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A New Approach to Expanding Interior Green Areas in Urban Buildings

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Abstract: Countries worldwide have implemented regulations on the green coverage ratio of new buildings to address the urban heat island effect. For example, Taipei City mandates that the green coverage rate of new buildings must be between 40% and 70%, while Singapore requires a green coverage rate of 100% or higher. Consequently, building greening is now a regulatory requirement rather than a preference. This study focuses on developing an indoor light-emitting-diode (LED) hydroponic inverted planting system to utilize ceiling space for expanding green areas in buildings. The light source of this system is suitable for both plant growth and daily lighting, thereby reducing electricity costs. The watertight planting unit does not require replenishment of the nutrient solution during a planting cycle for small plants, which can reduce water consumption and prevent indoor humidity. The modular structure allows various combinations, enabling interior designers to create interior ceiling scapes. Additionally, it is possible to grow aromatic plants and edible vegetables, facilitating the creation of indoor farms. Consequently, this system is suitable for high-rise residential buildings, office buildings, underground shopping malls, and indoor areas with limited or no natural light. It is also applicable to hospitals, clinics, wards, and care centers, where indoor plants alleviate psychological stress and enhance mental and physical health.

Keywords: building greening; inverted planting; energy-saving hydroponics; ceiling farming; ceiling scape

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1. Introduction

Unprecedented urban growth is happening globally right now [1–4]. Cities currently house more than half of the global population. Projections indicate that, by 2050, about two-thirds of the world's population will live in cities [5], worsening the urban heat island effect. As a result, nations globally are tightening regulations on the "green plot ratio" for new urban buildings. For example, the "Taipei City New Building Greening Implementation Rules" [6] require that the Green Plot Ratio (GnPR) of new buildings must reach 40~70%, while Singapore's building regulations require that the GnPR be greater than 100% [7]. The GnPR objectively measures the density of greenery within a development site. For instance, under Development Control (DC) guidelines in Singapore [8], the formula for calculating GnPR is defined as:

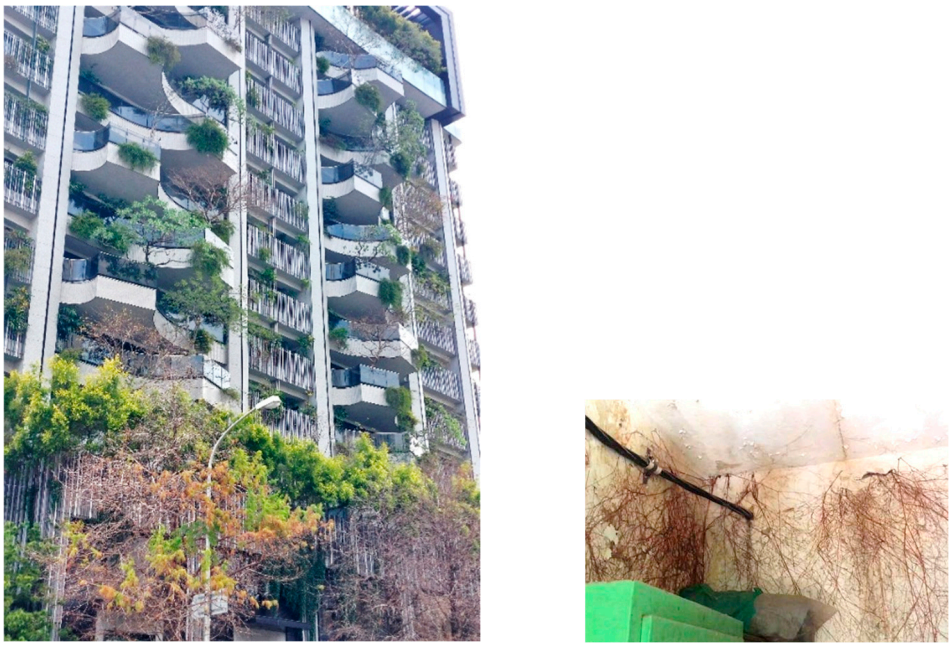
$$\text{GnPR} = \frac{\text{Total leaf area of greenery counted as Landscape Replacement}}{\text{Development Site Area}} \quad (1)$$

The Landscape Replacement Areas (LRA) requirements are calibrated by location, gross plot ratio, and development type. A development may count sky terraces, communal

planter boxes, and covered communal ground gardens, amongst other features, towards meeting the LRA requirement. The total leaf area should be computed based on the Leaf Area Index (LAI) for each plant species, canopy area, and the quantity planted. The plant species sub-categories and LAI values may be obtained online from National Parks' Flora Fauna Web [9].

Therefore, the degree of greening of buildings is no longer a matter of personal preference but an issue that must be considered in laws and regulations. As a result, vertical greening, urban gardens, and urban farms are gradually gaining attention.

However, high-density buildings pursuing urban greening face challenges like limited sunlight, strong winds, and rooftop space being occupied by utilities. Despite attempts to add greenery to high-rise balconies or exterior facades, large plants can obstruct views and sunlight on upper floors after maturation, as illustrated in Figure 1a. In tropical cyclones and storms, falling plants from high-rise buildings may endanger people and vehicles on the ground. Conflicting views on plant trimming and who pays for it often lead to disputes among residents. Moreover, root acids secreted by large plants can help roots penetrate concrete, damaging buildings (Figure 1b). Thus, the outdoor greening of high-rises frequently falls short of expectations, presenting an opportunity for indoor greening in urban buildings.



(**a**) (**b**)

Figure 1. (**a**) High-rise buildings' balconies with large plants may cause resident conflicts and hidden dangers from falling branches (a case study of a green building in Taiwan, photographed by the study team). (**b**) Plant roots penetrate the room by secreting root acid and damage the structure [10].

1.1. The Benefits of Indoor Greening

Nowadays, people spend about 87% of their time indoors daily [11]. Lower ventilation rates may contribute to higher indoor air pollutant levels, potentially causing some cases of sick building syndrome (SBS) [12].

Studies show some indoor plants can reduce carbon dioxide (CO_2), volatile organic compounds (VOCs), and microorganisms [13,14]. Thus, in areas with poor ventilation or where mechanical methods are unavailable, indoor plants can enhance air quality and improve the health of living spaces. Table 1 illustrates eight plants that are helpful for the indoor environment.

Table 1. Examples of plants that are helpful for the indoor environment.

Name of Plant	Feature and Application
Mentha canadensis	For tea, aromatherapy, mosquito repellent, cooking spice
Stevia rebaudiana	For tea, aromatherapy, mosquito repellent, cooking spice
Lavandula	For tea, aromatherapy, mosquito repellent, cooking spice
Salvia rosmarinus	For tea, aromatherapy, mosquito repellent, cooking spice
Euphorbia pulcherrima	Ornamental; high efficiency in absorbing CO_2; average ability in absorbing formaldehyde
Nephrolepis exaltata	Highly efficient in absorbing CO_2 and VOCs (formaldehyde, trichloroethylene, xylene, benzene)
Chamaedorea elegans	Highly efficient in absorbing CO_2 and VOCs (formaldehyde, ammonia, trichloroethylene, xylene, toluene)
Chlorophytum comosum	Highly efficient in absorbing CO_2 and VOCs (formaldehyde, trichloroethylene, xylene)

Compiled by authors, [15].

