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Dual-Benefit Enhancement of Air Purification by Hydroponic Plants Using Smart Planters

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Abstract

To address the scarcity of negative air ions (NAIs) in indoor environments and the high energy consumption of conventional air purification technologies, this study proposed a "smart planter-hydroponic plant" system for improving indoor air quality. Four common indoor hydroponic plant species were selected as monitoring objects. By integrating the precise regulation of light, temperature, water, and nutrients provided by smart planters, closed-environment simulation experiments were conducted to quantify plant-derived NAI release and formaldehyde removal performance, thereby evaluating the enhancement potential of intelligent control technologies. The results showed that: 1) *Chlorophytum comosum* was the optimal species for the smart planter-hydroponic plant system. When combined with the smart planter, the maximum NAI concentration in the closed environment reached 3681 ions/cm^3, representing an increase of more than approximately 1.8-fold compared with single-plant cultivation in a conventional planter, while the formaldehyde removal rate reached 60.51%; 2) The smart planter mitigated the decline in purification efficiency under low-light or dark conditions through an active NAI-generating module and intelligent regulation of plant physiological status, thereby ensuring sustained and stable indoor air quality improvement. This study demonstrates the dual enhancement effect of smart planters on hydroponic plants and provides a theoretical basis and technical approach for developing healthy indoor horticultural systems.

Keywords

Smart Planter, Hydroponic Plants, Negative Air Ions, Air Purification, Indoor Horticulture

1. Introduction

Driven by China's carbon peaking and carbon neutrality goals and the Healthy China strategy, the optimization of indoor ecological environments has become an emerging research focus. Modern people spend approximately 80% of their time indoors, where they are continuously exposed to pollutants such as formaldehyde and total volatile organic compounds (TVOCs) released from decorative materials. At the same time, negative air ions (NAIs) are often deficient in indoor environments, with ordinary indoor NAI concentrations typically below 200 ions cm^{-3}, only one-fifth to one-tenth of those in natural environments. Long-term exposure to these indoor pollutants poses substantial risks to human health [1]-[3]. Owing to its low-carbon and sustainable characteristics, plant-based ecological purification has greater application potential than technologies such as activated carbon adsorption and photocatalysis. However, conventional potted plants are constrained by low purification efficiency at the individual-plant scale and high maintenance requirements [4]-[6].

Smart planters integrate sensors and automatic regulation modules, enabling precise alignment with plant growth requirements and providing technical support for enhancing ecological purification performance [7]. Since Wolverton (1993) proposed the use of plants for indoor pollutant removal, most studies have focused on the purification capacity of individual plants, such as the absorption of formaldehyde by pothos. In contrast, little attention has been given to the synergistic compatibility between intelligent devices and plants, particularly the optimization of device-plant combinations for enhancing NAI concentrations [8]-[10]. Hydroponic plants, characterized by well-developed root systems, high ornamental value, and the absence of soil-related contamination, represent a preferred form of indoor horticulture. Their root oxygen-releasing capacity may further enhance microbially mediated purification. However, NAI release varies substantially among plant species and may be coupled in complex ways with the regulation of light, temperature, water, and nutrients by smart planters; the rules governing such compatibility remain unclear [11].

This study aimed to improve indoor air quality using a smart planter-hydroponic plant system. By screening common indoor hydroponic plants and quantifying their ecological purification performance, this study addressed the practical questions of which plant species should be selected and how effective such systems are under applied conditions. The findings provide theoretical support and technical guidance for the standardized and intelligent development of healthy indoor horticulture.

2. Materials and Methods

2.1. Equipment

The smart planter used in this experiment was the Meifu eBao 3C model (KJFMN3C). Its core functions included an active negative ion generation module, which continuously released negative air ions to improve microenvironmental air quality.

The device was also equipped with an intelligent maintenance system that dynamically optimized plant growth conditions through environmental sensing and automatic irrigation. In addition, the planter contained a large-capacity water reservoir, allowing up to 30 days of operation without manual water replenishment and thereby substantially reducing maintenance frequency. Compared with devices used in similar studies, this smart planter showed certain advantages in system integration and intelligent regulation [7].

