMA from indoor air using potted plants under dark and different light conditions. In terms of light conditions, fluorescent and LED lamps were used. The concentration of TMA was continuously measured using gas chromatography (GC).

METHODS

Preparation of Plants and Reactors

Eight species of potted plants were selected for this research, which were *Prickly pear cactus*, *D. sanderiana* Sander, *S. aureus*, *Dieffenbachia camilla*, *T. spathacea*, *Peperomia magnoliifolia*, *Chlorophytum comosum*, and *C. hexagonus* (L.) Mill. Two species among eight plants were cactus (*Prickly pear cactus* and *C. hexagonus* (L.) Mill.) with others as leaf plants. Eight species of potted plants were selected based on the removal rate of ammonia and size of potted plants. In these experiments, the efficiency of TMA removal by aerial parts of plants was investigated. Therefore, root parts were covered by aluminum foil. The surface area of leaves was selected around 130–150 cm² for each plant (Treesubuntorn and Thiravetyan, 2012; Boraphech and Thiravetyan, 2015).

The glass desiccators were selected as the reactors for indoor air condition. The volume of each desiccator was 15.6 L with cover lid (Fig. 1). The cover lid was used to control TMA concentration and take the samples. Gas sampling was sucked by glass syringe through the septum on top of the cover lid. Moreover, greases and parafilm were applied for gas leak protection (Boraphech and

Thiravetyan, 2015).

Preparation of TMA

TMA is a fishy odor. The critical concentration for living organism is 150 ppm in 30 min (Boraphech and Thiravetyan, 2015; Ruijten, 2005; U.S. EPA, 2016). Hence, the concentration of TMA which was used in this research was 150 ppm. TMA (40% aqueous solution) was obtained from Sigma Aldrich. The volume of TMA solution was calculated from Eqs. (1)–(3):

$$\text{ppm} = 10^6 \times \frac{W}{M_w} \times \frac{M_c}{V} \quad (1)$$

$$M_c = 24.47 \times \frac{760}{P} \times \left(\frac{T + 273.15}{298.15} \right) \quad (2)$$

$$\rho = \frac{W}{V_g} \quad (3)$$

where ρ is the density of TMA (1.88 g mL⁻¹), V_g (mL) is TMA volume, M_w (g mole⁻¹) is molecular weight of TMA, M_c is mole concentration, V is volume of glass chamber (15.6 L), P is pressure (mmHg), T is temperature (°C), and W is TMW weight (g).

From Eq. (4), the TMA which uptake by plant leaves was calculated by using plant leaf area. Therefore, the molar concentration is expressed as nmol per unit area (Wararat *et al.*, 2014):

$$\text{TMA removal per leaf area (nmol cm}^{-2}\text{)} = \frac{C_i - C_f}{A} \quad (4)$$

where C_i is initial concentration (nmol), C_f = final concentration (nmol), and A = total leaf area (cm²).

TMA Removal Experiments under Different Light Conditions

Three conditions were set in these experiments, which were light and dark conditions. For light conditions, a LED lamp (200 lux) which was 6500 K daylight (6 W, 50/60 Hz, 45 mA) was selected as a kind of light source because this

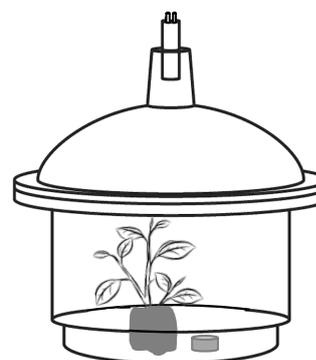


Fig. 1. Reactor for indoor air condition.

type of light source is suitable for plants and uses less electricity than other types (Taiz and Zeiger, 1998; Tang et al., 2010; Yorio et al., 2011). The second condition was fluorescent condition. Both sources are common light sources in an indoor condition such as houses and offices. The last condition was dark conditions. The experiments were conducted under dark condition. Each desiccator was covered by two black bags for light protection.

The selected plants were placed in each desiccator. TMA was injected into the foil cup near the selected plant. The experiments at different conditions were tests for 72 h at $25 \pm 2^\circ\text{C}$. The duplicate experiments were conducted for accuracy of results. Air samples were analyzed at 0, 2, 4, 8, 12, 24, 48, and 72 h. The concentration of TMA was measured by using GC (Boraphech and Thiravetyan, 2015).

