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RESEARCH ARTICLE

Novel insights into indoor air purification capability of microalgae: characterization using multiple air quality parameters and comparison with common methods

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Abstract

Indoor air purification received more attention recently. In this study, the effects of six common indoor ornamental plants (*Epripremnum aureum*, *Chlorphytum comosum*, *Aloe vera*, *Sedum sediforme*, *Cereus cv. Fairy Castle*, and *Sedum adolphii*) and three kinds of microalgae (*Chlorella* sp. HQ, *Scenedesmus* sp. LX1, and *C. vulgaris*) on the removal of four types of air pollutants (particulate matters less than 2.5 ($PM_{2.5}$) and 10 μm (PM_{10}) in size, formaldehyde (HCHO) and total volatile organic compounds (VOC_S)) in test chamber compared with common physical purification methods (high efficiency particulate air filter and nano activated carbon absorption) were investigated. Their effects on oxygen, carbon dioxide, and relative humidity were also evaluated. The results showed that microalgae, especially *C. vulgaris*, was more suitable for removing $PM_{2.5}$ and PM_{10}, and the removal rates were 55.42 ± 25.77% and 45.76 ± 5.32%, respectively. The removal rates of HCHO and VOCs by all three kings of microalgae could reach 100%. Part of ornamental plants took a longer time to achieve 100% removal of HCHO and VOCs. Physical methods were weaker than ornamental plants and microalgae in terms of increased relative humidity and O_2 content. In general, microalgae, especially *C. vulgaris* could purify indoor air pollutants more efficiently. The above studies provided data and theoretical support for the purification of indoor air pollutants by microalgae.

Keywords Indoor air purification · Particulate matters · Formaldehyde · Volatile organic compounds · Microalgae · Indoor ornamental plants

Abbreviations

$PM_{2.5}$	Particulate matters less than 2.5
PM_{10}	Particulate matters less than 10
HCHO	Formaldehyde
VOCs	Total volatile organic compounds
HEPA	High-efficiency particulate air filter
NAC	Nano activated carbon absorption

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Introduction

In recent years, economic rapid development has caused serious air pollution (e.g., frequent haze events), which not only affects transportation, but also has negative influences on human living health, such as increasing the risk of respiratory diseases (Beatty and Shimshack, 2014; Gao et al., 2017). Nowadays, people spend more than 90% of their time indoors (Luo et al., 2021). It is very important to pay attention to and maintain indoor air quality to protect human health. Therefore, it is necessary to develop air purification technology.

At present, the main methods that can be used for indoor air purification include filtration, adsorption, ozonation, ultraviolet photolysis, photocatalytic oxidation, and plasma (Luengas et al., 2015). Each of the above methods has advantages and disadvantages. Ozone can react with a variety of organic substances due to its strong oxidizing property and has the effect of disinfection and sterilization (Bertol et al., 2012; Kwong et al., 2008), but its irritation is harmful to the human body, and the reactants can also

cause secondary pollution (Hubbard et al., 2005). The photocatalytic oxidation technology based on ultraviolet light and photocatalyst can remove indoor air pollutants through the reaction of oxidant hydroxyl radicals and superoxide anion radicals, and also has the ability to remove bacteria and viruses (Mamaghani et al., 2017; Martinez-Montelongo et al., 2020; Yu and Brouwers, 2009). This technology has low investment cost and low energy consumption at room temperature. However, there are intermediate products in the reaction process, and potential secondary pollution is the main problems of this technology (Mamaghani et al., 2017). Filtration is currently the most widely used indoor air purification technology, such as high-efficiency particulate air filter (HEPA) (Barn et al., 2018). The filter material can remove suspended particles and large-diameter microorganisms (Liu et al., 2017), and the operation is simple and flexible, but the filter material exceeds its service life, efficiency will be reduced, and new pollution will occur after discarding (Yu et al., 2009). Adsorption is also a commonly used method of indoor air purification. For example, activated carbon, one of the most used adsorption materials, is widely used because of its large adsorption capacity and high adsorption efficiency. However, it is difficult to regenerate after the adsorption is saturated and the activity after regeneration is low, and the overall cost is high (Yu et al., 2009; Raso et al., 2014). Therefore, there is still a need to find low-cost and effective indoor air purification methods.

People often put some indoor ornamental plants for appreciation and decoration. Many of these plants do have good air purification capabilities, such as *Chlorophytum comosum, Epipremnum aureum*, *Aloe vera*, *Sansevieria trifasciata Prain*, and *Sedum sediforme.* Studies have shown that *C. comosum* and *E. aureum* not only can absorb formaldehyde (HCHO), benzene, and other pollutants (Xu et al., 2010; Gong et al., 2019; Aydogan et al., 2011), but also can promote the reduction of indoor particulate matter concentration (Gawronska et al., 2015; Panyametheekul et al., 2016). *S. sediforme*, *A. vera*, and *S. adolphii* can uptake HCHO (Ding et al., 2016; Xu et al., 2011). Su and Liang showed that HCHO was mainly accumulated in plant tissues when the concentration of HCHO in air was 3 mg/m^3, and after 48 h, the content of HCHO in leaves was 12.9 ± 1.1 mg/kg fresh weight (Su and Liang, 2015). Cao et al. reported that when the initial $PM_{2.5}$ concentration was about 200 μg/m^3, *E. aureum* could increase the removal rate of $PM_{2.5}$ in the test chamber from 42.0% (empty chamber without *E. aureum*) to 71.46% in 3 h (Cao et al., 2019). In addition to reducing the concentration of pollutants, some indoor ornamental plants also have a good cooling and humidifying effect. Compared with physical and chemical technology, the use of plants to purify indoor air is inexpensive and can avoid secondary pollution, so it is worthy of attention.