2.2. Plant Selection

Considering indoor ornamental value and public preference, plant selection followed the principle of "prioritizing adaptability while balancing functional performance and ornamental value". Based on the Catalogue of Indoor Ornamental Plants in China and hydroponic cultivation practices in the Jiangnan region, one species was selected from each of four families-Araceae, Asparagaceae, Araliaceae, and Acanthaceae-resulting in four common indoor ornamental plants as the study species, as shown in **Table 1**. According to the method of calculating plant leaf area, plants with irregular leaf shapes are transformed into corresponding geometric shapes for calculation, so that the leaf areas of the four samples are as similar as possible, in order to eliminate the interference of leaf area as a variable on the experimental results. To evaluate hydroponic growth adaptability, the four species were cultivated hydroponically for four weeks under 23˚C and 4000 lux, after which root rot incidence was measured.

All four experimental plant species were cultivated hydroponically using Hoagland nutrient solution at pH 5.5 - 6.0. This formulation has been verified by Liu Xiaojiao *et al.* as being highly suitable for the hydroponic cultivation of indoor foliage plants. The plants were transplanted into hydroponic pots measuring 10 cm × 10 cm × 11 cm, with approximately half of the root system immersed in the nutrient solution. After a two-week pre-cultivation period to allow root stabilization, the plants were used for subsequent experiments [12].

Table 1. Basic information on the hydroponic plants.

Family	Plant species	Hydroponic adaptability
Araceae	*Epipremnum aureum*	Excellent (root rot incidence: 1.8%)
Asparagaceae	*Chlorophytum comosum*	Excellent (root rot incidence: 3.2%)
Araliaceae	*Heptapleurum heptaphyllum*	Excellent (root rot incidence: 2.1%)
Acanthaceae	*Fittonia albivenis*	Excellent (root rot incidence: 2.5%)

2.3. Experimental Design

After pre-cultivation, the plants were transplanted into the smart planters, as shown in **Figure 1**. For each plant species, each plant was set up as a control group with ordinary flower pots, and a total of 8 plants were tested. The experiment was conducted in a customized sealed glass chamber measuring 80 cm × 80 cm × 80 cm.

Figure 1. Schematic diagram of four plant species cultivated in smart planters.

Environmental conditions were controlled as follows: temperature, 23˚C ± 1˚C; relative humidity, 50% - 70%. Two sets of experiments were conducted in the same office under the same natural lighting conditions. These conditions were designed to simulate the typical thermal and light environments of modern office and residential spaces. For the hydroponic system, the electrical conductivity of the nutrient solution was maintained at 1.4 $mS \cdot cm^{-1}$, natural light was used, and the nutrient solution in conventional planters was manually replaced once per week.

2.4. Measurement Indicators and Methods

NAI release: Negative air ion concentrations were measured in the customized sealed glass chamber using an air negative ion detector. To minimize spatial heterogeneity, three monitoring points were evenly arranged inside the chamber. Referring to the typical daytime period during which people remain indoors for work, monitoring was conducted daily from 09:00 to 18:00, with readings recorded at 1-h intervals. The hourly mean value from the three monitoring points was used as the NAI concentration. The smart planters records the total NAI output of the system, while the ordinary flowerpot records the release of negative oxygen ions from plants.

Purification performance: Place an equal amount of 5.0 μL 37% formaldehyde solution at the corner of the sealed box, seal and let it stand for 48 hours until the concentration reaches equilibrium, and then measure the initial concentration of formaldehyde in each box (the initial concentration of formaldehyde in the sealed box is less than 0.01 mg/m^3). Formaldehyde concentration was then monitored every 2 h for a total of six consecutive measurements. A portable pump-suction six-in-one gas detector was used to determine the initial and final formaldehyde concentrations, and the 12-h removal rate was calculated. The removal rate was calculated as follows:

$$\text{Removal rate} = (\text{initial concentration} - \text{final concentration})/\text{initial concentration} \times 100\%$$

The data was analyzed using SPSS 26.0 for one-way ANOVA to compare the differences in mean air negative ion concentrations of different plants under the same pot conditions and all images were generated using Origin 2023.

