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

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Abstract

A phytoremediation was selected to mitigate fishy odor or trimethylamine (TMA) that occurs from seafood industry or fresh market. A synthetic TMA chemical was used for fishy odor. For this research, eight types of potted plants (*Prickly pear cactus, Dracaena sanderina* Sander*, Dieffenbachia camilla, Tradescantia spathacea, Peperromia magnoliifolia, Cholorophytum comosum, Cereus hexagonus (L.)* Mill*, and Scindapsus aureus*) were selected as the representative of potted plant to remove TMA under light and dark conditions. The results showed that *S. aureus* had the highest TMA removal efficiency under light conditions at 72 h (> 95%). However, it had very low efficiency under dark conditions. This implied that *S. aureus* should be applied in the places having light sources all day. On the other hand, cactus type (*C. hexagonus (L.)* Mill*. and Prickly pear cactus*) had high TMA removal efficiency under both light and dark conditions at 72 h (> 90%). These plants might be more suitable to apply in a real system containing light and dark conditions.

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

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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 (Boraphech and Thiravetyan, 2015; OSHA, 1994; Kim et al., 2011). Degradation of plants and animal residuals by microorganisms, especially rotting marine animals, produce TMA (Chung and Lee, 2009; Chien et al., 2000; Chang et al., 2004; Zhu et al., 1997). 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 (Ding et al., 2007; Sintermann et al., 2014; Wolverton et al., 1989). 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; Nobel et al., 1999; Wolverton et al., 1996; 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, or ground water can be done by a phytoremediation process (USEPA, 1999). Phytoremediation is a natural process which consists of several mechanisms such as phytoextraction, rhizofiltration, biosorption, phytostabilization, phytovotalyzation, 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 (USEPA, 1999; Torok et al., 2015; Turker et al., 2013).

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 et al., 1998). The sun light and lamps can be the representative of light sources. Moreover, the different wave lengths of light sources can be applied for plants (Morh and Browese, 1995). Light-emitting diode (LED) lamp is a good alternative of light source (Chung et al., 2010; Nhut et al., 2003; Lin et al., 2013; Yurio et al., 2011). 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 odorous chemicals and volatile pollutants (Torok et al., 2015; Turkey et al., 2013; Drozdova et al., 2001; Yang et al., 2009). However, a few researchers have studied TMA. Therefore, the aim of this research was to remove TMA from indoor air using potted plants at different light conditions. The light conditions were separated into 2 conditions which are light and dark 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. sanderina* Sander*, S. aureus, Dieffenbachia camilla, T. spathacea, Peperromia magnoliifolia, Cholorophytum 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 cm^2 for each plant (Boraphech and Thiravetyan, 2015; Treesubsuntorn and Thiravetyan, 2012).

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; 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):

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

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

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

Where ρ is the density of TMA (1.88 g/mL), V_g (mL) is TMA volume, M_w (g/mole) 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 (^{o}C), and W is TMW weight (g).

From equation 4, the TMA which uptake by plant leaves was calculated by using plant leaf area. Therefore, the molar concentration is expressed as nmol/ 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 (cm^2)

TMA removal experiments under different light conditions

Three conditions were set in these experiments, which were light and dark conditions (Boraphech and Thiravetyan, 2015). For light conditions, LED lamp (200 lux) which was daylight 6500K. It was 6-watt lamp with 50/60 Hz and 45mA was selected as a kind of light source because this type of light source is suitable for plants and uses less electricity than other types (Taiz et al., 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 2 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 testes for 72 h at 25 °C ± 2 °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 (Agilent Model) was used to analyze TMA concentration by GC (Chung and Lee, 2009). The model number of GC was GC-6890N by Agilent. 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 (1×1 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 (Boraphech and Thiravetyan, 2015; Richardson et al., 2005). 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 (Boraphech and Thiravetyan, 2015; Ruijten, 2005). 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.

1. 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 was more than 80% within 8 h. After 72 h of experiments, *S. aureus* was the best species for TMA removal (95.4% ± 4.6) and the second one was *C. hexagonus (L.)* Mill. (93.6% ± 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; Chung et al., 2010; Nhut et al., 2003) 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 (Taiz et al., 1998; Morh and Browese, 1995). 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).