Gas Chromatography Analysis

The CP-Volamine GC Column (GC-6890N, Agilent) was used to analyze TMA concentration by GC (Chung and Lee, 2009). The condition of GC is shown in Table 1. A flame ionization detector (FID) was selected as a gas detector because TMA solution was a substance that can be burnt by flame (Chien et al., 2000).

Cuticle Wax Extraction

The amount of cuticle wax of all eight potted plants was determined. The leaves of each type of plants were cut into small pieces ($1 \times 1 \text{ cm}^2$) and put into glass bottles. The total surface area of leaves for each type of plants was around 130 cm^2 . The method of cuticle wax extraction was adopted from Richardson method (Richardson et al., 2005; Boraphech and Thiravetyan, 2015). Methanol and chloroform were used as the solvents for extraction at ratio of 1:1 by volume. Methanol (30 mL) and chloroform (30 mL) were poured into the bottle of each sample. In order to completely extract the wax, the prepared samples were shaken at 240 rpm for 8 h. After shaking process, the solvents were evaporated in each bottle around 12–16 h in fume hood. The remaining part was only wax.

RESULTS AND DISCUSSION

TMA Removal Efficiency by Plants under Different Light Conditions

Eight species of plants with different characteristics, such as thickness and roughness of leaves and quantity of wax in leaves, were screened (Ruijten, 2005; Boraphech and Thiravetyan, 2015). The photos and characteristics of selected plants are shown in Table 2. The experiments were conducted in the desiccators. Therefore, the height of plants could not exceed 20 cm. The duration time for each experiment was 72 h.

TMA Removal by Plants under LED Condition

Eight species of potted plants were placed in desiccators with TMA at 150 ppm under LED conditions. The results in Fig. 2(a) show that *C. hexagonus* (L.) Mill. and *S. aureus* had high TMA removal efficiency. Both types of plants could decrease TMA concentration in desiccators, which

Table 1. Condition of GC instrument.

Inlet	Temp.	200°C
	Total flow	40 mL min ⁻¹
	Split ratio	5:1
Column	Carrier gas	He
	Column flow	3 mL min ⁻¹
	Temp.	200°C
	Detector	FID detector
Detector	Temp.	240°C
	Flaming gas	
	-H ₂	35 mL min ⁻¹
	-Air zero	400 mL min ⁻¹
	Make up gas (N ₂)	20 mL min ⁻¹

was more than 80% within 8 h. After 72 h of experiments, *S. aureus* was the best species for TMA removal ($95.4 \pm 4.6\%$) and the second one was *C. hexagonus* (L.) Mill. ($93.6 \pm 1.3\%$) as shown in Fig. 2(a). It implied that both potted plants could uptake TMA at a higher rate compared to other plants. Moreover, *S. aureus* is well known as a plant which can treat pollutants including ammonia in offices and restrooms. On the other hand, *C. comosum*, *D. camilla*, and *P. magnoliifolia* had low TMA removal efficiencies which were less than 41% within 8 h. However, the removal efficiency of these three plants increased continuously (more than 80% within 72 h).

The results indicated that light sources (LED lamp) affected photosynthesis of plants (Morh and Browese, 1995; Nhut et al., 2003; Chung et al., 2010) and resulted in decreasing TMA concentrations. In addition, the removal efficiency of TMA of each plant also depends on plant species and their waxes. Normally, sunlight is a suitable light source for plants. It was quite similar to LED lamp conditions because of its wavelength. LED lamp has vital rays for plant growth at 450 nm (blue light), and 650 nm (red light) as sunlight conditions. Comparison among fluorescent lamp, LED lamp, and incandescent lamp, the proper light source which is good for growing plants is LED lamp (Morh and Browese, 1995; Taiz and Zeiger, 1998). In terms of incandescent lamp, its spectrum is quite fit for plant growth (blue and red light). However, incandescent lamp consumes much electric power and it is too hot when it is used for a long time (Morh and Browese, 1995).