Compared with plants, microalgae have stronger light utilization and carbon sequestration capacities (Cao et al., 2019). One-kilogram microalgae biomass can fix 1.8 kg of carbon dioxide, which accounts for about 40% of global carbon sequestration (Cheah et al., 2016; Chisti, 2007). At present, microalgae play an important role in many fields. In addition to sewage treatment and bioremediation, they can also be used for carbon capture, and even to synthesize alternative fuels and other high-value substances (Chai et al., 2020; Chai et al., 2021). In terms of absorbing flue gas, it has been reported that microalgae could absorb NOx and SOx in flue gas as nitrogen and sulfur sources for cell growth (Ng et al., 2017). Therefore, using flue gas to cultivate microalgae can reduce greenhouse gas and polluting gas emissions. Cheng et al. (2019) found that *Chlorella* sp. CV grew well in simulated flue gas containing 10 % CO_2, 200 ppm NOx, and 100 ppm SOx to present the growth rate of 0.53 g/L/day (Yen et al., 2015). At present, many microalgae-based air purification systems have been used for indoor air purification, which have good effect and can accumulate a large number of high value substances (Mata, et al., 2021). Hence, microalgae have the potential to purify indoor air, and the purification capacity of microalgae deserves further study.

In this study, six common indoor ornamental plants (*E. aureum*, *C. comosum*, *A. vera*, *S. sediforme*, *Cereus cv. Fairy Castle*, *and S. adolphii*) and three kinds of fresh water green algae (*C. vulgaris*, *Scenedesmus* sp. LX1, and *Chlorella* sp. HQ) were selected as the research objects. A simulation experiment was completed in a test chamber to study the reduction effects of indoor ornamental plants and microalgae on four types of air pollutants (particulate matters less than 2.5 ($PM_{2.5}$) and 10 μm (PM_{10}) in size, HCHO, and total volatile organic compounds (VOCs)), and their effects on carbon dioxide and oxygen contents and the value of relative humidity. Two physical methods, high-efficiency particulate air filter and nano activated carbon, were used in the study to test their effects on the above parameters for subsequent comparison. Based on the above research, the plant or microalgae species with the optimal potential for indoor air pollution purification are selected to provide technical support and data reference for the future development of indoor air pollution control technologies based on plants or microalgae.

Materials and methods

Indoor ornamental plants and microalgae species

E. aureum, *C. comosum*, *A. vera*, *S. sedifome*, *Cereus cv. Fairy Castlei*, and *S. adolphii* were purchased from commercial distributors. These plants were in stable growth phase and were healthy. And their average wet weight (including

their roots) used in the experiments was 54.7 ± 2.5, 11.7 ± 2.5, 66.0 ± 2.9, 27.7 ± 2.1, 131 ± 7.0, and 26 ± 4.5 g, respectively. Due to the different plant species, the plants available for indoor landscape and air purification used different biomass in their respective growth stages. In order to better simulate the purification state of conventional indoor landscape plants, the experimental biomass was set according to the amount of conventional indoor landscape plants, and they were all in a healthy growth state. The purification capacity of different plants was evaluated by comparing the amounts of pollutants removed per unit biomass. *Chlorella* sp. HQ was isolated in our previous study (GCMCC7601, in the China General Microbiological Culture Collection Center). *Scenedesmus* sp. LX1 (GCMCC3036, in the China General Microbiological Culture Collection Center) was obtained from Institute of Environmental Biology, School of Environment, Tsinghua University (Cheng et al., 2019). *Chlorella vulgaris* was purchased from Freshwater Algae Culture Collection at the Institute of Hydrobiology (FACHB), with collection number FACHB-8. All the microalgae were cultivated in SE medium, the ingredients of which were as follows: 250 mg/L of $NaNO_3$, 75 mg/L of $K_2HPO_4{\cdot}3H_2O$, 75 mg/L of $MgSO_4{\cdot}7H_2O$, 25 mg/L of $CaCl_2{\cdot}2H_2O$, 175 mg/L of KH_2PO_4, 25 mg/L of NaCl, 5 mg/L of $FeCl_3{\cdot}6H_2O$, 0.81 mg/L of $FeCl_3$, 10 mg/L of Na_2EDTA, 2.86 mg/L of H_3BO_3, 1.81 mg/L of $MnCl_2{\cdot}4H_2O$, 0.22 mg/L of $ZnSO_4{\cdot}7H_2O$, 0.079 mg/L of $CuSO_4{\cdot}5H_2O$, 0.039 mg/L of $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$.

Test chamber setting and experimental

Experiments were carried out in a test chamber (purchased from the Kangweinengte Environmental Technology Co., Ltd., Beijing) with 1 m length× 1 m width × 1 m height. *E. aureum*, *C. comosum* and *A. vera*, *S. sediforme*, *Cereus cv. Fairy Castle*, and *S. adolphii* were placed in the test chamber, respectively. And the 500-mL beakers were used to hold 350-mL cultures of microalgae with initial cell density of 5.5×10^6 cells/mL and then placed in the test chamber, respectively. This was designed according to the proportion of indoor area and reactor volume. In addition, considering that the microalgae were cultivated under the indoor conditions where the light intensity was weaker than that of the outdoor, the initial algae density in this experiment was conducive to the better growth of microalgae. These cultures were aerated at a flow rate of 1.5 L/min. A piece of HEPA membrane (3 cm × 6 cm, purchased from the Nantong Kangjing Environmental Protection Technology Co., Ltd., China) was stored in the bottleneck of 500-mL reagent bottle (SCHOTT DURAN narrow neck), through which an air pump was connected with 1.5 L/min of flow rate. Nano activated carbon particles (360 g) (Hengxinda Technology Co., Ltd., China) were laid on the bottom of the reagent bottle and connected with an air pump, and the flow rate was 1.5 L/min. Another nano activated carbon particles (360 g) were packed and dispersed in the test chamber. The microalgae liquid was replaced by distilled water to exclude the influence of water. And empty beaker was used to replace microalgae liquid to exclude the influence of the closed reactor on the experiment. When the experiment was carried out, the indoor light intensity was 300 lux, which was close to the actual indoor light intensity (Daugaard, et al., 2019).