3. Results and Analysis

3.1. Enhancement Effect of Smart Planters on NAI Release from Hydroponic Plants

To verify the effectiveness of the smart planters, NAI release was compared between hydroponic plants cultivated in smart planters and those grown in conventional planters. The closed chamber experiment showed that the intelligent regulation, together with the active NAI generation module, greatly improved the total output of negative air ions in hydroponic plants of the smart group. As shown by the time-series data in Figure 2, the smart planter markedly improved NAI release performance in all tested hydroponic plants. Under normal conditions, plant-derived NAI release may vary over time depending on species-specific growth characteristics. Nevertheless, the NAI concentration curves of *Epipremnum aureum*, *Chlorophytum comosum*, *Heptapleurum heptaphyllum* and *Fittonia albivenis* grown in smart planters were consistently higher than those of the conventional planter controls. In particular, during periods with sufficient daytime light, such as 12:00-14:00, the smart planter treatments generally reached higher concentration peaks. The active negative ion generation module continuously released NAIs, allowing the sealed chamber to maintain relatively high NAI concentrations for most of the day. By contrast, the conventional planter treatments showed greater concentration fluctuations and a pronounced decline in the afternoon, with overall baseline concentrations far lower than those of the smart planter treatments.

Based on the statistical data in Table 2, it can be further concluded that in the two key indicators of maximum and average values, the data under smart planter cultivation is significantly ahead of conventional planter. For example, the maximum NAI concentration of *Chlorophytum comosum* grown in the smart planter

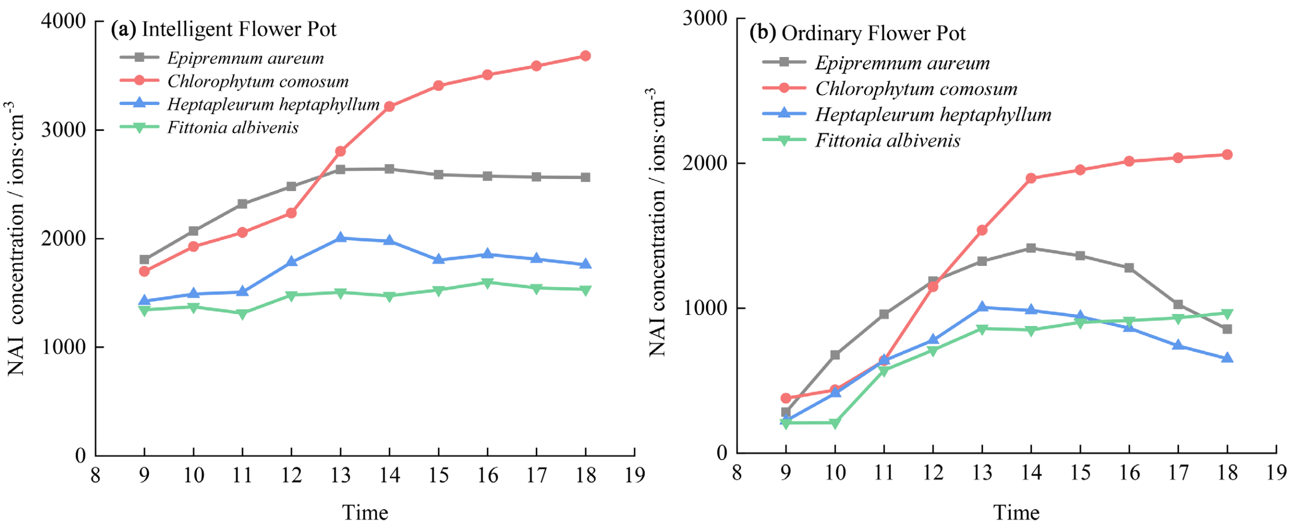

Figure 2. Temporal variation in negative air ion concentrations released by four hydroponic plant species.

Table 2. Characteristic values of negative air ion concentrations released by four hydroponic plant species.

Plant species	Negative air ion concentration under smart planter cultivation (ions/cm^{-3})			Negative air ion concentration under conventional planter cultivation (ions/cm^{-3})		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Epipremnum aureum	2639	1807	2423^{ab}	1415	284	1036^{a}
Chlorophytum comosum '*Variegatum*'	3681	1697	2811^{a}	2059	379	1410^{a}
Heptapleurum heptaphyllum	2003	1423	1740^{b}	1005	224	724^{b}
Fittonia albivenis	1598	1345	1469^{b}	967	208	713^{b}

The letters a and b represent the results of significant differences from multiple comparisons.