1.2. The Challenges of Indoor Greening

While indoor greening offers the benefits mentioned, traditional indoor planting presents certain challenges. For instance, using sunlight as a light source limits plant placement to window areas, and inconsistent weather makes light unreliable. Additionally, controlling watering in traditional soil-based planting can be difficult; over-watering may lead to water accumulation, increasing indoor humidity and promoting mold growth. The soil can also contain insect eggs, which upon hatching, allow caterpillars, moths, and ants to survive, reproduce, and feed on indoor plants.

Addressing the shortcomings of traditional soil-planting, scientists studied hydroponics. Between 1860 and 1865, German scientists Sachs and Knop discovered that supplementing water with macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and iron) allowed for typical plant growth, paving the way for new farming methods. Thus, the two scientists are viewed as pioneers in soilless farming [16]. The eight plants listed in Table 1 above have all been successfully grown through hydroponics.

Today, artificial lighting technology has made significant progress and is more stable than solar lighting. Therefore, it can increase the survival rate of indoor plants and help some functional plants show better characteristics, such as increasing the ability to absorb VOCs or increasing the amount of mosquito repellent pheromones released.

On the other hand, the carbon footprint of indoor hydroponic systems also warrants consideration. Dauchot et al. [17] found that a raw material for cosmetics, *Centella asiatica*, cultivated through indoor aeroponics in Paris had 4 to 40 times higher carbon emissions than imports from Madagascar. The reason is that the indoor farm is energy-intensive, with electricity consumption accounting for 60% of the carbon footprint, while *Centella asiatica* can grow like a weed in Madagascar, where the climate is suitable.

Other studies comparing the effects of local indoor urban agriculture with traditional imported food in the United Arab Emirates or Singapore also concluded that indoor agriculture is more greenhouse gas intensive [18]. This trend is consistent with Ricardo's theory of comparative advantage [19], which holds that a particular country's specific production advantages (in climate, resources, or infrastructure) give it an advantage in world markets. Therefore, reducing energy consumption to lower the carbon footprint is a critical consideration in the development of indoor planting systems.

Regarding indoor plantable space, the interior space in urban buildings is expensive, and the floors and walls have been fully utilized for various purposes that people need to live and work. Hence, the indoor space that can be provided for plant growth is fragmented

and insufficient. At this point, we believe it is worthwhile to investigate methods for planting on ceilings.

1.3. The Issues of Ceiling Planting

The most significant issues we face when planting on indoor ceilings are related to water and light.

Plants exhibit phototropism regardless of whether the light source is positioned above or below them. However, when planting on the ceiling with a light source above the plants, shadows cast by the plants and planting devices can obscure areas beneath. This situation may necessitate the installation of additional lighting for shadowed areas, resulting in increased lighting expenses and a higher carbon footprint. Conversely, if the light source is below the plants, the plants must grow inverted. Consequently, we must address questions such as how roots positioned at the top absorb water, how to ensure the proper amount of water is supplied, and whether excess water will drip onto the floor. These challenges impede the fulfillment of the aspiration to cultivate live plants on ceilings.

To increase the greening effect, today, many commercial spaces decorate the ceiling only with plastic artificial plants or dried plants. These simulated plants can be affixed to ceiling grids, light steel framing ceilings, grille ceilings, air conditioning ducts, and lighting grids to create a lifelike appearance. However, the fake plants lack the vitality and functional benefits of real plants, such as absorbing CO_2, absorbing VOCs, and emitting fragrances.

Below, we introduce some previous cases of "growing real plants on ceilings", including several Los Angeles restaurants, an international architecture firm in Taipei City, and the Pasona Tokyo headquarters. We summarize the advantages and disadvantages of these cases in Table 2.

Table 2. The case studies of growing real plants on ceilings.

Case	Introduction	Advantage	Disadvantage
The restaurants in Los Angeles [20]	Restaurants in Los Angeles, like Bavel, Coffee for Sasquatch, and Rosaliné, use wooden trusses for long planting troughs with hidden irrigation and drainage systems for ferns and ivy.	Ivy drapes down to the dining area, creating a green roof that gives customers the feel of dining under a rainforest canopy instead of in a busy city center.	The planting systems rely on sunlight that enters through the skylight. However, seasonal changes and climate fluctuations can result in unstable sunlight, which may hinder the healthy growth of plants. As a result, restaurants must incur substantial maintenance costs to ensure the greening.
SED-IA Architects [21]	This international architects' office in Taipei features a composite ceiling with planting troughs. Passiflora edulis is planted under fluorescent lights, growing horizontally across the ceiling grid.	The office's indoor temperature of 25 degrees Celsius is ideal for growing passion fruit. Gardening can also help employees relax during busy periods.	The embedded fluorescent lights above the plants may cast shadows from the leaves and troughs to the workspace below. Additionally, the planting device for upward-growing plants is primarily suited for climbing plants growing horizontally, limiting its use for ornamental, vegetable, and functional plants on ceilings.

Table 2. *Cont.*

Case	Introduction	Advantage	Disadvantage
Pasona Tokyo headquarters [22]	The company grows edible crops, vegetables, and ornamental plants using indoor office ceilings, floors, and walls, employing both soil and hydroponic methods.	The headquarters building showcases a green corporate image and is a model for urban greening demonstration and education.	The spray irrigation soil-based farming system increases humidity, attracting pests and mildew that can harm office environments. Additionally, it raises electricity consumption and carbon footprint, making it impractical for most offices and homes.

The above cases of "growing real plants on ceilings" all utilize planters that support upward-growing plants. However, it becomes difficult for people beneath the ceiling to see the greenery if the plants only grow upwards. In the cases above, the ceiling greenery can only be successful if climbing plants are planted and their leaves grow sideways, then either climb onto the ceiling grid or hang downward. Therefore, upward-planting planters limit the types of plants that can help produce greenery on ceilings.

Moreover, to avoid shadows from the plants, rising electricity costs, and an increased carbon footprint, we need to position the light sources beneath the plants and identify a device that can truly facilitate upside-down planting. Currently, we can only find three types of devices in the global market capable of achieving this objective. The comparison of these three devices is presented in Table 3:

Table 3. The comparison of three devices achieving upside-down planting.