2. 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. sanderina* Sander 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% ± 0). Moreover, after 72 h of experiments (Fig. 2(b)), plants which could reach 100% removal were *Prickly pear cactus, Peperromia 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.

3. 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 remove 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% ± 2.7

and 90.9% ± 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% ± 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.

Quantity of cuticle wax

The cuticle wax quantities of eight kinds of potted plants were studied by using Richardson method (Boraphech and Thiravetyan, 2014; Richardson et al., 2005). 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.

1. 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% ± 4.6), as shown in Fig. 2 and Table S.1. 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 close under dark conditions for C_3 plants. Therefore, TMA was mainly removed by stomata during day time (light conditions). Moreover, the amount of wax may be another factor which decreased the concentration of TMA (Boraphech and Thiravetyan, 2015; Treesubsuntorn and Thiravetyan, 2012). 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% confident 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.

2. 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,* and *D. sanderina* 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. sanderina* 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% confident showed that different species of plants including *C. hexagonus (L.)* Mill*, Prickly pear cactus,* and *D. sanderina* 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 showed that the selected plants could be divided into two groups: (i) plants with high removal efficiency under light conditions, and (ii) plants with high TMA removal efficiency under light and dark conditions. For the first group, the highest TMA removal efficiency was *S. aureus*. The main mechanism in this group (C_3 plant) was plant uptake via photosynthesis and open stomata during light conditions. For the second group, cactus type (*C. hexagonus (L.) Mill and Prickly pear cactus*) had high removal efficiency under light and dark conditions. These plants (CAM) open stomata at night and absorb TMA. Moreover, the result of ANOVA with 95% confident could confirm that different species of plant (8 types) and light conditions (i.e. LED, fluorescent, and dark conditions) have had a significant impact on TMA removal at 24 h.

ACKNOWLEDGMENTS

This research was financially supported by the KMUTT Research Fund and Research Strengthening Project of Faculty of Engineering, King Mongkut's University of Technology Thonburi. The authors thank staffs from Environmental Engineering Department. The authors also thank Dr. Chairat Treesubsuntorn and Dr. Phattara Boraphech for their helps.

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Table Captions

Table 1. Condition of GC instrument.

Table 2. Details and characteristic of selected plants.

Table 1. Condition of GC instrument.

Inlet	Temp.	200 °C
	Total flow	40 mL/min
	Split ratio	5:1
Column	Carrier gas	He
	Column flow	3 mL/min
	Temp.	200 °C
Detector	Detector	FID detector
	Temp.	240 °C
	Flaming gas	
	-H_2	35 mL/min
	-Air zero	400 mL/min
	Make up gas (N_2)	20 mL/min

Table 2. Details and characteristic of selected plants.

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

Figure Captions

Fig. 1. Reactor for indoor air condition.

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)).

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.

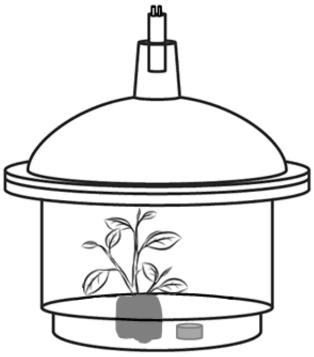


Fig. 1. Reactor for indoor air condition.