The six-in-one module and oxygen measuring module were placed in the middle position of the test chamber. The six-in-one module (purchased from Hong Rui Tai Electronic Co., China) was used to measure the concentrations of $PM_{2.5}$, PM_{10}, VOCs, and HCHO; the content of carbon dioxide; and the relative humidity. And oxygen measuring module (purchased from Dingyu Huanxin Technology Co., Ltd., China) was used to measure the oxygen content. The indoor air pollution was simulated by straw module combustion. The leaf powder of corn stover (10 mesh) was mixed with starch (w:w = 10:1) to make a paste. Then it was stirred with straw powder (10 mesh) at a volume ratio of 1:1 and compressed into small modules with a diameter of about 8 cm and a thickness of about 5 mm and placed in an oven at 60 °C for drying for 1 day. In each experiment, the straw module was cut into 1 cm length × 1 cm width and ignited, and then placed in the test chamber for experimental simulation to keep PM_{10} at about 2800 μg/m^3 and $PM_{2.5}$ keep slightly larger than 999 μg/m^3. First, the concentrations of $PM_{2.5}$, PM_{10}, VOCs, and HCHO; contents of carbon dioxide and oxygen; and relative humidity in the test chamber were measured before experiment. After that, the straw module was put into the test chamber and ignited, and these indicators were measured again after the combustion was complete. And then the air pump started to be aerated. The experimental indicators were recorded every 30 min, and the reaction period was 3.5 h. Each experiment was conducted in triplicate. The schematic diagram of the experimental device is shown in Fig. 1.

Data processing and analysis

The optical density of *Chlorella* sp. HQ at 690 nm (OD_{690}) was measured with a microplate reader (Multiskan-K3, Thermo Fisher Scientific, USA) to determine the cell dry weight. The linear correlation between OD_{690} and cell dry weight was pre-determined, the detailed correlation is shown Eq. (1). The dry weight of *Scenedesmus* sp. LX1 was calculated according to Li et al. (2010). The removal efficiency of $PM_{2.5}$, PM_{10}, VOCs, and HCHO used Eq. (2) to calculate. In order to compare the HCHO removal capacity of unit biomass of common ornamental plants and microalgae, the total concentration of HCHO (mg/m^3) was calculated by Eq. (3). The change multiple of relative humidity, carbon dioxide, and oxygen content were calculated by Eq. (4).

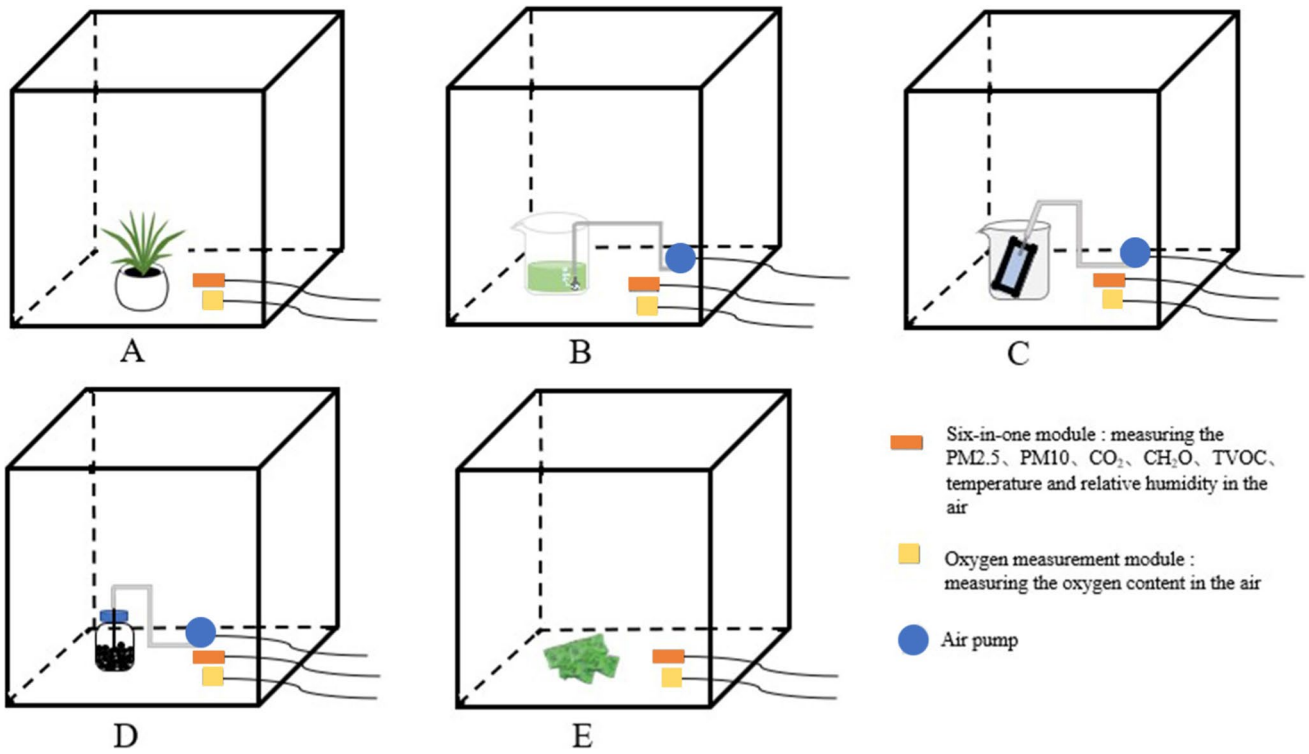

Fig. 1 Simulation experiment setting of ornamental plants, microalgae and common purification methods **A** represented using ornamental plants to purify polluted air, **B** represented using microalgae to purify polluted air, **C** represented using HEPA membrane to purify polluted air, **D** represented using nano activated carbon particles which were laid on the bottom of the reagent bottle and connected with an air pump to purify polluted air, **E** represented using nano activated carbon particles which were packed and dispersed to purify polluted air)

$$\mathrm{DW(g/L)} = 0.1728 \times \mathrm{OD}_{690} - 0.0026, R = 0.9985 \quad (1)$$

$$\text{Removal rate}(\%) = \frac{C_0 - C_i}{C_0} \times 100\% \quad (2)$$

where C_0 and C_i denote the concentration at the beginning of reaction and some 30 min, respectively. And when calculating the removal rate of $PM_{2.5}$, the C_0 was based on 999 μg/m^3.

$$X = \frac{M \times C}{22.4} \quad (3)$$

where X is the concentration of the pollutant in milligrams per standard cubic meter; C is the concentration of the pollutant in ppm; M is the relative molecular mass of HCHO and CO_2.

$$\text{Multiple of Change} = \frac{A_i}{A_0} \quad (4)$$

where A_0 and A_i denote the value of relative humidity, carbon dioxide, and oxygen content at the beginning of reaction and the end of experiment, respectively.

