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Evaluating the Energy Efficiency and Carbon Footprint of Small-Scale Distributed and Centralized Vertical Farming Systems

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ABSTRACT

This paper discusses the potential of small-scale distributed vertical farming in buildings to be a more sustainable and energy-efficient alternative to large-scale centralized vertical farming. While vertical farming has the potential to revolutionize urban agriculture by providing fresh produce year-round and reducing transportation emissions, the energy consumption required to power the lighting systems can be significant, particularly in centralized systems. The study compares the energy consumption and growth of pak choi cabbage plants between centralized and distributed vertical farming systems while adopting a traditional cultivation process as a reference. The data from the experiment are used to simulate the carbon emissions generated by vertical farms. The paper concludes that distributed vertical farming offers higher energy efficiency, with a potential 60% reduction in energy consumption and a 30% decrease in carbon footprint relative to large-scale integrated vertical farms. Yielding over twice the crop output compared to conventional agriculture, this approach may serve as a potential solution to address global food challenges.

Keywords: Vertical farming; Energy; LED lighting; Carbon Footprint; Food Security

1. INTRODUCTION

As global population growth continues to put pressure on food production and land use, vertical farming is becoming an increasingly popular alternative to traditional agriculture[1]. Vertical farming involves growing crops in vertically stacked layers using advanced technologies such as hydroponics, aeroponics, and LED lighting systems[2]. It has the potential to revolutionize urban agriculture by providing fresh produce year-round in dense urban environments and reducing transportation emissions[3]. Researchers have endeavored to explore the sustainable characteristics of vertical farming as a resilient solution for addressing food security concerns. Notable examples include a case study conducted in Singapore[4], Shanghai[5] and Naples, Italy[6] and so on.

Even though vertical farms have notable benefits, their energy consumption and carbon footprint must be carefully evaluated to determine their environmental impact. The energy consumption required to power the lighting, heating, and cooling systems in vertical farms can be significant, especially in large-scale centralized systems[7], and electricity bills account for more than 30% of the total expense [8]. In order to provide sufficient lighting for crops to ensure photosynthesis, vertical farms often require 24-hour LED lighting, which can account for more than half of the total energy consumption [9]. The high energy consumption in existing centralized vertical farms can contribute to the carbon footprint, offsetting some of the environmental benefits.

One potential solution to reducing the energy consumption and carbon footprint of vertical farming is through small-scale distributed vertical farming in public buildings [10]. Systems like these can make use of natural light, waste heat, and carbon dioxide within the building, thereby reducing the reliance of vertical farming on artificial lighting[2], at the same time lowering the cooling and heating load of the building[11,12]. Distributed vertical farming can be placed in urban spaces such as commercial buildings, residential areas, schools, and public places that are closer to consumers

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and markets, thereby reducing transportation and storage costs[13].

Small-scale distributed vertical farming systems in buildings have the potential to be more energy-efficient and have a lower carbon footprint compared to large-scale integrated vertical farms. Presently, there exists a dearth of empirical investigations examining the potential of utilizing natural lighting to mitigate the energy consumption of small-scale vertical farming within conventional building spaces. Furthermore, there is a need for a comparative analysis of the carbon footprint between small-scale distributed vertical farming and large-scale centralized vertical farming. Therefore, it is essential to investigate the energy cost and carbon footprint of both systems to determine their sustainability and potential as a solution to global food production challenges.

2. METHODS AND MATERIALS

A key distinction between distributed and centralized vertical farms lies in their use of natural and artificial lighting respectively. While distributed farms are integrated within regular buildings and can utilize natural daylight during the day and supplemented with LED lighting during the night, centralized farms mostly rely on full LED lighting. This research conducted an experimental study, comparing the energy consumption and growth of plants between the two approaches while adopting a traditional cultivation process with no artificial lighting as a reference. The data from the experiment will be used to simulate the carbon emissions generated by vertical farms.

2.1 Experiment

The key variable of this study is the illumination condition of the vertical farming, and thus a fixed environment was established to reduce other factors that may affect plant growth rate in vertical farming units. Based on this assumption, the centralized and distributed vertical farming systems were configured to provide consistent environmental temperature and humidity, while offering different illumination conditions for the plants.