Device	Introduction	Advantage	Disadvantage
Down Under Pot [23]	The pot has two openings. The large opening makes it easy to place a mature plant facing upwards in the container, and then cover it with soil and compact it. After waiting about a week, allow the plant roots to grasp the soil in the pot, then hang the pot upside down.	• Allow the plant to grow downward when the light source is below. • The pot is made of clay, which does not deteriorate in the sun and can be used indoors or outdoors.	• The pot requires frequent manual watering through a small hole. • When the soil becomes saturated, water will drip onto the floor. • The soil in the pot is exposed to air, which can facilitate the growth of pests and diseases. • The inclusion of water and soil results in a unit weight greater than that of a hydroponic unit.
New Improved Hanging Tomato Planter [22]	This soil-based planter comprises a frame and nonwoven fabric, with a bottom hole for downward plant growth. A container positioned above this planter can store 1 gallon of water. This container utilizes capillary matting, enabling water to gradually infiltrate the soil beneath through capillary action.	• Allow the plant to grow downward when the light source is below. • The planter is made of nonwoven fabric, which does not deteriorate in the sun and can be used indoors or outdoors. • The container above the device can store water, so frequent manual watering is not required. • The isolated soil prevents it from harboring pests and diseases.	• The rate of water infiltration cannot be controlled. If the soil becomes saturated, excess water will drip onto the floor. • The soil in the pot is exposed to air, which can facilitate the growth of pests and diseases. • The inclusion of water and soil results in a unit weight greater than that of a hydroponic unit.

Table 3. *Cont.*

Device	Introduction	Advantage	Disadvantage
Sky Planter [24]	• The main structure of the Sky Planter is a flowerpot that can be filled with soil or coco coir. When the pot is hung upside down, a water container with a small hole at the bottom is positioned above the pot. Water from the container can gradually seep into the soil through the small hole.	• Allow the plant to grow downward when the light source is below. • The container above the device can store water, so frequent manual watering is not required. • A mesh barrier at the base of the Sky Planter prevents soil loss. • A plastic rod is designed to float on the surface of the water within the container, extending through the top cover. The visible length of the rod serves as an indicator of the remaining water volume in the container.	• The rate of water penetration into the soil cannot be controlled; excess water will drip onto the floor. • The semi-open design of the soil and water containers can facilitate the growth of pests and diseases. • Due to the inclusion of water and soil, its unit weight is greater than that of a hydroponic unit. • It is not easy to view the length of the plastic rod extending through the top cover clearly on the ground when the planter hangs on the ceiling.

1.4. The Objectives for Developing a New Indoor Planting System

Based on the analysis of the above cases, this study identifies the following objectives for improving the shortcomings of existing devices and creating a better solution for developing a new indoor planting system:

1. A planter designed for inverted planting of various species with a watertight cultivating unit.
2. An artificial light source will be integrated beneath the planter to ensure adequate and consistent illumination for both plant growth and daily activities.
3. The system will not incur extra costs on daily electricity consumption under the proposed conditions.
4. The planter will be an enclosed environment, allowing air exchange while preventing insect breeding and indoor humidity.
5. To avoid overwatering, the system should enable plants to directly regulate their nutrient solution intake, rather than relying on artificial capillary action or other physical methods.
6. Frequent replenishment of water or nutrient solutions will not be necessary, thereby reducing the maintenance workload.

2. Materials and Methods

2.1. System Structure

Based on the six objectives above, this study has developed a new indoor hydroponic system that utilizes the ceiling space to augment the green areas within buildings. The integrated grow light can also function as daily lighting, reducing additional electricity costs. The planting units are designed to prevent insect intrusion while maintaining air permeability. A substantial amount of nutrient solution can be introduced at one time according to the plant growth cycle requirements, minimizing maintenance frequency. Furthermore, the system is compatible with interior design, allowing for single or multi-form combinations that offer aesthetic and practical advantages.

This study focuses on integrating greenery into everyday living, work, and public spaces. The goal is to maximize green areas in indoor urban buildings. This research has received an Invention Patent in Taiwan. Figure 2 shows the patent diagram, with detailed component descriptions provided below:

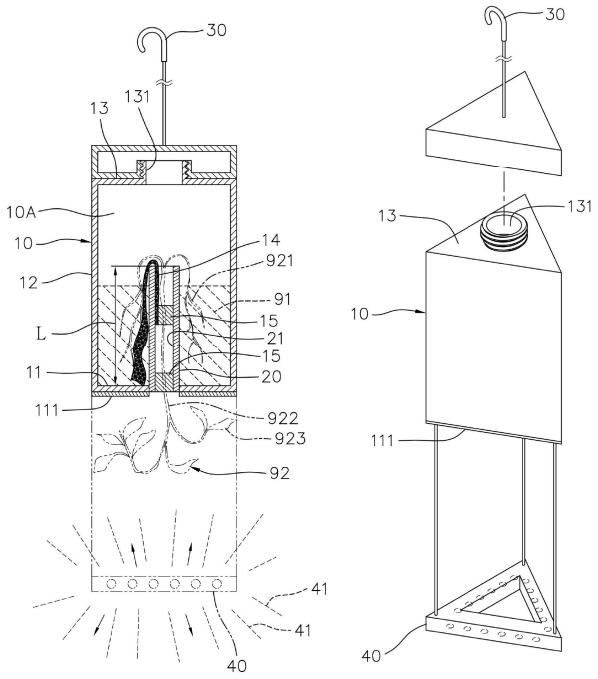


Figure 2. The detailed structural diagram of the Invention Patent of this study.

A container unit (10) comprises a bottom plate (11), a surrounding wall (12), and a containing space (10A). The containing space (10A) is between the bottom plate (11) and the surrounding wall (12).

A plant extension unit (20) penetrates the bottom plate (11) in a way that is watertight and extends height L into containing space (10A). The plant extension unit (20) features an extension channel (21), which connects the containing space (10A) to the outside.

The containing space (10A) is used to store nutrient solution (91) and a plant unit (92), where the nutrient solution (91) level remains below height L. The plant unit (92) comprises a root portion (921), a stem portion (922), and a flower–leaf portion (923). The root portion (921) is immersed in the nutrient solution (91), while at least one of the stem portions (922) and the flower–leaf portion (923) extend to the outside through the extension channel (21), thus forming an inverted hydroponic system.

The container unit (10) further includes a top cover (13) designed to seal the containing space (10A). The top cover (13) has a working hole (131) for introducing nutrient solution (91). The plant extension unit (20) is configured as a tubular structure for securing a plant unit (92).

The system may include a hanging unit (30) attached to the container unit (10) for the purpose of hanging the container unit (10).

The lighting unit (40) emits light (41) to the stem portion (922) or the flower–leaf portion (923), meeting hydroponic lighting requirements. Additionally, the lighting unit (40) directs light (41) downward for daily illumination. The bottom plate (11) has a reflective surface (111) facing the lighting unit (40), which reflects light (41) towards the stem (922) or the leaf (923), or redirects light for general lighting purposes, thereby improving lighting efficiency.