TMA Removal by Plants under Fluorescent Condition

From the results in the Fig. 2(b), *Prickly pear cactus*, *S. aureus*, *T. spathacea*, *C. hexagonus* (L.) Mill., and *D. camilla* could decrease TMA concentration which was more than 50% within 8 h. After 24 h of experiments, *Prickly pear cactus* was the best species for TMA removal ($100 \pm 0\%$). Moreover, after 72 h of experiments (Fig. 2(b)), plants which could reach 100% removal were *Prickly pear cactus*, *Peperomia magnoliifolia*, *C. hexagonus* (L.) Mill., *S. aureus*, and *T. spathacea*. So, the result implied that *Prickly pear cactus* which is grouped in CAM plant was the best plant to remove TMA concentration in this condition. The rate of TMA removal at 8 h under fluorescent condition was lower than the rate of TMA removal under LED condition.

Table 2. Details and characteristic of selected plants.

Image	Species	Family name	Outlook characteristics
	<i>Prickly pear cactus</i>	<i>Opuntia</i>	Desert flora
	<i>Cereus hexagonus (L.) Mill.</i>	<i>Cactaceae</i>	Desert flora
	<i>Dracaena sanderiana Sander.</i>	<i>Asparagaceae</i>	Leaf plant
	<i>Tradescantia spathacea</i>	<i>Commelinaceae</i>	Leaf plant
	<i>Dieffenbachia camilla</i>	<i>Araceae</i>	Leaf plant
	<i>Chlorophytum comosum</i>	<i>Liliaceae</i>	Leaf plant
	<i>Scindapsus aureus</i>	<i>Araceae</i>	Leaf plant
	<i>Peperomia magnoliifolia</i>	<i>Piperaceae</i>	Leaf plant

TMA Removal by Plants under Dark Condition

Fig. 2(c) shows removal of TMA in the desiccators after treatment by eight potted plants under dark conditions for 72 h. The result showed that *C. hexagonus (L.) Mill.* and *Prickly pear cactus* were the suitable potted plants for TMA removal under dark conditions among the eight species. Both types of plants could decrease TMA concentration, which was between 50% and 65% within 8 h. CAM is good at adapting itself in a condition which has no light. The efficiency was not different when compared to the potted plants under light conditions. However, the efficiencies of both plants trended to increase after 72 h of experiments which were

$87.9 \pm 2.7\%$ and $90.9 \pm 0.1\%$ for *Prickly pear cactus* and *C. hexagonus (L.) Mill.*, respectively. Both plants had high removal efficiency under dark conditions. The reason was *Prickly pear cactus* and *C. hexagonus (L.) Mill.* (CAM plant) open stomata at night and absorb TMA. Moreover, they had fleshy pads which look like leaves and have several functions such as water storage, photosynthesis and flower production (Boraphech and Thiravetyan, 2015; Taiz, 1998). On the other hand, *S. aureus* had the lowest TMA removal efficiency at 72 h ($57.2 \pm 1.9\%$). It indicated that *S. aureus* preferred light for its activity because it had the highest TMA removal efficiency at 72 h under light conditions.