Results and discussion

Removal efficiency of particulate matters

Previous studies have demonstrated that plants can reduce the concentration of particulate matter in the air; however, the capabilities of decreasing particulate matter concentration vary from species to species (Nowak et al., 2006). In this study, not only were the removal abilities of different ornamental plants compared, but also microalgae and physical purification methods were compared. These common ornamental plants and microalgae could reduce PMs concentration, but their abilities of reducing pollutants were different. According to the volume ratio of *Chlorella* sp. HQ (40.55 ± 20.67 μm^3/cell) to *C. vulgaris* (45.27 ± 30.92 μm^3/cell), the dry weight of *C. vulgaris* was estimated, and further the pollutant removal per unit biomass was also counted. As shown in Tables 1 and 2, indoor ornamental plants could decrease these larger diameter particles PM_{10} effectively, and the reduction of PM_{10} by unit biomass of *C. comosum* were higher than others. Microalgae could also reduce indoor PM_{10} concentration, and the unit biomass of

Table 1 The removal amount of $PM_{2.5}$ by unit biomass ($\times 10^{-3}$ g/g)

Time (h)	1#	2#	3#	4#	5#	6#	7#	8#	9#
0	0	0	0	0	0	0	0	0	0
0.5	0	1.81±0.57	0	0	0	0	0	0	0
1	0	4.52±0.59	0	0	0	0	0	0	0
1.5	0	8.48±0.61	0	0	0	0	0	0	0
2	0	11.31±1.06	0	0	0	0	0	0	0
2.5	0	14.27±0.95	0	0	0	0	0	0	0
3	7.67±6.11	15.69±1.11	0	0	0	0	0	0	0
3.5	13.82±5.52	17.93±1.11	0	0	0	0	0	0	0

1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1 (with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*

The influence of the control group was not deducted in the calculation

Table 2 The removal amount of PM_{10} by unit biomass (the unit of 1#, 2#, and 3# is $\times 10^{-3}$ g/g, while the unit of the others is $\times 10^{-6}$ g/g)

Time(h)	1#	2#	3#	4#	5#	6#	7#	8#	9#
0	0	0	0	0	0	0	0	0	0
0.5	20.08±1.53	2.52±0.75	0.97±0.47	0.69±0.12	0.07±0	0.53±0.12	0.15±0.12	2.88±1.49	0.29±0.00
1	27.75±2.28	7.86±1.25	2.03±1.00	1.72±0.18	0.14±0.02	1.25±0.37	0.47±0.13	8.29±1.71	0.66±0.00
1.5	34.83±2.32	13.16±0.81	2.73±1.01	3.34±0.30	0.19±0.02	2.22±0.27	1.63±0.33	20.72±5.56	0.89±0.00
2	41.34±2.46	15.73±1.15	3.48±0.95	4.31±0.40	0.32±0.08	3.19±0.10	2.59±0.14	16.10±6.07	1.48±0.00
2.5	48.51±2.65	18.99±1.07	4.21±0.88	5.30±0.29	0.48±0.15	4.13±0.01	3.51±0.17	22.28±6.48	1.92±0.00
3	54.27±2.78	20.87±1.31	4.74±0.98	6.70±0.35	0.55±0.13	5.18±0.06	4.09±0.15	27.58±7.28	2.53±0.00
3.5	58.20±2.80	25.09±1.69	5.21±0.94	8.06±0.54	0.62±0.13	6.17±0.28	4.98±0.13	34.50±8.53	2.98±0.00

1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1 (with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*

The influence of the control group was not deducted in the calculation

microalgae (g) could decrease $(5.21 \pm 0.94) \times 10^{-3} - (58.20 \pm 2.80) \times 10^{-3}$ g PM_{10}. Microalgae had stronger abilities to reduce PM_{10} than ornamental plants. Among them, the removal amount of PM_{10} per unit biomass by *Chlorella* sp. HQ was 2.3 and 11.2 times higher than that of *C. vulgaris* and *Scenedesmus* sp. LX1 in one experimental cycle, respectively, which indicated that *Chlorella* sp. HQ had a stronger ability to remove PM_{10}. The ability of ornamental plants to remove $PM_{2.5}$ was much lower than that of microalgae. Among the tested ornamental plants and microalgae, only *Chlorella* sp. HQ and *C. vulgaris* could decrease the $PM_{2.5}$ concentration below the maximum detection limit in 3.5 h. And *Chlorella* sp. HQ and *C. vulgaris* could remove $(13.82 \pm 5.52) \times 10^{-3}$ g and $(17.93 \pm 1.11) \times 10^{-3}$ g $PM_{2.5}$ per unit biomass (g), respectively. In general, the ability of microalgae to reduce particulate matter concentration was better than that of ornamental plants.

In addition, the removal rates of $PM_{2.5}$ and PM_{10} by different purification methods (including indoor common ornamental plants, microalgae and physical methods) were compared, as shown in Fig. 2. It was found that the abilities of indoor ornamental plants to remove $PM_{2.5}$ and PM_{10} in 3.5 h were weak. The highest removal rates of $PM_{2.5}$ and PM_{10} were 3.50 ± 4.95% and 25.46 ± 3.50% realized by *C. comosum* and *S. sediforme*, respectively. The decrease of PM by common physical methods and microalgae was compared. HEPA membrane could remove 100% $PM_{2.5}$ and PM_{10} in 2 h, while *C. vulgaris* had the second highest removal rate of $PM_{2.5}$ than HEPA membrane, and 37.26 ± 2.57% of $PM_{2.5}$ could be reduced by *C. vulgaris*. The removal rate of $PM_{2.5}$ by nano activated carbon (in natural state) was lower than that of *C. vulgaris*, but it was still higher than that of *Chlorella* sp. HQ. And their removal rates were 34.50 ± 5.85% and 22.32 ± 7.28%, respectively. The removal rates of PM_{10} by *C. vulgaris* and *Chlorella* sp. HQ were similar, and slightly higher than those of nano activated carbon (in natural state). Finally, 45.76 ± 5.32%, 45.34 ± 0.77%, and 42.61 ± 3.86% of PM_{10} were removed by them, respectively. The removal rates of $PM_{2.5}$ and PM_{10} in distilled water control group were 0% and 19.41 ± 1.11%,