The watertight but air permeable sponge (15) in Figure 2 is treated with a nano-coating to secure the plant stem while maintaining air permeability within the containing space. The container is watertight to prevent pest intrusion. The LED lighting unit depicted in Figure 3a features an adjustable structure to modify the light distance during various stages of plant growth. The method for adding nutrient solutions is straightforward, as illustrated in Figure 3b. However, if the plant's growth cycle is brief, replenishment of the nutrient solution may not be necessary.

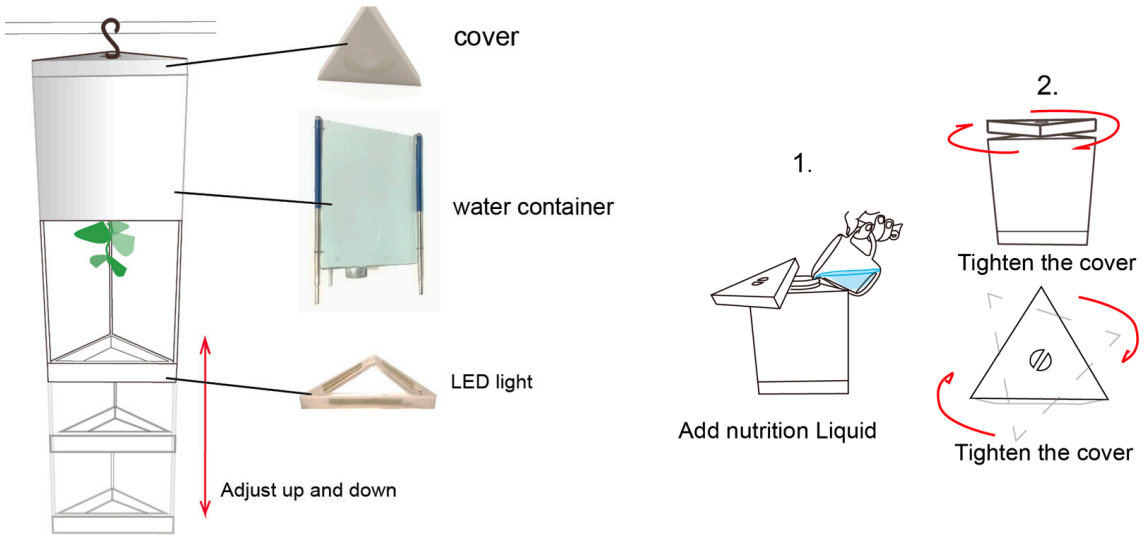


Figure 3. (**a**) The main structural components of the planting unit include a distance-adjustable LED light. (**b**) The method for supplementing the nutrient solution is quite intuitive. Once the top cover is secured, the entire container becomes watertight, eliminating concerns about the nutrient solution spilling due to shaking.

Each planting unit in this system can function independently or in conjunction with multiple planting units. Figure 4 shows the cross-sectional structure of the single planting unit and the photo of its real model. Figure 5 shows the photo and 3D simulation image of the multiple planting units. Multiple planting units combine six single planting units into a hexagonal structure, which can share a circular or hexagonal LED lamp. This lamp can be replaced with a customized one.

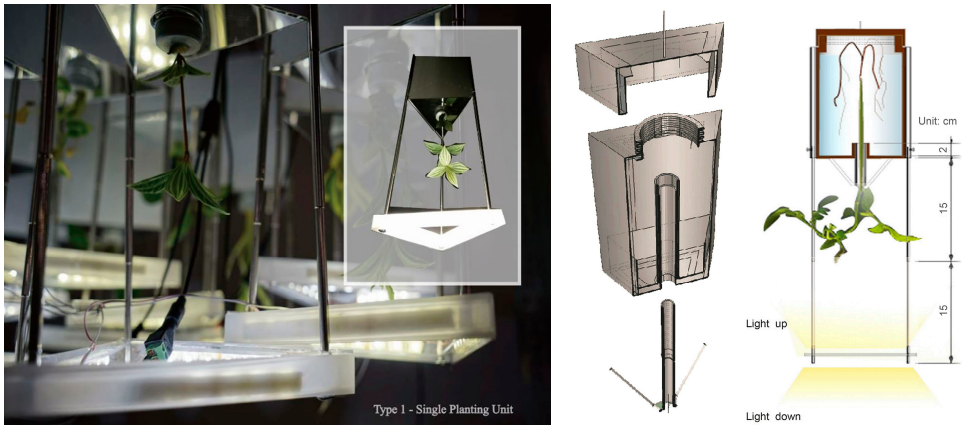


Figure 4. The photo and cross-sectional structure diagram of a single planting unit.

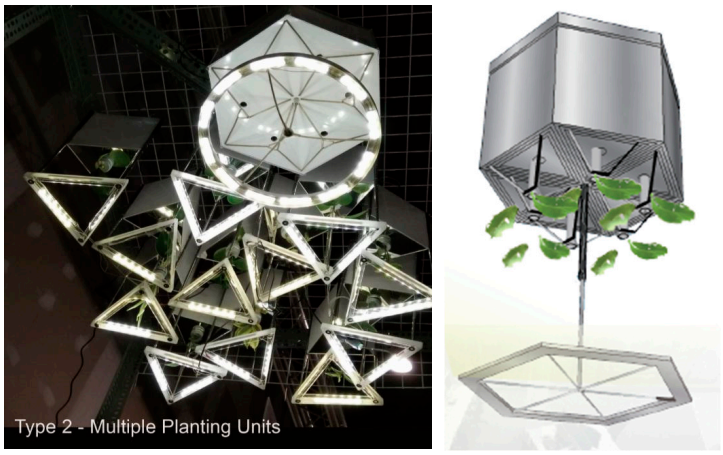


Figure 5. The photo and 3D simulation image of the multiple planting units.

2.2. Lighting Source

Photosynthesis is essential for plant growth, and each wavelength of light has a different effect on plant photosynthesis. Among them, 400~520 nm (bluish light) and 610~720 nm (red light) contribute the most to photosynthesis, while 520~610 nm (greenish light) has a slightly lower efficiency in terms of promoting plant growth (Figure 6).

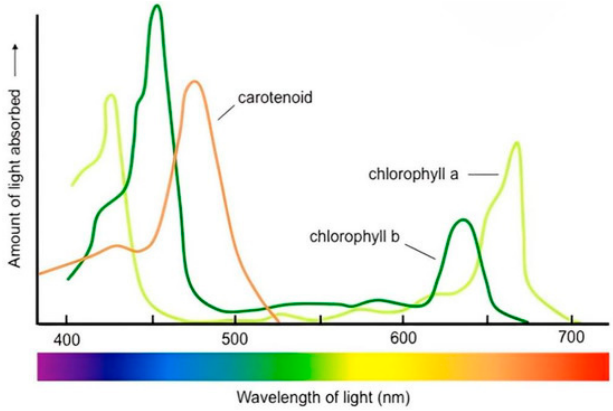


Figure 6. Absorption spectrum of chlorophyll a, b, and carotenoid [25].