reached 3681 ions/cm^3, with a mean value of 2811 ions/cm^3, approximately 1.8 and 2.0 times higher than those in the conventional planter treatment, respectively, which were 2059 ions/cm^3 and 1410 ions/cm^3. In addition, the smart planter markedly increased the lower limit of plant-associated NAI concentrations. The minimum values in the conventional planter treatments were generally low, with *Heptapleurum heptaphyllum* reaching only 224 ions/cm^3. This indicates that the total negative ion output of the smart planter system is much higher than that of the conventional group, which can maintain a more stable and long-lasting air purification efficiency. This may be due to the significant synergistic effect of the smart planter automatic adjustment system on all tested plants, or the reinforcement of the active negative ion generation module. One-way ANOVA showed that, under smart planter cultivation, the mean NAI concentration of *Chlorophytum comosum* differed significantly from those of *Heptapleurum heptaphyllum* and *Fittonia albivenis* ($p < 0.05$). Similarly, the mean NAI concentration of *Epipremnum aureum* differed significantly from those of *Heptapleurum heptaphyllum* and *Fittonia albivenis* ($p < 0.05$), whereas no significant difference was observed between *Chlorophytum comosum* and *Epipremnum aureum*. These results indicate that the combination of smart planter and variegated spider plant achieved the highest NAI release, significantly outperforming the other plant-planter combinations.

3.2. Ecological Purification Performance of Smart Planter-Hydroponic Plant Combinations

The ecological purification performance of the four hydroponic plant species was evaluated through a 12-h closed-chamber experiment, as shown in **Figure 3**. The dynamic curves of formaldehyde concentration indicate that the smart planter markedly enhanced the formaldehyde purification process of hydroponic plants. In the sealed chamber, formaldehyde concentrations declined more rapidly in the smart planter treatments (**Figure 3(a)**) than in the conventional planter treatments (**Figure 3(b)**). By the end of the experiment, after 12 h, formaldehyde concentrations in the smart planter treatments had generally decreased to approximately 1.0 mg·m^{-3} or lower, whereas those in the conventional planter treatments remained at relatively high levels above 1.8 mg·m^{-3}.

As shown in Table 3, the formaldehyde removal performance of the smart planter treatments over 12 h was consistently superior to that of the conventional planter controls. Among the smart planter treatments, *Chlorophytum comosum* showed the highest formaldehyde absorption capacity, reaching 1.67 mg·m^{-3}, with a removal rate of approximately 60%. Even *Fittonia albivenis*, which exhibited a relatively lower absorption capacity, reached 0.78 mg·m^{-3}. In contrast, the corresponding values in the conventional planter treatments were only 0.74 mg·m^{-3} and 0.21 mg·m^{-3}, respectively, with the highest removal rate reaching only 29.84%. Overall, formaldehyde absorption by plants grown in smart planters was generally about twice that observed in conventional planters. This suggests that, through its material properties and ecological regulation of plant physiological status, the smart planter can optimize the root-zone microenvironment, enhance plant physiological activity, and thereby accelerate the reduction of residual formaldehyde in indoor air.

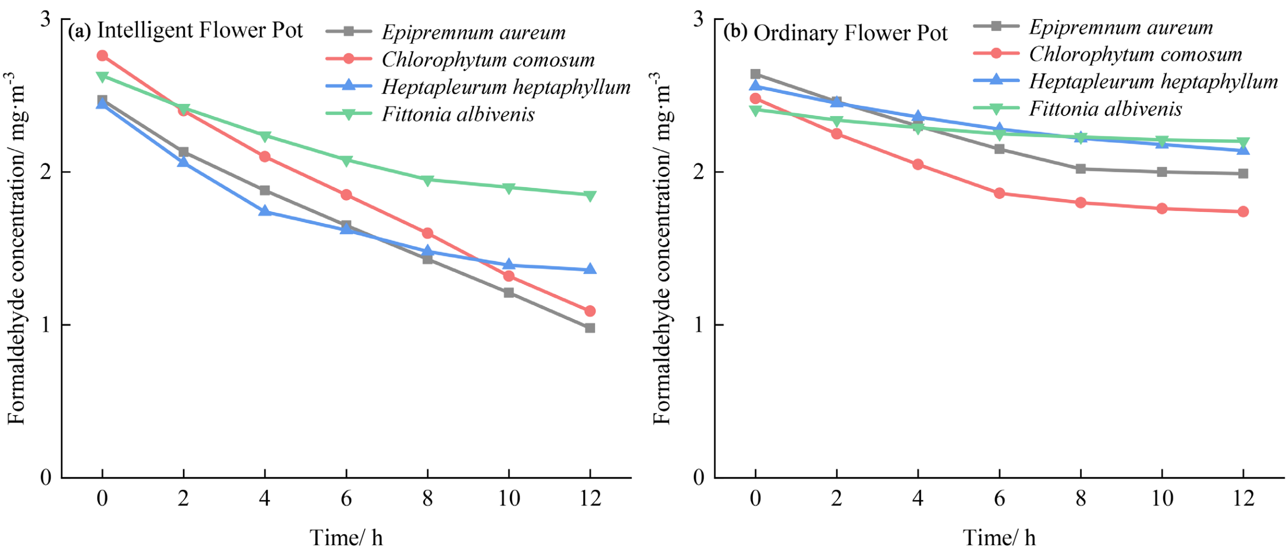

Figure 3. Temporal variation in formaldehyde concentrations in sealed chambers containing four hydroponic plant species.