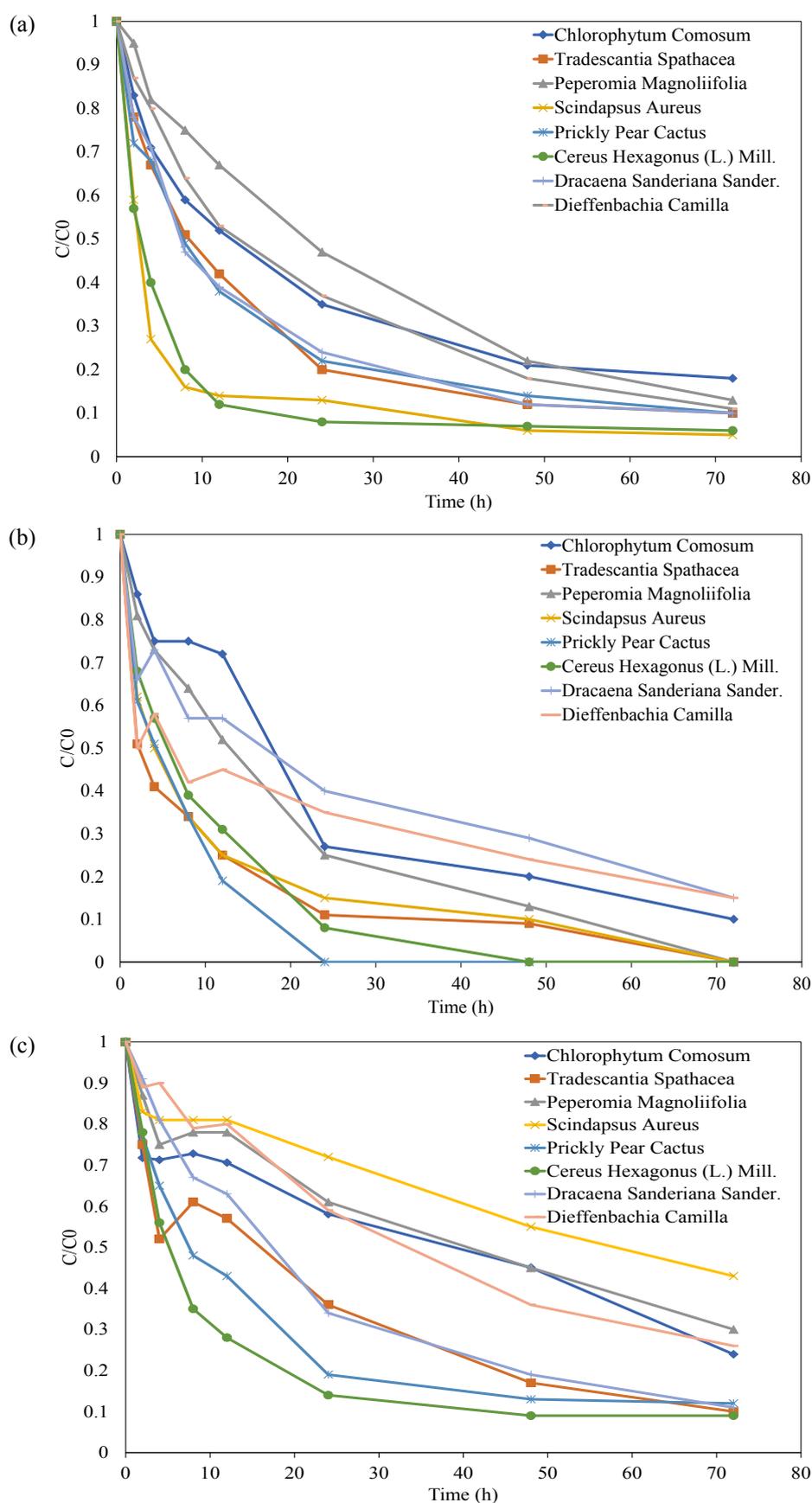


Fig. 2. Removal of TMA by various potted plants under (a) LED condition, (b) fluorescent condition, and (c) dark condition (C_0 = initial TMA concentration (ppm), C = remaining TMA concentration at different time (ppm)).

Quantity of Cuticle Wax

The cuticle wax quantities of eight kinds of potted plants were studied by using Richardson method (Richardson *et al.*, 2005; Boraphech and Thiravetyan, 2014). The result showed that *D. sanderiana* Sander had the highest wax concentrations (7.06 mg cm^{-2}) as shown in Fig. 3. The second and third plants were *Prickly pear cactus* (2.86 mg cm^{-2}) and *C. hexagonus* (L.) Mill. (1.17 mg cm^{-2}). The remaining potted plants (*T. spathacea*, *C. comosum*, *D. camilla*, and *S. aureus*) had low wax concentrations which were lower than 1 mg cm^{-2} with the lowest wax concentrations for *S. aureus* (0.56 mg cm^{-2}).

Considering wax quantities of eight plants under dark conditions at 8 h, the results showed that quantity of wax had a significant effect on TMA removal efficiency (Boraphech and Thiravetyan, 2015). Two plants (*Prickly pear cactus*, and *C. hexagonus* (L.) Mill.) with high amounts of wax in the leaves had the highest TMA removal efficiency. It was consistent with the study by Treesubsuntorn *et al.* (2012) who reported that 46% of total benzene uptake was by crude wax of *D. sanderiana* Sander at 72 h. The results suggested that the crude wax could act as a biosorbent. The crude wax can be one important factor for adsorbing air pollutants (Treesubsuntorn and Thiravetyan, 2012). Moreover, a previous study from Treesubsuntorn *et al.* (2015) suggested that not only the quantity of wax but also the composition of wax affects pollutant adsorption.