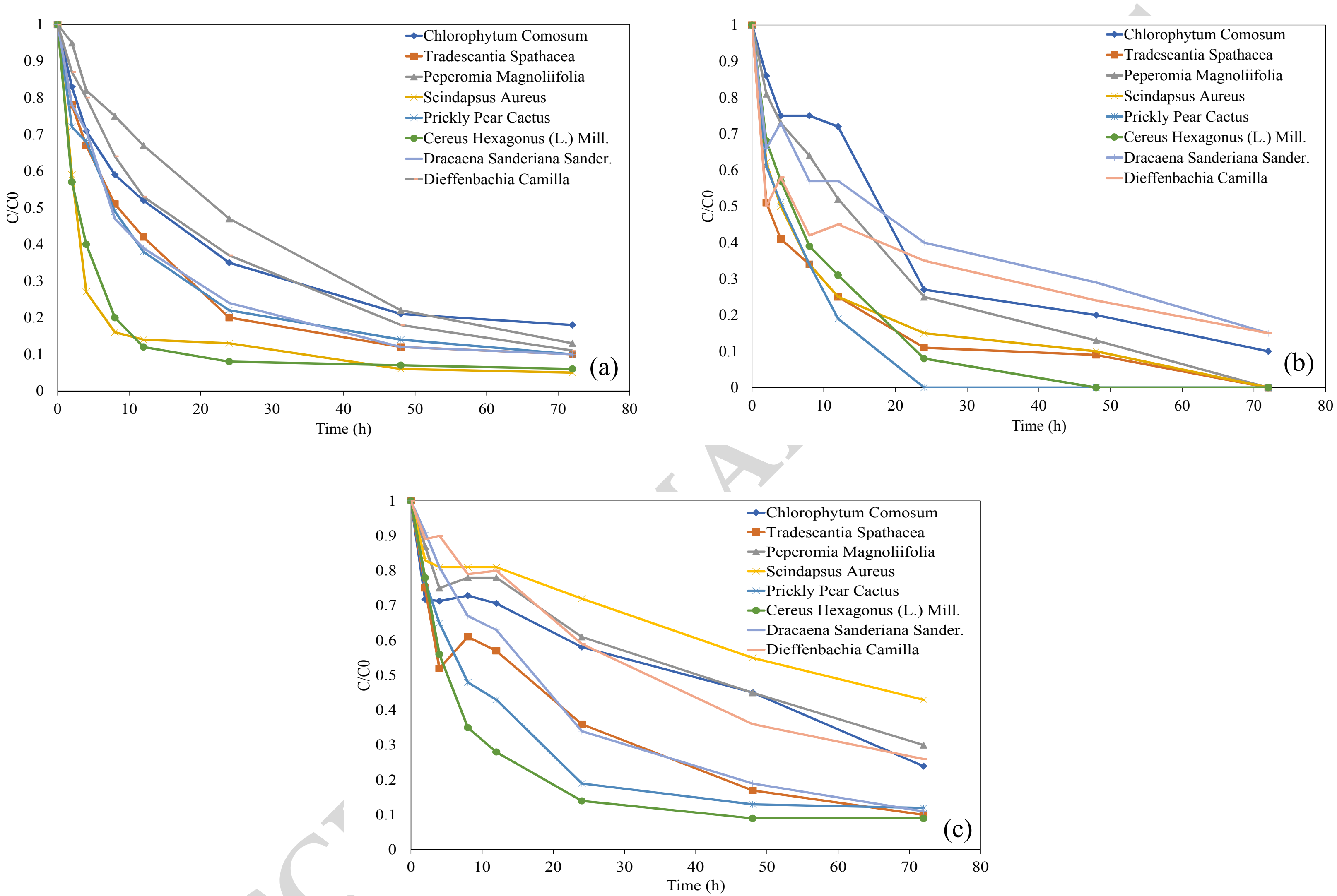
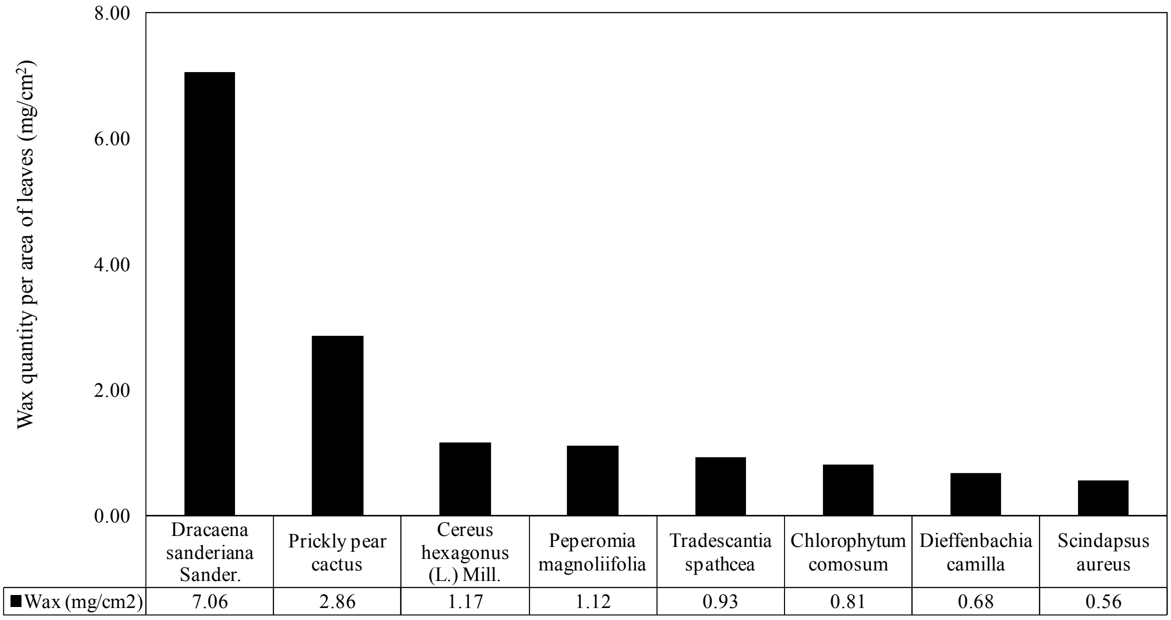