Plants respond differently to light quality, intensity, and photoperiod [26,27]. Blue light at 430–450 nm aids germination, while red light at 640–660 nm boosts photosynthesis and flowering [28]. Studies show that alternating light/dark cycles (8 h of light and 4 h of dark) benefit plant growth and quality indices (soluble sugars and proteins) [29]. The distance between LED lights and plants, as well as lighting coverage, also affect growth [30,31]. Therefore, artificial lighting significantly impacts plant growth and quality [32].

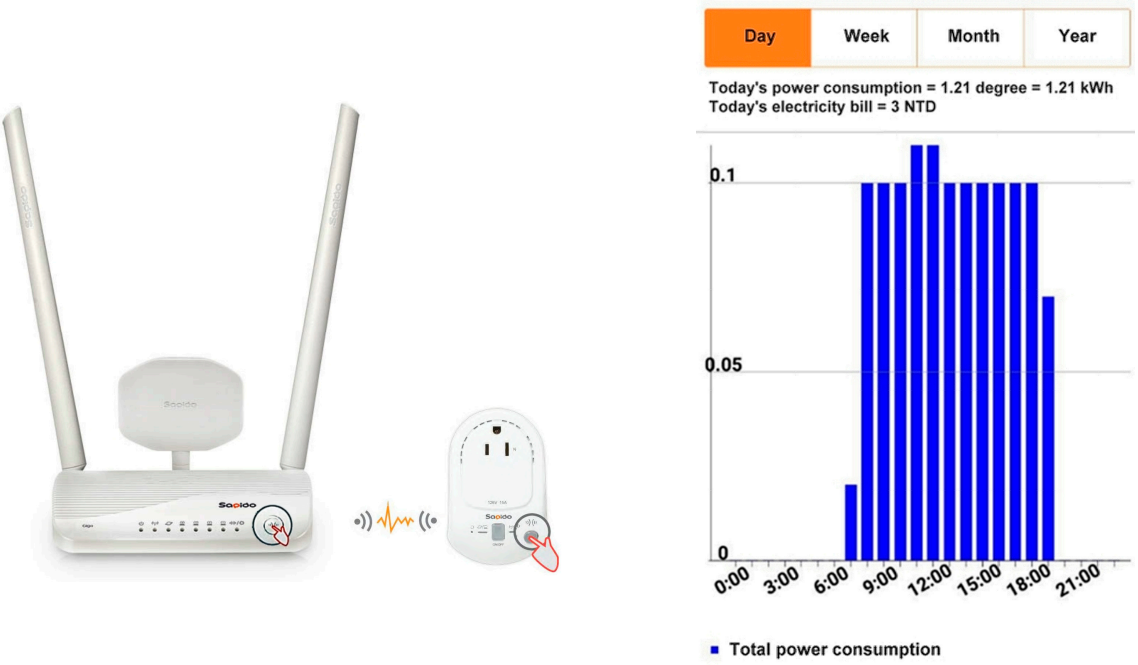
The hydroponic system in this study uses adjustable LED light strips to control intensity and color, and the distance between the lights and plants can be adjusted to meet different species' needs at various growth stages.

2.3. Power Consumption

As studied above, reducing energy consumption to achieve a lower carbon footprint is important for indoor planting systems. One method to achieve this is through demand response (DR) programs. Javier Penuela [33] conducted research on indoor agriculture in the Russian Federation, where local indoor agriculture generates a significant electrical load. His study indicated that participation in demand response programs for indoor plant cultivation did not negatively impact plant production and could reduce supplemental lighting energy costs by 15.34% to 23.03%.

The interior LED hydroponic inverted planting system developed in this study reduces power consumption more effectively than participating in a DR program. This planting system is ideal for indoor workspaces, providing necessary lighting during working for 6 to 8 h and synchronously turning off after working hours. In other words, the same power consumption initially used solely for working illumination is now also used for plant cultivation. On an appropriate layout, the system does not increase electricity costs but doubles energy consumption efficiency, while people benefit from indoor greening.

We applied WSG70n [34] Smart Control Insight Switches to record and control the power consumption of the hydroponic planting units. The switches transmit power data to a Wi-Fi host, then send it to a mobile phone via the internet. Users can remotely manage appliance schedules via phone (Figure 7a).



(**a**) (**b**)

Figure 7. (**a**) WSG70n can transmit power consumption data to the Wi-Fi host, allowing users to monitor and configure it remotely. (**b**) WSG70n displays the daily time frame during which electricity is used, and the amount consumed.

Through WSG70n, power consumption was calculated: twelve hydroponic units' LEDs operated for 13 h, using 1.21 kWh of electricity, costing about NTD 3 (USD 0.09) in Taiwan (Figure 7b).

2.4. Nutrient Solution

The principle of hydroponic cultivation is straightforward if the essential needs of plants—oxygen, water, and nutrients—are provided. Certain xerophytic plants also tolerate water well as they develop adaptive ventilation pores when immersed in water.

After experimenting with various nutrient solution formulas, this study used a modified universal solution formula for indoor hydroponic cultivation. The nutrient solution ingredients include organic carbon, calcium ammonium nitrate, potassium nitrate, potassium dihydrogen phosphate, magnesium sulfate, potassium sulfate, magnesium nitrate, EDTA (iron, manganese, zinc, and copper), boric acid, and ammonium molybdate. The concentration of nutritional elements in 1 L of nutrient solution is presented in Figure 8.