Comparison of TMA Removal by Plants under Light and Dark Conditions

Based on the results from previous sections, the selected plants could be divided into two groups: (i) high removal efficiency under light conditions and (ii) high removal efficiency under light and dark conditions.

High Removal Efficiency under Light Conditions

The plants in this group (C_3 plants), which were *C. comosum*, *D. camilla*, *P. magnoliifolia*, and *S. aureus*, had high removal efficiency under light conditions but had low removal efficiency under dark conditions. The results showed that they had a very high TMA removal efficiency under light conditions at 72 h ($> 80\%$ removal), especially *S. aureus* had the highest removal efficiency ($95.4 \pm 4.6\%$), as shown in Fig. 2 and Table S1. However, they had quite low removal efficiency under dark conditions ($< 60\%$ at 24 h) as shown in Fig. 4.

It indicated that these plants need light source for their photosynthesis (Wolverton *et al.*, 1989; Yang *et al.*, 2009) and enhanced TMA removal. The stomata were observed to close under dark conditions for C_3 plants. Therefore, TMA was mainly removed by stomata during daytime (light conditions). Moreover, the amount of wax may be another factor which decreased the concentration of TMA (Treesubsuntorn and Thiravetyan, 2012; Boraphech and Thiravetyan, 2015). As mentioned in the previous section, *S. aureus* had the lowest amount of waxes including epicuticular and cuticular wax. Thus, these waxes and the physical structure of the wax of *S. aureus* had low TMA removal efficiency under dark condition. It implied that these plants might be suitable for application only under light conditions.

Moreover, analysis of variance (ANOVA) was used to determine whether the differences between the species of plants and light conditions for TMA removal. According to Fig. 4, the results from ANOVA with 95% confidence showed that different species of C_3 plants including *C. comosum*, *D. camilla*, *P. magnoliifolia*, and *S. aureus* have no effect to TMA removal. However, different light conditions (i.e., LED, fluorescent, and dark conditions) have had a significant impact on TMA removal at 24 h.

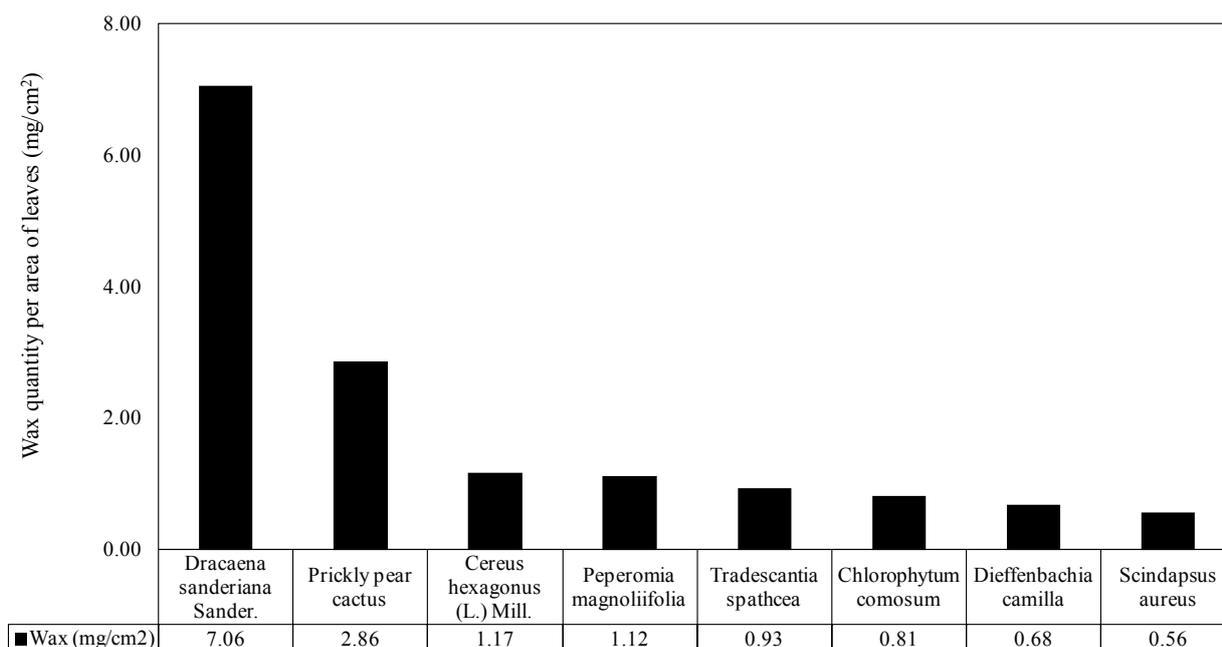


Fig. 3. Amount of cuticle wax per leaf area of various potted plants.