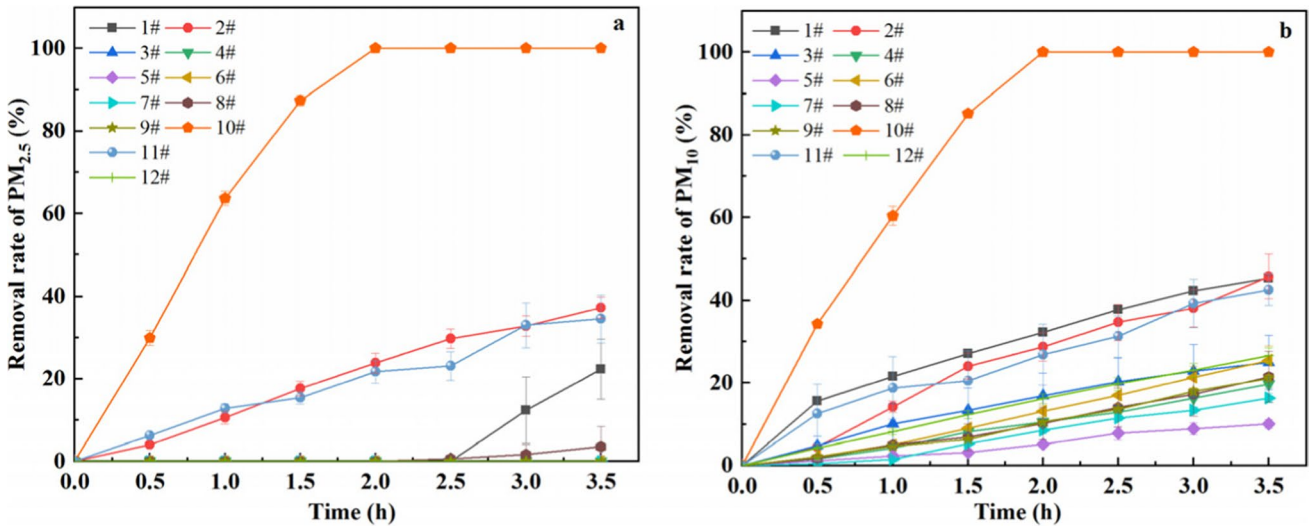

Fig. 2 Removal rates of particulate matter by ornamental plants, microalgae, and physical purification methods (1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min) , 3# *Scenedesmus* sp. LX1(with air pump flow 1.5 L/min) , 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*, 10# HEPA (with air pump flow 1.5 L/min), 11# nano activated carbon (natural conditions) , 12# nano activated carbon (with air pump flow 1.5 L/min)

which indicated that the cells of *C. vulgaris* and *Chlorella* sp. HQ had strong removal ability to $PM_{2.5}$.

All these results indicate that green plants and microalgae are advantageous to decrease particulate matter where microalgae were more efficient at removing $PM_{2.5}$ and PM_{10}. Some studies suggested that the positively charged air particles might be captured by the negatively charged microalgae surface, and the functional groups on the cell surface were ionized at a specific pH, thereby promoting the absorption of particles by the microalgae (Lu et al., 2019). Some studies have suggested that plants can reduce $PM_{2.5}$ and PM_{10} in indoor air (Gawronska et al., 2015; Peng et al., 2020). The ability of plants to reduce particulate matter in the air is influenced by many factors, such as species, leaf surface characteristics, and air relative humidity. Popek et al. studied the particulate matter accumulation of 13 species of plants, and the experimental results showed that there were significant differences among species (Peng et al., 2020). Leaf traits such as size, rugosity, and wax layer play important roles in accumulation of particulate matter (Popek et al., 2013). Stapleton and Rui-Rudolph (2016) believed that plant area was the most important factor affecting the deposition of ultrafine particles, and plants with complex leaf morphology and/or surface roughness may be the most successful in reducing indoor and outdoor ultrafine particles (Stapleton and Ruiz-Rudolph, 2016). Cao et al. (2019) studied the leaf microstructure of six potted plants, found obvious ridge like protuberances on the leaf surface of *E. aureum* and *C. comosum*, while the leaf surface of *Aloe Vera* was relatively flat, so the removal rate of $PM_{2.5}$ by *E. aureum* and *C. comosum* was higher. A similar result was found that the removal efficiency of $PM_{2.5}$ by *C. comosum* was higher. Additionally, plants placed indoors could provide more internal surfaces for the retention, attachment, or adhesion of particulate matter, and stable indoor environment was also conducive to the reduction of particulate matter concentration (Kim et al., 2017). In this study, the concentration of $PM_{2.5}$ could not be reduced to the upper limit of detection in 3.5 h by *E. aureum*; *its* removal efficiency of particulate matter was not great.

Removal efficiencies of HCHO and VOCs

Previous studies have shown that numerous ornamental plants can remove HCHO and volatile organic compounds from indoor air (Xu et al., 2011; Zhao et al., 2019; Wood et al., 2006; Orwell et al., 2006). In this study, the HCHO and VOCs could be completely reduced by all microalgae and most ornamental plants, while in the physical methods, only nano activated carbon had the effect of removing HCHO and VOCs, as shown in Fig. 3. Compared with ornamental plants, the advantage of microalgae was that it could reach the equilibrium time in a shorter time (0.5h), while in ornamental plants groups only *S. sediforme* among ornamental plants could achieve 100% removal of HCHO and VOCs within 0.5 h. In order to further explore the abilities of ornamental plants to removal HCHO, the reductions of HCHO by unit biomass (g) were calculated. It was found that only the unit biomass (g) of *C. comosum* could realize the HCHO reduction of $(1.14 \pm 0.73) \times 10^{-7}$ g, while the removal amount by unit biomass (g) of other plants were in

