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Article

A New Approach for Vertical Plant Cultivation Maximizing Crop Efficiency

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Abstract: The publication presents an innovative tower cultivation device designed to significantly increase vertical farming efficiency. The device divides the cultivation system into separate chambers. One division corresponds to the different growth phases of the plants, while another reflects the daily variation in conditions. Each chamber presents slightly different conditions and cultivation patterns from the others. For the early stages, crops are grown horizontally in trays once they mature, transplanted into mobile cultivation towers. The closed circulation of ventilation and irrigation reduces water consumption by up to 95%. A unique separate day-night division optimises light, temperature and humidity conditions, mimicking natural growth patterns. This approach not only saves water and energy but also optimises cultivation in a three-dimensional space. The presented solution focuses on the often overlooked aspects of cultivating in vertical farms and makes this method of growing much more cost-effective and feasible to implement on a large scale.

Keywords: vertical farming; plant cultivation; sustainable agriculture; hydroponics; aeroponics; aquaponics; food security; climate change

1. Introduction

It is estimated that the world population will exceed 9 billion people by 2050, the vast majority of whom will live in cities [1,2]. The global warming currently observed in many regions of the world leads to water shortages and, consequently, to a decline in agricultural production and even hunger. Moreover, about 30% of all agricultural production is wasted [3,4]—the main reasons are the long food supply chain and its waste by final recipients, i.e., individual consumers, restaurants, shops. In order to compensate for the loss, the agricultural industry must produce much more than actual needs.

Vertical farming, an innovative agricultural concept, traces its roots back to antiquity with the Semiramida Hanging Gardens in Babylon, Iraq, serving as an early example of vertical cultivation. The modern interpretation of vertical farming was conceptualized by D. Despommier [5,6]. Vertical farms, also known as "vertical farmers," provide an alternative to traditional horizontal farming by multiplying agricultural layers vertically. This approach conserves horizontal space while maintaining or even increasing the total area available for agriculture. Vertical farms aim to produce high-quality food for larger populations in an environmentally friendly manner[7,8]. By stacking plants one above the other, vertical farms optimize farming space and enable crop production even in urban centers.

One of the key advantages of vertical farming is the control over environmental conditions [9]. Plants are grown indoors in specially designed facilities, miminsing the influence of external weather. This allows for year-round cultivation regardless of climate, reducing the risk of crop damage from adverse weather conditions such as rain, snow, wind, or hail [10,11]. As a result, vertical farms can achieve significantly higher yields per unit area compared to traditional farms. Moreover, vertical farming may employ soilless growing techniques using nutrient-rich water solutions, either through submersion or spraying, with plant roots partially exposed to enhance oxygen absorption [12,13].

This closed-loop system conserves water efficiently, making vertical farming a sustainable and resource-saving agricultural method.

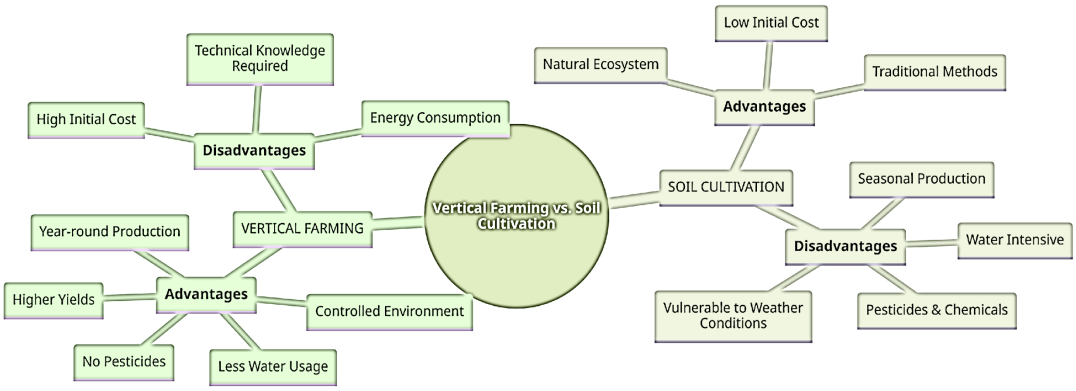

Figure 1. The vertical farming approach: advantages and disadvantages compared with traditional soil cultivation.