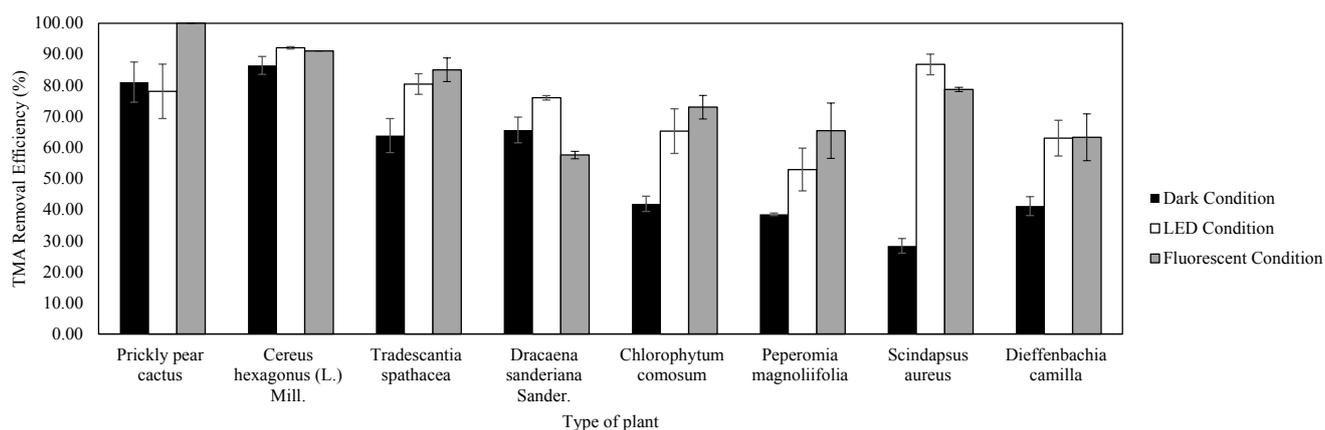


Fig. 4. TMA removal efficiency of 8 species of plant at 24 h.

High Removal Efficiency under Light and Dark Conditions

The plants in this group (C_3 and CAM plants), which were *C. hexagonus* (L.) Mill., *Prickly pear cactus*, *D. sanderiana* Sander, and *T. spathacea*, had high removal efficiency under light and dark conditions. The result showed that TMA removal efficiency for these four plants under light and dark conditions were quite similar, especially at 72 h (> 90% removal). It indicated that light sources did not have a significant effect on these plants. For TMA removal, CAM plants (*C. hexagonus* (L.) Mill. and *Prickly pear cactus*) open stomata at night and absorb TMA. Therefore, CAM plants can reduce TMA under dark condition. Moreover, there are some species of C_3 and C_4 plants which can under stress conditions switch to the CAM system (facultative CAM). *T. spathacea* (C_3 plant) is included in facultative CAM. In case of *D. sanderiana* Sander, it had the highest amount of waxes including epicuticular and cuticular wax. Thus, these waxes and the physical structure of the wax may help for TMA removal under dark condition.

In addition, the results from ANOVA with 95% confidence showed that different species of plants including *C. hexagonus* (L.) Mill., *Prickly pear cactus*, *D. sanderiana* Sander and *T. spathacea* and light conditions have no effect to TMA removal. It indicated that these 4 plants could remove TMA under dark and light conditions.

CONCLUSIONS

The results, the selected plants can be divided into two groups: (i) those with high TMA removal efficiency in light conditions and (ii) those with high removal efficiency in light and dark conditions. In the first group, *S. aureus* exhibited the highest removal efficiency. The main mechanism in this group (C_3 plants) was plant uptake via photosynthesis and open stomata during light conditions. In the second group, cactus type (*C. hexagonus* (L.) Mill. and *Prickly pear cactus*) exhibited a high removal efficiency during both light and dark conditions. These plants (CAM) open their stomata at night and absorb TMA. Moreover, ANOVA results confirm, with 95% confidence, that the species of plant (chosen among 8 types) and the light

conditions (viz., LED lighting, fluorescent lighting, or dark conditions) have a significant impact on TMA removal after 24 h.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aqr.org>.