For this experiment, pak choi cabbage, a common fast-growing crop commonly used in vertical farms, was selected. Its growth period from sprouting to harvesting is usually 10-15 days, and it is a heliophile plant that benefits from long-term exposure to light[14]. The experiment used a hydroponic method, placing the same number of sprouted pak choi cabbage in three identical hydroponic units. The units were placed in the same indoor space with the same indoor environment. One unit only had natural lighting, while the second unit was covered with a light-blocking cover and only had 24-hour LED lighting. The third one was supplemented with LED lighting from 6 pm to 6 am. These three units were used to simulate traditional planting, centralized large-scale vertical farms and distributed small-scale vertical farms, respectively, as shown in Table 1.

Table 1 Three planting scenarios

	Crop type	**Cultivation method**	**Plant area**	**Lighting condition**
Traditional planting	Pak choi cabbage	Hydroponics	290 cm^2	Natural lighting
Centralized planting				LED lighting (24 hours)
Distributed planting				Natural lighting + LED lighting (6pm – 6 am)

2.2 Testing instruments

To evaluate the energy efficiency and carbon footprint, we used a variety of instruments to measure environmental conditions in the growing area as shown in Table 2. A PPFD (Photosynthetic Photon Flux Density) meter was used to measure the light intensity and distribution within the growing area, which is an important factor affecting plant growth and energy consumption. Temperature and humidity sensors were used to monitor the growing environment and ensure appropriate conditions for plant growth. CO_2 sensors were used to measure the levels of CO_2 within the growing area, which is an indicator of plant photosynthesis and can also affect energy consumption. All measurements were taken at regular intervals throughout the day and over a period of several weeks to capture variations in environmental conditions and assess the overall energy efficiency and carbon footprint of the vertical farming system.

Table 2 Testing instruments.

Instruments	**Model**	**Specification**	**Settings**	**Description**
LED lights	KW-ZWD03-T8	560nm-570nm	20cm above the crop	

PPFD meter	PR-300AL-GH-V05	±5%	Nearby plants	Continuous measurement with 10 seconds interval
Temperature and Humidity sensor	SNL-AIRLIGHT	0~85℃ ±1℃ 0~100%RH ±7%RH	Integration with the planting unit.	
CO_2 sensor	SNL-AIRLIGHT	0-8000ppm ±10%	Nearby plants	
Camera	ATLI	CMOS	Fixed above the plant	with 60 minutes interval

2.3 *Measurement of plant growth rate*

The growth rate, a crucial indicator of plant health and development, can provide valuable insights into the plants' overall performance and potential yield. In this study, the leaf coverage area is used to identify the growth rate of plants. Color channels are used to quickly estimate leaf areas, which is an effective index for assessing plants growth and indicator of photosynthetic capacity in plants[15]. In this experiment, as the plant species were all the same type and the seeds were randomly selected in equal numbers from the same batch of seeds, the color channels from the images were used to measure the leaf areas which can represent and contrast the photosynthetic capacity directly. K-means has been used to cluster the colors in the image. The following figure 1 is an example processing about the cluster partitions.

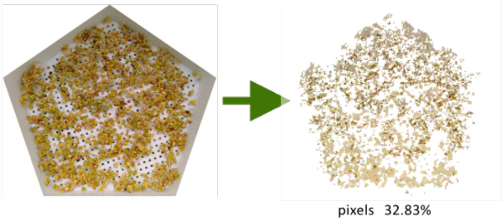

Fig. 1. Color channel detection example

2.4 *Calculation of carbon footprint*

According to literature on the carbon footprint analysis of vertical farms, carbon emissions from vertical farms are generated in the upstream, downstream, and end-of-life emissions of the crop life cycle. This means that not only carbon emissions during crop cultivation need to be calculated, but also emissions from before and after crop production (from the supply chain and facilities)[16].

The unit will be used to assess carbon footprint is kg of carbon dioxide equivalent (CO_2-eq). The greenhouse gas emissions represent the carbon footprint of each case can be calculated as follows:

$$CO_{2_{eq}} = activity\ data\ \times EF$$

CO_2 emissions associated with each case can be estimated using the product of activity data and emissions factors (EFs), which are derived from the Intergovernmental Panel on Climate Change Global Warming Potentials 100a characterization method [17,18].

In estimating the carbon footprint of centralized vertical farms, this study uses experimental data on crop cultivation, and additional parameters are obtained from a case study of a centralized vertical farm in Shanghai[18], which is used as a benchmark to compare with distributed vertical farms. To simplify the research content, the following assumptions were made:

- Only one type of crop is planted.
- Transportation range is limited to public buildings in the area where the farm is located.
- The market demand for the crop within the area is the same.