The most common modern vertical farming technologies are:

1) In terms of environments:
   - Hydroponics: This method uses nutrient-rich water to deliver nutrients directly to plant roots, eliminating the need for soil. It is one of the most common methods used in vertical farming. Hydroponics, specifically containerized vertical farming, involves growing plants in vertical layers within mobile shipping containers. A 2023 study by D. Mahalingam et al. [14]explored the automation of farming operations like transplantation and harvesting using collaborative robots (cobots). This approach, which requires just a single demonstration from a farmer, has shown the feasibility of performing tasks without specific programming.
   - Aeroponics: In this system, plants are grown in an air or mist environment without the use of soil. Nutrient-rich water is misted directly onto the plant roots. Aeroponics is a method where plants are grown without soil, with nutrient-rich water provided to the suspended roots via an atomized spray system. A study by Narasegowda and Kumar in 2022 characterized spray nozzles based on parameters like spray drift, height, angle, width, and droplet sizes. This research is pivotal for selecting the appropriate spray system for specific canopies and can be beneficial for controlled agricultural practices in greenhouses and apartment rooms [15].
   - Aquaponics: This is a combination of aquaculture (raising fish) and hydroponics. The waste from the fish provides nutrients for the plants, and the plants help filter and clean the water, which is then recirculated back to the fish tanks. Aquaponics combines vegetable and fish farming in a single water loop, offering a sustainable approach to urban development and food production. Traditional systems often require manual intervention for water circulation and quality control. However, a 2023 study by Agrawal et al. introduced a Cyber Physical Aquaponics (CyPhA) system [16]. This system, which has been successfully operated for 75 days, uses sensors for various water parameters and provides LED-based alerts for critical conditions.
   - Soil-based vertical farming: While less common, some vertical farms use traditional soil as a growing medium, stacking plants in layers.
   - Hybrid system: usually combining the aeroponics and hydroponics approaches.
2) In terms of mechanical systems used:
   - Stationary: plants are grown in stationary horizontal trays.
   - Rotating vertical farms: plants are placed on a rotating conveyor system, ensuring that all plants receive equal amounts of light and nutrients.
   - Tower: vertical systems where plants are grown in a tower-like structure. They can be used for both hydroponic and aeroponic systems.

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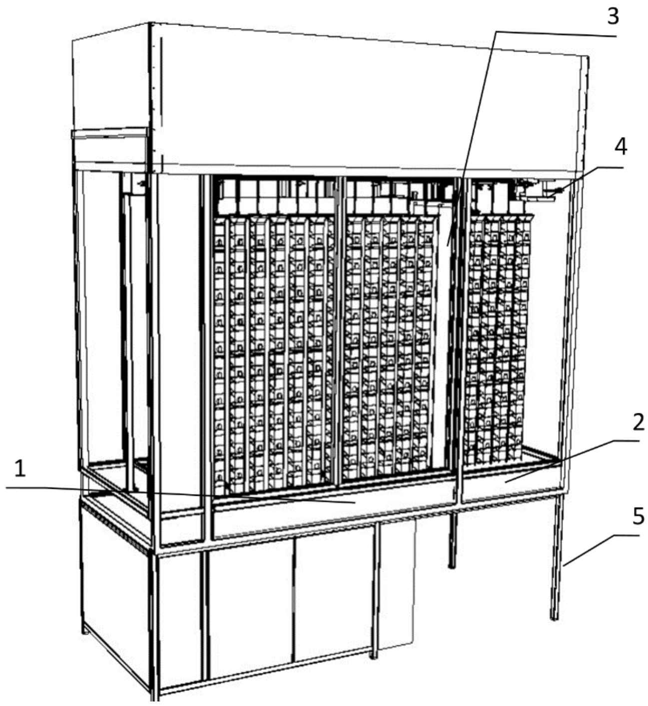
One of the primary advantages of vertical farming is the ability to cultivate plants in highly controlled environments, optimizing conditions for faster maturity and enhanced yields compared to traditional farming [17]. However, the energy-intensive nature of vertical farming poses significant challenges. Recent research has delved into optimizing wheat growth using control theory, focusing on efficient resource utilization to maximize net profit and annual yield. Aeroponics, a subset of vertical farming, eliminates the need for soil, instead relying on an atomized spray system to deliver nutrient-rich water directly to suspended roots [18]. This method's efficiency is contingent on the precise characterization of spray nozzles, which influence water distribution and droplet interaction with plant roots. Technological advancements have further enhanced the precision and efficiency of vertical farming. The integration of robotics, such as hybrid robots equipped with cameras and manipulators, facilitates high-accuracy plant monitoring in vertical hydroponic farms [19]. Such innovations enable non-destructive plant mass estimation, providing valuable insights into plant growth dynamics. The potential of vertical farming extends beyond large-scale commercial operations. Studies have explored the feasibility of urban farming within residential buildings, utilizing 3D city models to identify suitable micro-locations based on photosynthetically active radiation (PAR) levels [20]. Such approaches highlight the scalability and adaptability of vertical farming techniques. Lastly, the Modular Automated Crop Array Online System presents an open hardware system designed for plant transport in automated horticulture settings, including vertical farms [21]. This system underlines the potential of automation in reducing labor costs and enhancing operational efficiency in vertical farming.