REFERENCES

- Boraphech, P. and Thiravetyan, P. (2015). Trimethylamine (Fishy odor) adsorption by biomaterials: Effect of fatty acids, alkanes, and aromatic compounds in waxes. *J. Hazard. Mater.* 284: 269–277.
- Chang, C.T., Chen, B.Y., Shiu, I.S. and Jeng, F.T. (2004). Biofiltration of trimethylamine-containing waste gases by entrapped mixed microbial cells. *Chemosphere* 55: 751–756.
- Chen, X.L., Guo, W.Z., Xue, X.Z., Wang, L.C. and Qiao, X.J. (2014). Growth and quality responses of 'GreenOak Leaf' lettuce as affected by monochromic or mixed radiation provided by fluorescent lamp (FL) and light-emitting diode (LED). *Sci. Hortic.* 172: 168–175.
- Chien, Y.C., Uang, S.N., Kuo, C.T., Shih, T.S. and Jen, J.F. (2000). Analytical method for monitoring airborne trimethylamine using solid phase micro-extraction and gas chromatography-flame ionization detection. *Anal. Chim. Acta* 419: 73–79.
- Chung, J.P., Huang, C.T. and Dai, T.E. (2010). Spectral

- effects on embryogenesis and plantlet growth of *Oncidium* ‘Gower Ramsey’. *Sci. Hortic.* 124: 511–516.
- Chung, K.H. and Lee, K.Y. (2009). Removal of trimethylamine by absorption over zeolite catalysts and deodorization of fishy oil. *J. Hazard. Mater.* 172: 922–927.
- Ding, Y., Shi, J.T., Wu, W.X., Yin, J. and Chen, Y.X. (2007). Trimethylamine (TMA) biofiltration and transformation in biofilters. *J. Hazard. Mater.* 143: 341–348.
- Drozdova, I.S., Bondar, V.V., Bukhov, N.G., Kotov, A.A., Kotva, M.M., Maevskaya, S.N. and Mokronosov, A.T. (2001). Effects of light spectral quality on morphogenesis and source-sink relations in radish plant, Russ. *J. Plant Physiol.* 48: 415–420.
- Geraets, L., Bessems, J.G., Zeilmaier, M.J. and Bos, P.M. (2014). Human risk assessment of dermal and inhalation exposures to chemicals assessed by route-to-route extrapolation: The necessity of kinetic data. *Regul. Toxicol. Pharm.* 70: 54–62.
- Ho, K.L., Chung, Y.C., Lin, Y.H. and Tseng, C.P. (2008). Biofiltration of trimethylamine, dimethylamine, and methylamine by immobilized *Paracoccus* sp. CP2 and *Arthrobacter* sp. CP1. *Chemosphere* 72: 250–256.
- Kim, S.G., Bae, H.S. and Lee, S.T. (2011). A novel denitrifying bacterial isolate that degrades trimethylamine both aerobically and anaerobically via two different pathways. *Arch. Microbiol.* 176: 271–277.
- Lin, K.H., Huang, M. Y., Huang, W.D., Hsu, M.H., Yang, Z.W. and Yang, C.M. (2013). The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. *capitata*). *Sci. Hortic.* 150: 86–91.
- Morh, H. and Browese, J. (1995). *Plant physiology*. Springer, Berlin.
- Nhut, D.T., Hong, L.T.A., Watanabe, H., Goi, M. and Tanaka, M. (2003). Growth of banana plantlets cultured in vitro under red and blue light-emitting diode (LED) irradiation source. *Acta Hortic.* 575: 124–117.
- NIOSH (1981). *Occupational health guidelines for chemical hazards*. DHHS (NIOSH) Publication, National Institute for Occupational Safety and Health, Ohio, USA.
- Nobel, P.S. (1999). *Physicochemical & environmental plant physiology*, 2nd edn. Academic Press, San Diego.
- OSHA (1994). *Occupational safety and health guideline for trimethylamine, computerized information system, occupational safety and health administration*. Department of Labor, Washington DC, USA.
- Oyabu, T., Ayako, S., Onodera, T., Tanaka, K. and Wolverton, B.C. (2003). Characteristics of potted plants for removing offensive odors. *Sens. Actuators, B* 89: 131–136.