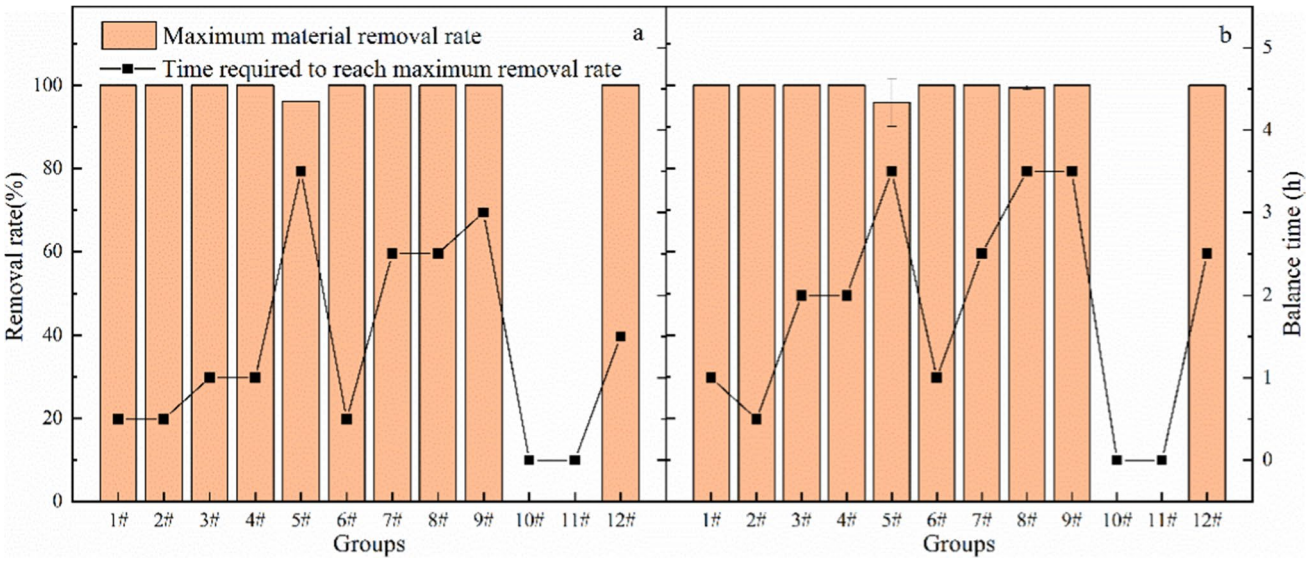

Fig. 3 The maximum removal rates of HCHO (**a**) and VOCs (**b**) by ornamental plants, microalgae, and physical purification methods and the time required to reach maximum removal rates (1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1(with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*, 10# nano activated carbon (with air pump flow 1.5 L/min))

the range of $(5.38 \pm 7.61) \times 10^{-10} - (3.45 \pm 0.88) \times 10^{-8}$ g. From this perspective, *C. comosum* had the best ability to remove HCHO. This finding was similar to the Xu et al. (2011), which showed compared with *A. vera*-soil system and *E. aureum*-soil system, and *C. comosum*-soil system achieved the strongest capacity to remove HCHO, which realized 90% HCHO removal efficiencies at the light intensity of 80 μmol/m^2/s; moreover, HCHO removal efficiencies also affected with its initial concentration. The VOC removal efficiencies for *E. aureum*, *S. sediforme*, *A. vera*, and *C. comosum* were 100%, 100%, 100%, and 99.46 ± 0.54%. It was generally believed that plants could absorb air pollutants through stomata during the gas exchange process, and then transfer to other areas of the plant to be degraded. The removal rate of HCHO mainly depends on the decomposition of HCHO by plant stems and leaves, and the main process is an enzymatic reaction. The removal of VOCs mainly depended on the rhizosphere microorganisms in plant pots (Aydogan and Montoya, 2011; Zhao et al., 2019). Although ornamental plants had a good purification effect on HCHO and VOCs, it also faced the defect of long removal time. Among the tested microalgae, all three species of microalgae could achieve 100% removal for HCHO and VOCs. The purification time of *Scenedesmus* sp. LX1 was longer (2 h), while the purification of the other two microalgae only required 0.5 h or 1 h. The removal amounts of HCHO by unit biomass among these microalgae were also compared. The results showed that the unit biomass of *Chlorella* sp. HQ and *C. vulgaris* could decrease $1.11 \pm 0.39 \times 10^{-5}$ and $1.49 \pm 2.10 \times 10^{-5}$ g HCHO, respectively. In general, the ability of removing HCHO and VOCs by microalgae was better than that of indoor ornamental plants, especially *Chlorella* sp. HQ and *C. vulgaris*. In the physical purification methods, only nano activated carbon (with air pump flow rate of 1.5 L/min) could reflect the reduction of HCHO, and finally completely remove HCHO and VOCs. Although the removal rates of HCHO and VOCs by green plants and microalgae were equal to that of nano activated carbon (air pump flow rate was 1.5 L/min), their treatment capacities are not comparable since they took different time. *Chlorella* sp. HQ and *C. vulgaris* took shorter time to removal HCHO and VOCs completely than that of ornamental plants and nano activated carbon (air pump flow rate was 1.5 L/min).

Changing trends of relative humidity and its effect on particulate matters

Both the evaporation of water and transpiration of green plants can disperse water into the air, thus increasing the relative humidity in the ambient air. It can be clearly seen from Fig. 4 that both ornamental plants and microalgae could realize an increase in relative humidity of indoor air. *S. adolphii* had weaker ability of increasing relative humidity, which only increase relative humidity to 1.23 times, while other plants could increase this to 1.41–1.60 times. Microalgae had higher humidification capacity than ornamental plants. *Chlorella* sp. HQ, *C. vulgaris*, and *Scenedesmus* sp. LX1 could increase the relative humidity to 3.44, 2.77, and 2.27 times in 3.5 h, respectively. In the distilled water control group, the relative humidity was increased by 2.99 times,

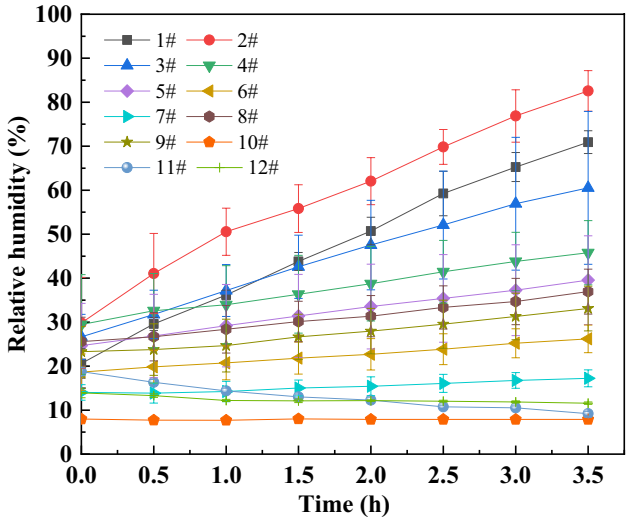

Fig. 4 The changes of relative humidity by ornamental plants, microalgae, and physical purification methods (1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1 (with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*, 10# HEPA (with air pump flow 1.5 L/min), 11# nano activated carbon (natural conditions), 12# nano activated carbon (with air pump flow 1.5 L/min))