Vertical farming allows for year-round cultivation, overcoming environmental limitations, and ensuring food security. However, one of the challenges is the high energy consumption. Due to the fact that all available solutions for vertical plant cultivation can only work in one climate, the life of the lighting system is reduced by its constant switching on and off, and the consumption of water and energy is economically unjustified due to the constant need to change the climate in the module. This is why the authors present a novel approach here. The proposed solution to this problem is the construction of a system of vertical farms with modular rotating towers, in which plants are grown in strictly controlled physical and chemical conditions and move from one chamber (day) to the second one (night) on the rotating towers. The presented invention focuses on the often overlooked aspects of cultivating in vertical farms and makes this method of growing more cost-effective and feasible to implement on a large scale. The currently dominant solutions for micro and small-scale vertical farming allow crops to be grown in a fully controlled environment, but due to their high initial cost (Capex) and high operating costs (Opex), they are only an adjunct to cheaper food produced by incumbent methods (mainly in greenhouses) [22,23].

2. Materials and Methods

In the literature, we can report only one maturation zone in vertical farms which works both as a daytime/nighttime zone for a certain amount of time in 24-hour period [24] In the authors' system, the above-mentioned problem is solved by using a day and night division system. Because the "day" zone is lit and the "night" zone is unlit, the life of the lighting system is extended. This is due to the fact that there is no need to constantly turn the lighting on and off, taking into account the well-being of the plants. Irrigation and energy consumption are economically justified due to the fact that similar conditions are maintained in each zone at all times. The use of the tower rotation system allows proper light emission to each plant. The essence of the system, depicted in Figure 2, is that the plants are grown in a day-night system. The vertical farming module is divided into two modules: day and night, in a 2:1 ratio. This is a reflection of the natural growth mode of cultivated plants. The plants are exposed to light for 16 hours, after which they are transported to the night zone for another 8 hours. Then, they are transported back to the irradiated zone (climate module "day"). There is an opening and closing partition between the two zones separating them. The "day" climate module is characterized by the lighting panel working 24 hours a day, which makes its service life longer than in vertical farms that are not divided in such a way.



1– climate module "day" A1
2–"night" climate module A2
3–separation device climatic zone divider
4–suspension system
5–tower system frame
6–towers
7–roller for roller shutters for climatic zone partitions
8–exposure panel
9–device sliding system for separating climatic zones
10–tower cart
11–pot
12–mechanism for changing the driving track
13–front door

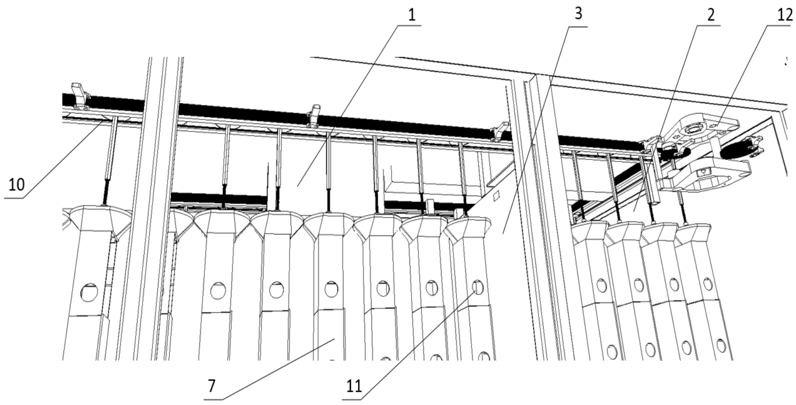


Figure 2. The upper row—an axonometric view of a system for tower plant cultivation The lower row—a side view from the "day" and "night" climate module with a focus on the towers and the separation device.