3. RESULT AND DISCUSSION

3.1 *Plant Growth Rate*

The growth level of crops showed significant differences under three different light conditions, namely traditional planting, centralized planting, and distributed planting. Two independent repeated tests were conducted and consistently yielded the same results.

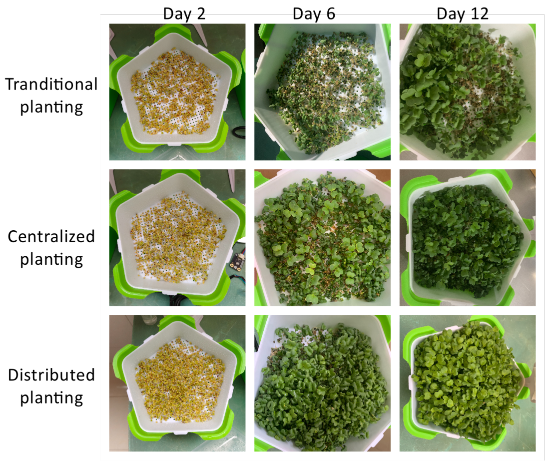

Fig. 2. Plant state in 3 check points

Figure 2 shows the pictures of plant growths at three key checkpoints, the 2nd, 6th, and 12th days after germination, with the final harvest time on the 16th day.

The leaf coverage area served as a proxy for plant growth and was quantified through pictures captured by the fixed cameras and subsequent image recognitions, as shown in Table 3.

Table 3 Leaf area at check points and final weight

Check point:	**Day2**	**Day 6**	**Day 12**	**Final weight**
Traditional planting	32.83%	49.24%	56.51%	40g
Centralized planting	42.53%	55.64%	60.17%	44g
Distributed planting	52.43%	57.12%	78.50%	94g

Based on the images, it can be seen from the leaf area coverage that the growth level of crops under distributed planting was significantly better than the other two planting methods, especially at the third check point. Secondly, the growth level of crops under centralized planting was higher than that under traditional planting methods. Among all three planting methods, the growth level of crops under mixed light supplementation performed the best, followed by that under LED supplementation, while the growth level under natural light conditions was the lowest. The final harvest weight also indicated these results, with the final harvest weight under distributed planting significantly higher than the other two planting methods.

The results indicate that distributed planting offers a significant advantage, with a growth rate nearly double that of the other two planting methods. The observed differences in growth rate can be attributed to the unique combination of advantages offered by distributed planting. Specifically, traditional planting offers high sunlight intensity but short light exposure time, while centralized planting offers a long light exposure time but low light intensity. In contrast, distributed planting combines the advantages of high light intensity from traditional planting and long light exposure time from centralized planting, resulting in a significantly improved plant growth rate.

3.2 *Energy efficiency*

Evaluation of the impact of environmental conditions on plant growth and energy consumption in the small-scale and integrated vertical farming system.

Traditional planting relies solely on natural sunlight without introducing external light sources. The average total power of 9.76 W/cm^2, the lowest among the three planting methods. Centralized planting utilizes external LED light sources for prolonged exposure, resulting in the highest unit total power of 23.84 W/cm^2. Distributed planting adopts a combination of natural sunlight and LED light within a fixed time frame, with an average total power 15.48 W/cm^2 that falls between that of traditional planting and Centralized planting. Therefore, considering energy consumption factors, distributed planting is the most appropriate choice for plant cultivation.

Table 4 Energy consumption of 3 cases

	Total Illumination power (W)	**Control sys power (W)**	**Illumination power (W/ cm^2)**	**Total power (W/cm^2)**
Traditional planting	0	1600	0	9.76
Centralized planting	2560		14.67	23.84
Distributed planting	1296		7.43	15.48

3.3 *Carbon dioxide absorption rate*

The absorption rate for CO_2 increases with a lower CO_2 concentration. As show in Figure 3, the results revealed that the CO_2 concentrations at the three planting units, traditional planting, centralized planting, and distributed planting, decreased over time compared to the baseline CO_2 concentration without plants. In particular, distributed planting exhibited the strongest CO_2 absorption capacity, decreasing from 3000 ppm to 500 ppm with in 2 hours. Consequently, the findings suggest that distributed planting can effectively reduce