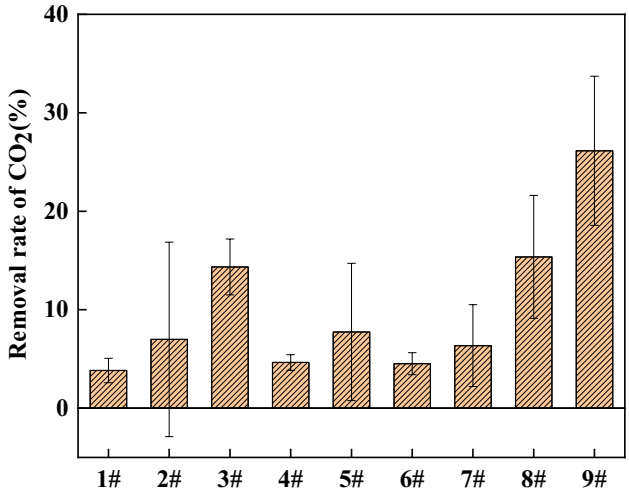

Fig. 5 The Removal rates of CO_2 by ornamental plants and microalgae (1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1 (with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*)

indicating that the moisture had great influence on the relative humidity in the enclosed space. All the ornamental plans and microalgae could raise relative humidity, while HEPA membrane and nano activated carbon particles would absorb water from indoor air while purifying the air, resulting in the decrease of relative humidity in the confined space.

Additionally, relative humidity is an important factor affecting the concentration of particulate matter. Previous studies have shown that there is a correlation between relative humidity and particulate matter, especially $PM_{2.5}$, but the correlation is different. Lou et al. showed that in the Yangtze River Delta, the relationship between relative humidity and $PM_{2.5}$ concentration was inverted U-shaped (the peak appeared when the relative humidity reached 45–70%), and the relationship between relative humidity and PM_{10} was inverted-V-shaped (the peak appeared when the relative humidity reached 40 ± 5%) (Lou et al., 2017). However, Han et al. showed that the concentration of $PM_{2.5}$ in ambient air was positively correlated with relative humidity, while the relative humidity was negatively correlated with residual $PM_{2.5}$ (Han et al., 2015). When the relative humidity is more than 65%, the fine particles will aggregate into larger particles. In this study, the increase of relative humidity in microalgae experiment groups was higher than that in green plants, so it may promote the change of $PM_{2.5}$ to larger particle size particles, resulting in the decrease of concentration of $PM_{2.5}$ in the air.

Changes of CO_2 and O_2 contents

Green plants (including microalgae) can use light energy to convert CO_2 and H_2O into energetic organic matter and release O_2 at the same time. This process can be expressed as $CO_2 + H_2O \rightarrow (CH_2O) + O_2$, where (CH_2O) is carbohydrate. It can be seen from Fig. 5 that *C. comosum* and *A. vera* had high CO_2 removal rates, which were 15.37 ± 6.24% and 26.14 ± 7.57%, respectively, while the other plants had lower CO_2 removal rate, ranging from 4.52 ± 1.12% to 7.74 ± 6.98%. *Scenedesmus* sp. LX1 had high CO_2 absorption capacity and reduced 14.34 ± 2.84% CO_2, while *Chlorella* sp. HQ and *C. vulgaris* only made CO_2 concentration reduced by 3.83 ± 1.24% and 6.89 ± 9.88%, respectively. The amount of CO_2 absorbed by plants and microalgae per unit biomass (g) was further calculated, which is shown in Table 3. *C. comosum* and *A. vera* were still the most effective carbon sequestration plants, which realized 0.012815 ± 0.005748 g and 0.004375 ± 0.001576 g reduction in 3.5 h, respectively. The decreasing order of CO_2 content by unit biomass of ornamental plants was *C. comosum* > *A. vera* > *S. adolphii* > *S. sediforme* > *Cereus cv. Fairy Castle* > *E. aureum.* Although the removal rate of CO_2 by *C. vulgaris* was only 6.98 ± 9.88%, the highest CO_2 uptake per unit biomass (g) of it was 3.85 ± 5.45 g. The second is *Chlorella* sp. HQ, which removed 1.95 ± 0.65 g by unit biomass. The content of CO_2 in the distilled water control group did not change all the time, indicating that microalgae cells had a strong ability to absorb CO_2. Compared with the carbon fixation capacity of ornamental plants, microalgae have stronger

Table 3 CO_2 absorption by unit biomass (the unit of 1#, 2#, and 3# is g/g, while the unit of 4#, 5#, 6#, 7#, and 8# is $\times 10^{-4}$ g/g)

Time(h)	1#	2#	3#	4#	5#	6#	7#	8#	9#
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	1.46±0.88	3.85±5.45	0.15±0.09	1.44±1.44	0.30±0.24	0.30±0.24	2.77±1.01	82.82±99.61	82.82±82.66
1	1.95±0.65	3.85±5.45	1.01±0.26	4.85±0.90	0.58±0.42	0.58±0.42	4.66±2.39	99.61±73.44	99.61±73.44
1.5	1.95±0.65	3.85±5.45	1.27±0.29	6.10±0.36	0.82±0.59	0.82±0.59	6.04±3.78	114.16±64.28	114.16±64.28
2	1.95±0.65	3.85±5.45	1.27±0.29	7.00±1.26	1.40±1.16	1.40±1.16	7.05±4.78	128.15±62.19	128.15±62.19
2.5	1.95±0.65	3.85±5.45	1.27±0.29	7.00±1.26	1.18±0.91	1.18±0.91	7.05±4.78	128.15±57.48	128.15±57.48
3	1.74±0.46	2.87±4.06	1.27±0.29	7.00±1.26	1.78±1.66	1.78±1.66	7.05±4.78	136.55±64.78	136.55±64.78
3.5	1.95±0.65	3.85±5.45	1.27±0.29	7.00±1.26	1.82±1.71	1.82±1.71	7.05±4.78	128.15±57.48	128.15±57.48

1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1 (with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*

carbon fixation capacity, especially *Chlorella* sp. HQ, and *C. vulgaris*. Microalgae have always been considered organisms with high carbon sequestration capacity (Klinthong, et al., 2015). In some large-scale microalgae culture processes, the carbon dioxide fixed by microalgae per unit biomass could even be as high as 4.32 (g/g) (Ryu, et al., 2009).