- Oyabu, T., Onodera, T., Kimura, H. and Sadaoka, Y. (2001). Purification ability of interior plant for removing of indoor-air polluting chemicals using a tin oxide gas sensor. *J. Jpn. Soc. Atmos. Environ.* 34: 319–325.
- Richardson, A., Franke, R., Kersriens, G., Jarvis, M., Schreiber, L. and Fricke, W. (2005). Cuticular wax deposition in growing barley (*Hordeum vulgare*) leaves commences in relation to the point of emergence of epidermal cells from the sheaths of older leaves. *Planta* 222: 472–483.
- Ruijten, M. (2005). *Personal Communication from Dr. Marc Ruijten*, National Institute of Public Health and Environment (RIVM), AEGL-2 Committee Member, The Netherlands.
- Sintermann, J., Schallhardt, S., Kajos, M., Jocher, M., Bracher, A., Munger, A., Johnson, D., Neftel, A. and Ruuskanen, T. (2014). Trimethylamine emissions in animal husbandry. *Biogeosciences* 11: 5073–5085.
- Sriprapat, W., Boraphech, P. and Thiravetyan, P. (2014). Factors affecting xylene-contaminated air removal by the ornamental plant, *Zamioculcas zamiifolia*. *Environ. Sci. Pollut. Res.* 21: 2603–2610.
- Taiz, L. and Zeiger, E. (1998). *Plant physiology*, 2nd edn. Sinauer Associates, Inc., MA, USA.
- Torok, A., Gulyas, Z., Szalai, G., Kocsy, G. and Majdik, C. (2015). Phytoremediation capacity of aquatic plants is associated with the degree of phytochelatin polymerization. *J. Hazard. Mater.* 299: 371–378.
- Treesubuntorn, C. and Thiravetyan, P. (2012). Removal of benzene from indoor air by *Dracaena sanderiana*: Effect of wax and stomata. *Atmos. Environ.* 57: 317–321.
- Turker, O.C., Bocuk, H. and Yakar, A. (2013). The phytoremediation ability of a polyculture constructed wetland to treat boron from mine effluent. *J. Hazard. Mater.* 252–253: 132–141.
- U.S. EPA (1999). *Phytoremediation resource guide*. EPA 542-B-99-003, Solid Waste and Emergency Response Technology Innovation Office, U.S. Environmental Protection Agency, Washington, DC, USA.
- U.S. EPA (2006). Method 8260C (SW-846): Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS). U.S. Environmental Protection Agency, Washington, DC, USA. <http://www.epa.gov/osw/hazard/testmethods/pdf/8260c.pdf>.
- Wolverton, B.C., Johnson, A. and Bounds, K. (1989). *Interior landscape plants for indoor air pollution abatement*. Final Report. NASA Stennis Space Centre, Mississippi, USA.
- Wolverton, B.C. and Wolverton, J.D. (1993). Plants and soil microorganisms, removal of formaldehyde, xylene, and ammonia from the indoor environment. *J. Miss. Acad. Sci.* 38: 11–15.
- Wolverton, B.C. (1996). *How to grow fresh air*. Penguin book, New York, USA.
- Wood, R.L., Orwell, R.L., Tarran, J. and Burchett, M.D. (2001). Pot-plants really do clean indoor air. The Nursery Papers, No. 2001/2, NIAA, Sydney, Australia.
- Yang, D.S., Pennisi, S.V., Son, K. and Kays, S.J. (2009). Screening indoor plants for volatile organic pollutant removal efficiency. *HortScience* 44: 1381–133.
- Yorio, N.C., Goins, G.D., Kagie, H.R., Wheeler, R.M. and Sager, J.C. (2011). Improving spinach, radish, and lettuce growth under red light-emitting diodes (LED) with blue light supplementation. *HortScience* 36: 380–383.
- Zhu, J., Bundy, D.S., Li, X.W. and Rashid, N. (1997).

Reduction of order and volatile substances in pig slurries by using pit additives. *J. Environ. Sci. Health A* 32: 605–619.

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