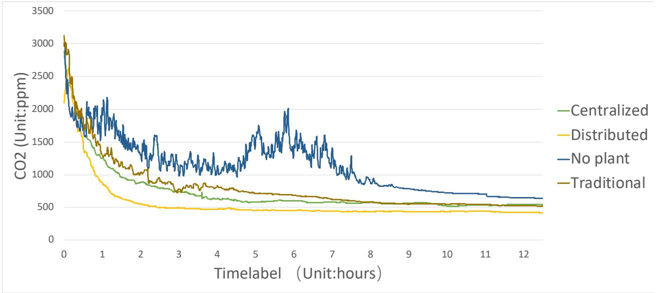

Fig. 3. Carbon dioxide absorption rates

indoor CO_2 levels in buildings and decrease the energy consumption required for providing fresh air.

3.4 Carbon footprint

Figure 4 illustrates the carbon footprint chart, highlighting the differences among various planting methods. The carbon footprint of traditional planting primarily originates from transportation-related emissions (25 kg). In contrast, centralized planting's carbon footprint is predominantly due to the core component (37.632 kg), which consists of energy consumption for LED lighting and control systems. The carbon footprint of distributed planting arises solely from the core component, demonstrating the lowest emissions (19.05 kg).

In accordance with an urban-scale survey[18], traditional planting is located averagely 100 km away from the end-users. Thus, long-distance transportation is the main source of its carbon emissions, leading to almost five times more than that of centralized planting. In contrast, the distributed planting can cut down almost all transportation-related CO_2 emissions as the planting sites are situated very close to the end-users. Centralized planting requires long-term external light source irradiation, which produces a large amount of carbon emissions during the process. Distributed planting does not require transportation, and combined with natural lighting, the duration and intensity of external light source illumination are fixed, and the carbon footprint is maintained at a low level.

The distributed plant unit generates a total of 42.719 kg of CO_2 emissions per unit during each growth cycle. This is in contrast to the centralized plant unit, which emits 66.301 kg of CO_2, and the conventional plant unit, which releases 48.669 kg of CO_2.Therefore, considering the factor of carbon footprint, distributed planting is the most sustainable and environmentally friendly planting method.

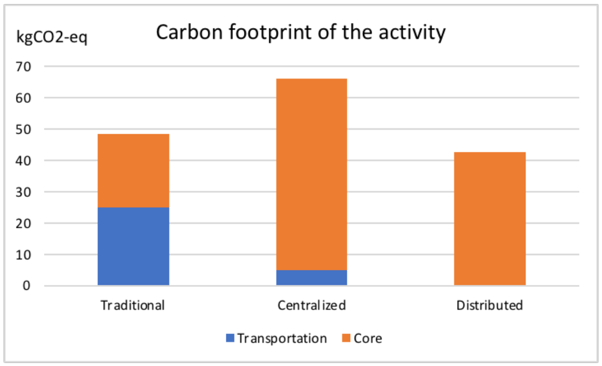

Fig. 4. Carbon footprint of 3 cases

4. RESULT AND DISCUSSION

In conclusion, the present study evaluated the growth rate, energy efficiency, CO_2 absorption rate, and carbon footprint of three different planting methods, namely traditional planting, centralized planting, and distributed planting. The results indicate the following key findings:

- Distributed planting exhibited the highest growth rate among the three planting methods, with a growth rate nearly double that of traditional planting and a final harvest weight significantly higher than the other two planting methods.
- Distributed planting is the most energy-efficient option for plant cultivation, for it adopts a combination of natural sunlight and artificial lighting. The distributed planting only emits 42.719 kg CO_2 per unit in each growth cycle, compared with 66.301kg CO_2 for the centralized planting unit and 48.669kg CO_2 for the traditional plant unit.
- Owing to the highest growth rate, distributed planting exhibited the strongest CO_2 absorption capacity. Thus, buildings that incorporate adequate small-scale distributed vertical farms will obtain benefits such as improved indoor air quality and reduced air conditioning requirements.

Based on the aforementioned points, the implementation of small-scale distributed vertical farms within buildings presents a more sustainable and environmental-friendly alternative, as it exhibits a lower carbon footprint in comparison to large-scale centralized vertical farms.

Future work in this field could focus on exploring the potential of optimizing the light environment in distributed planting for further enhancing plant growth, as well as investigating the economic feasibility of small-scale distributed vertical farming with different settings.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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