Table 3. Ecological purification performance of four hydroponic plant species.

Plant species	Smart planter treatment		Conventional planter treatment	
	Formaldehyde removal amount (mg/m^3)	Removal rate (%)	Formaldehyde removal amount (mg/m^3)	Removal rate (%)
Epipremnum aureum	1.49	60.32	0.65	24.62
Chlorophytum comosum ‘*Variegatum*’	1.67	60.51	0.74	29.84
Heptapleurum heptaphyllum	1.08	44.26	0.42	16.40
Fittonia albivenis	0.78	29.66	0.21	8.71

4. Discussion

This study verified, using multiple indicators, that the combination of smart planters and common indoor plants can effectively achieve a "dual enhancement" of air purification performance. This effect can be attributed to the planter's intelligent regulation of plant physiological status, its active NAI generation module, and the strong adsorption capacity of its materials, which together provide effective support for healthy indoor horticultural systems. In terms of NAI release, the smart planter not only markedly increased the peak concentration of negative air ions, but more importantly, mitigated the sharp decline in NAI concentration commonly observed in conventional hydroponic plants during nighttime or low-light periods by actively releasing NAIs, thereby maintaining a high and stable health-promoting baseline concentration. The modular and scientifically designed product structure further highlights the importance and development potential of intelligent technologies in indoor horticulture [13] [14]. For formaldehyde purification, the removal amount in the smart planter treatment was generally more than twice that of the conventional planter treatment within 12 h. This improvement cannot be attributed solely to physical filtration by the planter material; rather, it is more likely associated with the alleviation of plant stress responses through intelligent regulation, which may enhance enzymatic activity and thereby strengthen metabolic transformation pathways [15].

The smart planter transforms conventional hydroponic plants from a mode of "passive adsorption" to one of "active and efficient purification", effectively overcoming the limitations of hydroponic plants alone under daily living conditions, including large fluctuations in purification efficiency and rapid saturation [16]. This enhancement was particularly evident for species with relatively weak inherent purification capacity, such as *Fittonia albivenis*, indicating that intelligent regulation may provide a new approach for diversifying the selection of indoor greening plants. The smart planter-hydroponic plant system can maintain indoor NAI abundance and ecological cleanliness throughout the day, offering a low-cost and ecologically efficient solution for the development of healthy indoor horticultural systems.

This study also has several limitations. First, the experiments were conducted mainly in static sealed chambers and did not account for practical indoor factors such as ventilation and temperature fluctuations. Future studies should therefore evaluate the long-term operational performance of smart planters in complex household environments, with particular attention to the risk of microbial proliferation in nutrient solutions and its potential secondary impacts on indoor air quality. Second, this study focused on only four common horticultural plant species. Future research should include a broader range of species and further examine the ecological benefits of plant combinations relative to single-species systems [17] [18]. Third, future studies could incorporate more foliage-colour varieties and integrate horticultural therapy theory to optimize the landscape diversity of plant combinations and explore the psychological healing effects of compatible smart planter-plant systems [19].

5. Conclusion

This study investigated the dual enhancement effect of smart planters on air purification by hydroponic plants. Among the four tested plant species, *Chlorophytum comosum* was identified as the optimal species for the smart planter-hydroponic plant system, showing the best performance in both NAI release and formaldehyde purification. In the sealed chamber, the maximum NAI concentration reached 3681 ions/cm^3, and the formaldehyde removal rate reached 60.51%. By integrating an active NAI generation module with intelligent regulation, the smart planter not only substantially increased the peak NAI release from plants, but also fundamentally altered the diurnal fluctuation pattern of NAI concentrations observed in conventional hydroponic systems. The intelligent system maintained a high baseline NAI concentration throughout the day, significantly reduced the difference between daytime and nighttime concentrations, mitigated the decline in purification efficiency under low-light or dark conditions, and thereby ensured the sustained stability of indoor air quality.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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