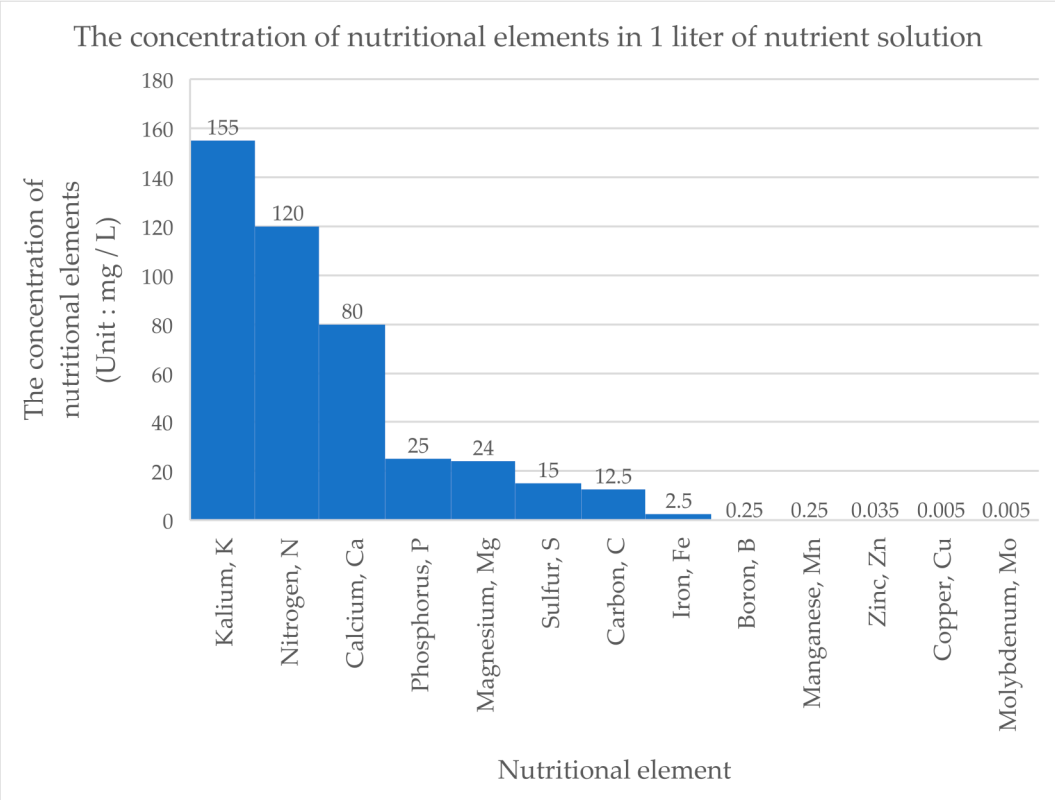
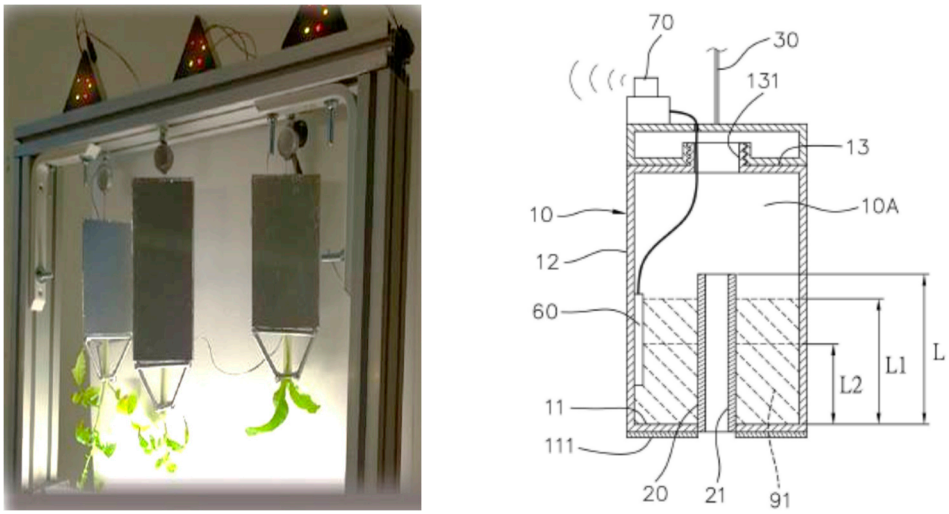


Figure 8. The concentration of nutritional elements in 1 L of nutrient solution.

The planting unit created in this study is designed to store the nutrient solution required for a growth cycle of small leafy vegetables. If monitoring the water level in the container is needed, the system's electronic water level sensor can be utilized, as shown in Figure 9. In the improved design, the container unit will be made of transparent materials, allowing the water level of the yellow-colored nutrient solution to be easily visible.



(**a**) (**b**)

Figure 9. (**a**) The triangular device above the metal frame is the water level sensing device. (**b**) The section diagram of the planting unit with the water level sensor installed. The water level sensor (60) can display different LED lights according to the detected low, medium, and high water levels and transmit the information to the central control computer through the wireless transmitter (70). The numbers of other parts in the Figure are the same as those in Figure 2.

The water level sensing device includes 12,220-ohm resistors, 2 red LEDs, 2 yellow LEDs, 2 green LEDs, and 6 BC547 transistors. In Figure 9b, all LEDs light up at a solution height of L (400 mL); at L1 (250 mL), only yellow and red LEDs light up; and at L2 (100 mL), only the red LED lights up.

3. Results and Discussion

3.1. Plant Cultivation and Transplanting

In fact, numerous plants are suitable for hydroponic cultivation. Certain seeds, such as Cockscomb, Cosmos, and Zinnia, germinate more effectively in darkness [31], making them particularly well-suited for indoor hydroponic cultivation. Additionally, young plants, whether initially grown in soil or hydroponically, can be purchased and transplanted into a hydroponic planting system to easily create an indoor green environment.

To place young plants into the planting unit developed in this study, begin by using the provided sponge treated with a nano-coating to secure both the top and bottom of the plant stem. Then, use a plastic straw of suitable length with a diameter that is slightly smaller than that of the extension channel (21), as shown in Figure 2. Cut the plastic straw lengthwise and position the stem with the sponge inside the straw. Insert the straw into the extension channel (21) carefully, with the root side facing upward.

The inverted planting system features an LED structure whose length can be adjusted according to the plant's growth stage. The typical length ranges from 15 to 30 cm, which is particularly suitable for growing vegetables with stems not exceeding 30 cm. However, plants with longer stems can be accommodated with extension parts or a customized LED structure.

After about a month, when the plant has grown a bit (depending on the condition of the plant), we can perform maintenance such as lengthening the planter's LED structure to keep the light source about 10–15 cm away from the plant's leaves, and supplement nutrient solutions if necessary.

If fast-growing vegetables such as *Brassica rapa* subsp. chinensis (Bok Choy) are grown, they can be harvested in about 1 to 1.5 months [35]. For cultivating plants, choose those suitable for growth in the current season, as they generally have a higher success rate.

3.2. Pest Control

Plant pathogens can be transmitted through water, soil, air, insects, animals, and humans [36]. When transitioning soil-grown plants to hydroponics, selecting plants that are robust and free from diseases and insect infestations is advisable. An appropriate amount of baking soda water may be used to rinse the roots, carefully removing any soil attached to them and eliminating yellow or diseased leaves.

After each planting cycle with our planting system, it is essential to thoroughly clean and disinfect the containers to prevent subsequent plants from becoming infected. Failure to do so may lead to pest and disease levels like those in soil cultivation. Therefore, despite the relative convenience of indoor hydroponics, plants always require proper care and protection in all planting methods.

3.3. Temperature Control

The LED hydroponic inverted planting system is designed to operate in alignment with the workspace's schedule. Although LEDs produce significantly less heat compared to other artificial light sources [37], continuous use will still result in heat accumulation, particularly during hot summer months or rainy periods. Thus, efficient heat dissipation and ventilation are crucial. The preferences of indoor foliage plants are very similar to our bodies; we all like temperatures between 18 and 28 degrees Celsius [38,39]. Although

various indoor plants from different latitudes prefer specific temperature ranges, it is advisable to maintain an indoor temperature that is comfortable for humans. Only native plants that align with human comfort levels are suitable for living indoors alongside people.