Fig. 2. Removal of TMA by various potted plants under (a) LED condition, (b) fluorescent condition, and (c) dark condition (C_0 = initial TMA concentration (ppm), C = remaining TMA concentration at different time (ppm)).



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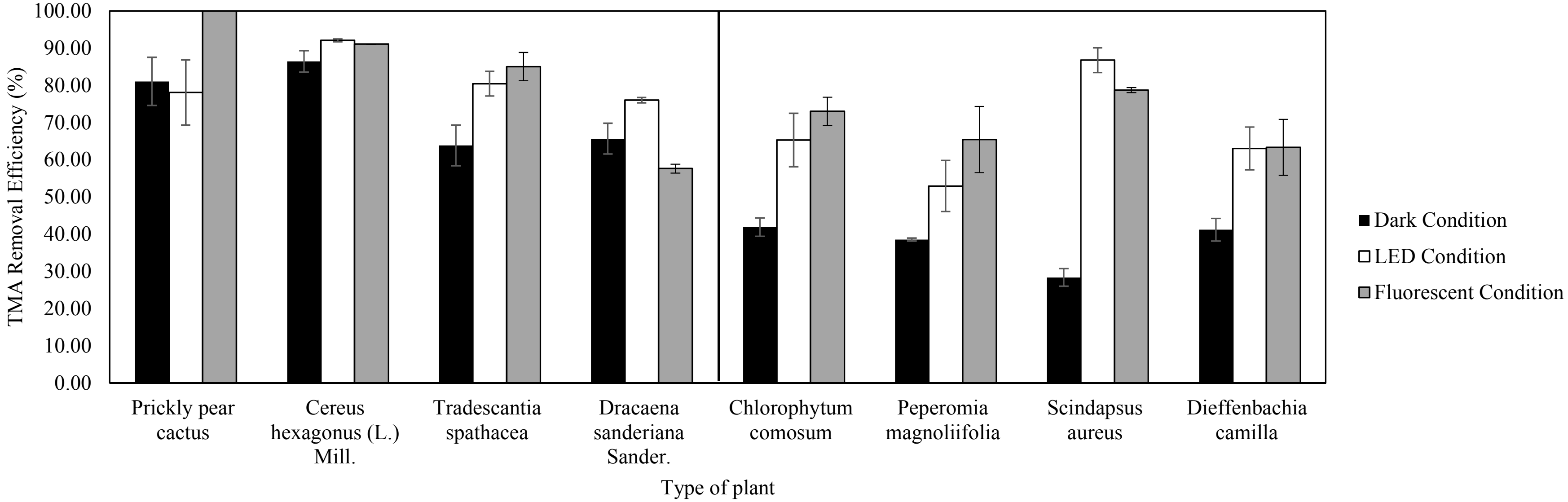

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