Most ornamental plants and microalgae can increase the oxygen content in the test chamber, mainly because plants and microalgae can carry out photosynthesis under light

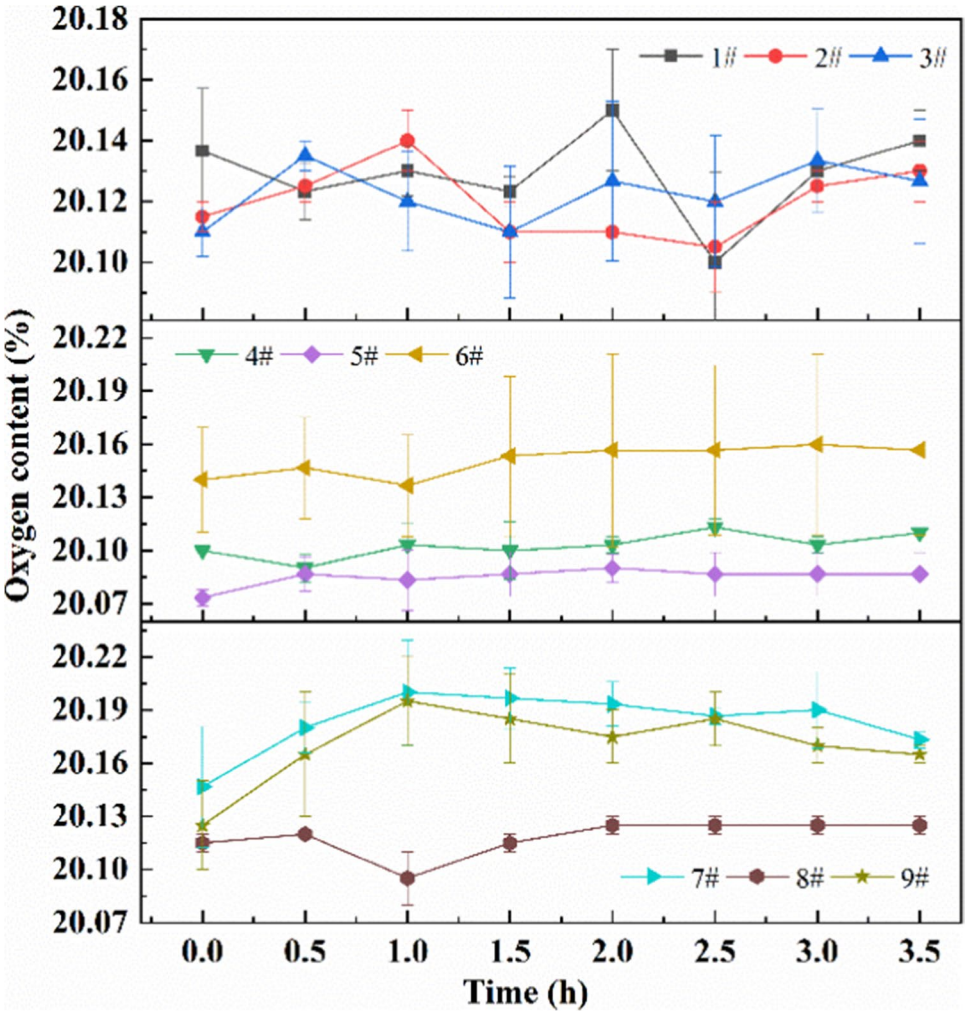

Fig. 6 The changes of O_2 content (1# *Chlorella* sp. HQ (with air pump flow 1.5 L/min), 2# *Chlorella vulgaris* (with air pump flow 1.5 L/min), 3# *Scenedesmus* sp. LX1(with air pump flow 1.5 L/min), 4# *Epipremnum aureum*, 5# *Cereus cv. Fairy Castle*, 6# *Sedum sediforme*, 7# *Sedum adolphii*, 8# *Chlorophytum comosum*, 9# *Aloe vera*

conditions. The influence of ornamental plants and microalgae on the change of oxygen content is shown in Fig. 6. *A. vera* can increase the oxygen content the most, from 20.13 ± 0.02% to 20.17 ± 0.00%, while other plants and microalgae can only increase the oxygen content by 0.01–0.02%.

Conclusions

The microalgae and ornamental plants investigated in this study were capable of pollutants removal from indoor air. Microalgae can not only absorb HCHO and total volatile organic compounds, but also decrease the particulate matter concentration, especially *C. vulgaris*, which could reduce 55.42 ± 25.77% $PM_{2.5}$ and 45.76 ± 5.32% PM_{10}. Microalgae and most ornamental plants could completely remove HCHO, while microalgae especially *C. vulgaris* and *Chlorella* sp. HQ took less time. Both microalgae and ornamental plants could increase relative humidity and oxygen concentration. In general, microalgae could achieve indoor air purification more efficiently, especially in removing particulate matters.

Author contributions Qiao Wang: data curation, formal analysis, methodology, visualization, software, validation, writing—original draft. Li-Hua Li: data curation, formal analysis, visualization. Yu Hong: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, writing—review and editing. Qing-Yu Zhai: investigation, visualization. Yi-Tian He: investigation, funding acquisition.

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Data availability The datasets generated during and/or analyzed during the current study are available in the manuscript.

Declarations

Ethical approval Ethics approval was not required for this research.

Consent to participate All authors made contributed to this work and approved the manuscript to be published.

Consent to publish All authors express their consent to publish.

Competing interests The authors declare no competing interests.

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