A notable advantage of this hydroponic system is that the LED lighting period for plant growth aligns with the general lighting used by individuals in their living or working spaces. Consequently, when occupants find indoor conditions stuffy, they typically activate air conditioning or ensure adequate air circulation to maintain a comfortable environment. This practice also helps reduce the heat generated by LED lights.

However, it is essential to avoid positioning plants close to the air conditioner's outlet when managing room temperature using air conditioning. If the air conditioning is turned off, maintaining natural ventilation indoors is recommended to foster optimal plant growth.

4. Applications and Further Improvement

The LED hydroponic inverted planting system is designed for environments with limited or no natural light, such as high-rise residential buildings, office buildings, underground shopping malls, and indoor spaces. Additionally, this system is suitable for hospitals, clinics, wards, and care centers where indoor plants can reduce psychological stress and promote mental and physical well-being.

Since this system can grow plants on scattered and small indoor ceilings, it does not require ample space with special conditions. Therefore, even separated small shops, studios, and offices in a commercial building can utilize this system to replace the original lighting fixtures and expand the Green Plot Ratio of the whole building.

Taking the Development Control (DC) guidelines in Singapore as an example. If a commercial building (including offices) is located in a Strategic Area in Singapore [8] with the following data:

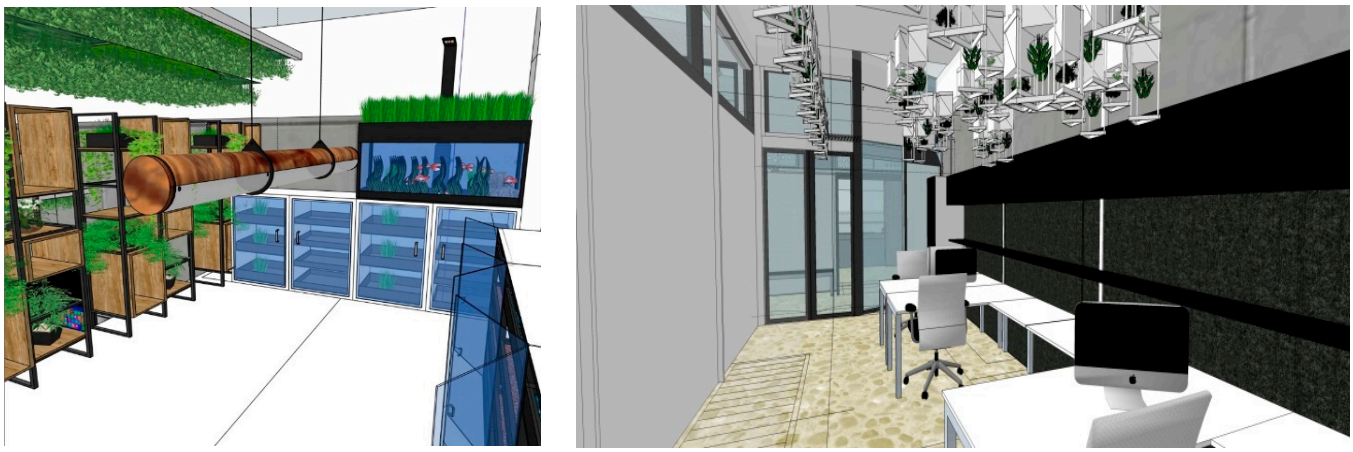
- Minimum GnPR requirement: 4.0.
- Landscape Replacement Areas (LRA) requirement:100%.
- Site Area: 10,000 m^2.
- Building coverage ratio: 50%.
- Floor area of a single floor: 5000 m^2.
- Total number of floors in the building: 10.
- Ceiling cultivation plant: *Brassica rapa* subsp. chinensis (Bok Choy); Leaf Area Index (LAI): 2.
- Total number of ceiling planting floors: 8 floors.
- Greenery ratio of the ceiling on each floor: 25%.

Then we can calculate the Green Plot Ratio contributed by ceiling planting according to the following Formula (1):

$$\frac{5000\ \text{m}^2 \times 25\% \times 8\ (\text{floors}) \times 2(\text{LAI})}{10,000} = 2.0 \quad (1)$$

Therefore, we can understand that ceiling greening technology is of great help to the greening of urban buildings. Even when the building coverage ratio is only 50%, the greenery ratio of the ceiling on each floor is only 25%, and only 8/10 floors are planted, the ceiling greening area can contribute 1/2 of the Green Plot Ratio in areas with the strictest requirements in terms of Singapore regulations.

Figure 10 depicts the 3D virtual simulated images of the ceiling planting in commercial and office spaces.



(**a**) (**b**)

Figure 10. The 3D virtual simulation images of the application of the inverted planting hydroponic system: (**a**) the greenery in a small commercial space of around 25 square meters and (**b**) the replacement of lighting above the working area in a personal studio or a small office space.

We believe economic benefits and interior aesthetics are essential for greening commercial, office, and residential spaces. Therefore, the triangular planting units developed in this study are designed to be versatile. These units can function individually or in combination with several others to create various shapes. They also have the capability to share electrical power in series, allowing them to adapt to different ceiling conditions and improving the overall feasibility of interior greening (as depicted in Figure 11).

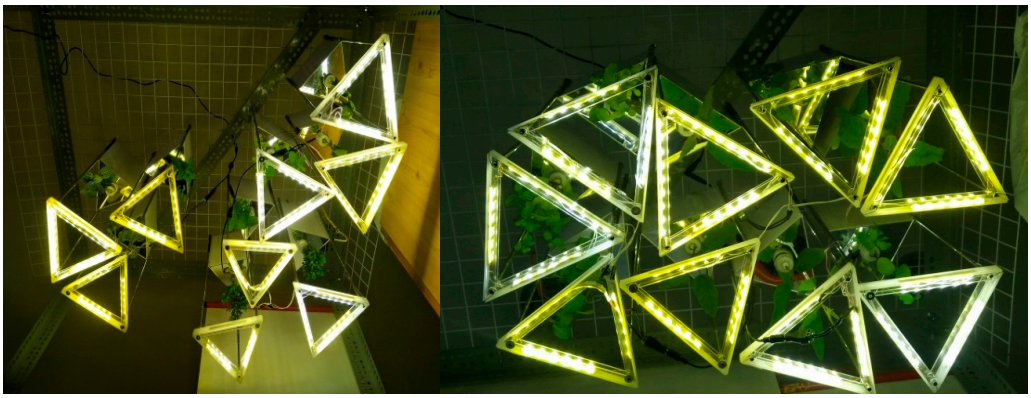
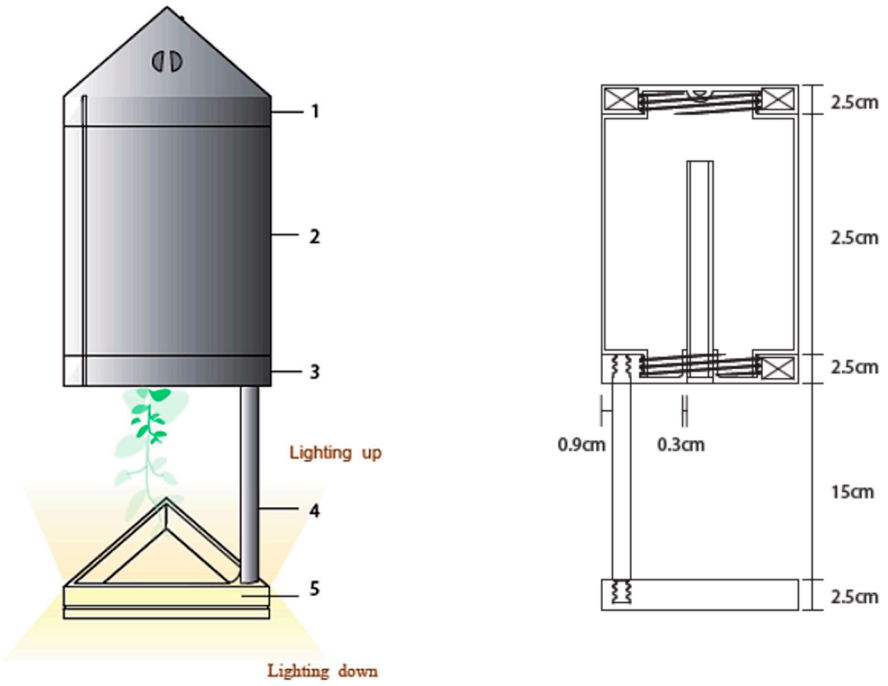


Figure 11. Triangular planting units can be connected for power sharing, with flexible numbers based on preference and demand.

To enhance the simplicity of unit assembly, improve operational ease during plant harvesting, and optimize the potential for large-scale applications in the future, this study has modified and improved a previously patented system to develop a new version of the structure (as depicted in Figure 12). The redesigned planting unit consists of a container unit (2) with a watertight upper cover (1), a watertight lower cover (3), a supporting structure (4), and a lighting unit (5).

This planting unit substitutes the original lighting unit's three extendable poles with one pole, thereby reducing its weight and improving aesthetics by concealing the wires. The container's top opening is enlarged, and a similarly sized lower opening is added to create two interconnected openings. These openings facilitate cleaning the container's interior to prevent bacterial growth that could cause plant infections upon replanting.



(**a**) (**b**)

Figure 12. Perspective and cross-sectional views of the newly improved planting unit. (**a**) The surfaces of the planting unit have horizontal and vertical ridges and grooves, allowing the units to be connected and hiding the wires. (**b**) The newly designed planting unit has added detachable components to increase the convenience of cleaning.

The holes in the lower cover are designed to secure a straw while maintaining watertightness. The straw can be replaced after each planting cycle and trimmed according to the plant stem length. The single pole structure beneath the container has threads at both ends to stabilize the LED light unit below. For harvesting, the pole and LED light unit can be removed to increase convenience (Figure 12). Additionally, the redesigned planting unit can be equipped with a transformer to receive electricity through the track of the track lighting system, as illustrated in Figure 13.



Figure 13. The redesigned planting unit can receive electricity through the track of the track lighting system.

The newly improved planting units can be spliced via ridges and grooves on their surface, allowing for the creation of larger modular planting systems. These larger modules can incorporate several triangular LED lighting fixtures from single units or can employ specially made circular or other shaped LED lights.

Spliced units enhance space utilization, reduce lighting power consumption, and can be arranged at varying elevations. This setup enables interior designers to implement an "edible ceiling scape", which integrates various edible, aromatic, and ornamental plants into the ceiling design. This approach creates diverse green ceiling scapes above indoor working and living spaces, as depicted in Figure 14.

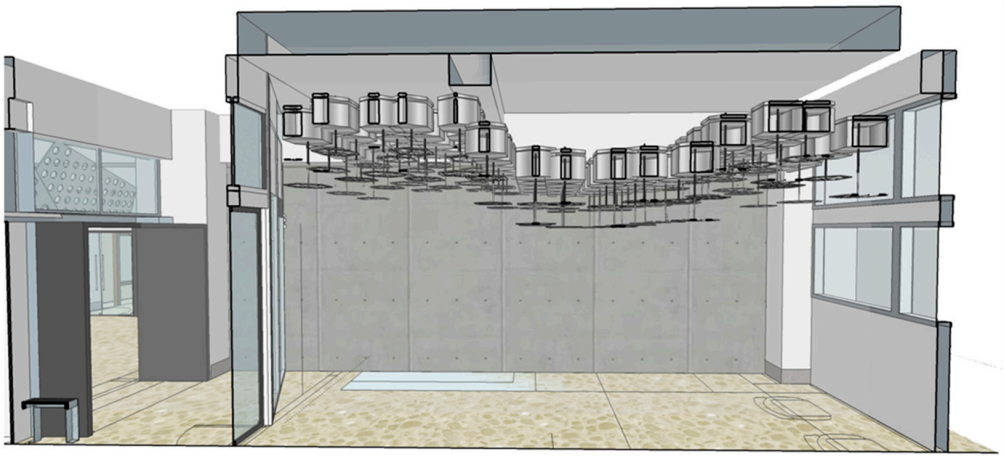


Figure 14. The modular units can be positioned at different elevations to form varied ceiling scapes.

5. Conclusions

The indoor LED hydroponic inverted planting system developed in this study features LED light sources that illuminate both upward and downward, serving the dual purposes of plant growth lighting and general illumination. This innovation results in a reduction in lighting power consumption and diminishes the carbon footprint associated with the planting process. The planting unit secures the plant stem centrally within a thin tube, wherein roots either remain inside or extend from the upper end to the periphery to absorb nutrient solutions, allowing the plant to grow downward. The watertight but air-permeable planting unit prevents nutrient solution from dripping onto the floor, protects against pest invasion, and offers recyclability and multiple-use capabilities.

The structure of the planting unit can be horizontally connected via ridges and grooves on its surface to form larger modular planting units. These larger modules can utilize either individual triangular LED lighting fixtures or single circular or custom-shaped LED fixtures. Power can be supplied to planting units either in series or through track lighting systems.

This system is designed to be suspended from the ceiling, the largest yet often underutilized area in indoor spaces, thus increasing green plot ratio in urban buildings without hindering daily activities. Horizontally connected single units or larger modules can be varied in height, creating vertical changes in the ceiling space. The planting setup accommodates air-purifying, aromatic, and edible plants based on demand. This arrangement enables interior designers to craft diverse green ceiling scapes within indoor environments.

6. Patents

The results of this study have been successfully applied for an Invention Patent in Taiwan. Patent Number: I663907.

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