The plants are placed in pots, with at least one plant per pot. These pots are arranged at an angle within a structure called a tower. The system includes many towers, each containing at least 10 pots. Each tower is equipped with a trolley that allows it to move along rails suspended from the ceiling. The towers move in a straight line, but they can change direction by 90 degrees using a track change mechanism. This allows the plants to be transported to different climatic zones. Climate zones are separated by a roller shutter or sliding doors, which have insulating and thermal properties. The movement of the roller shutters is enabled by the sliding system within the module.

Moreover, access to each plant in the module is equally easy, and the tower suspension system itself allows the towers to reach the front door (see Figure 3), thus increasing the ergonomics of the entire system. The "day-night" mode is possible thanks to the moving towers system and the shutter which separates climate zones, thermally isolates them and reflects the light emitted by the illumination system. The device for separating climate zones is a flat surface, with an insulating layer and good thermal-isolation properties.

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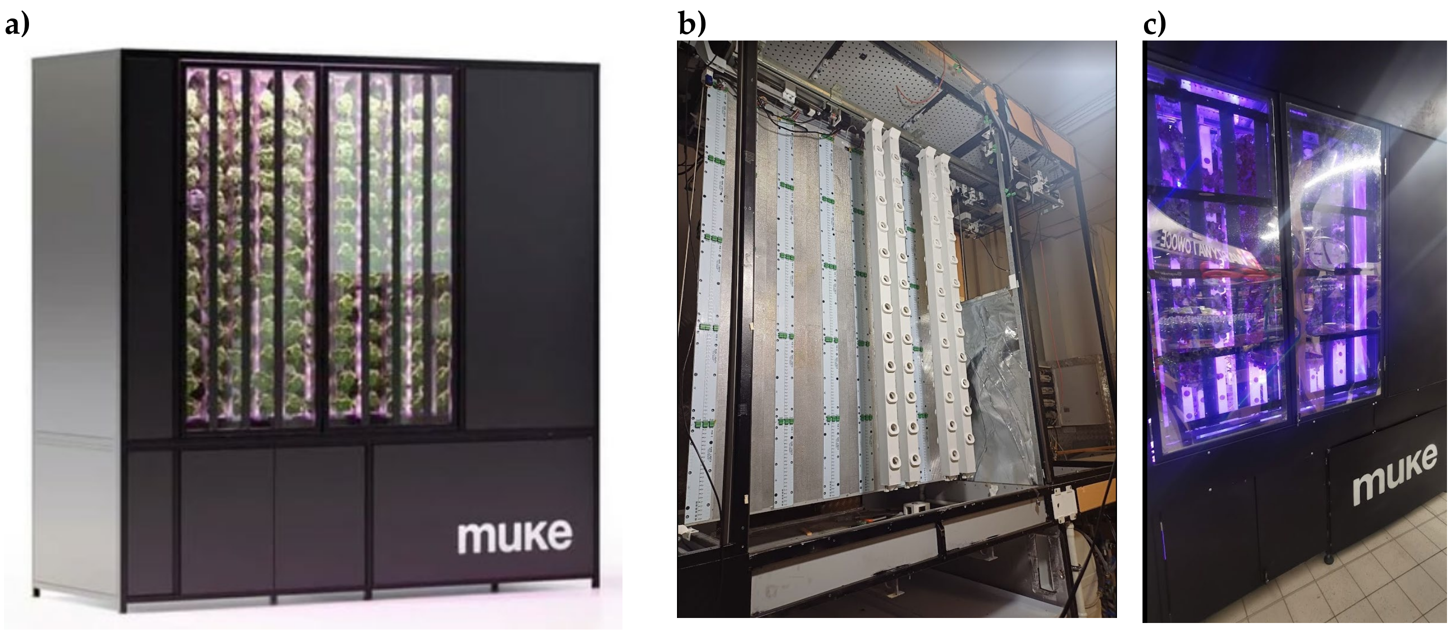

Figure 3. The vertical farming with the day/night chambers; **a)** computer-aided design model **b)** the system during assembly—the towers (in white) are visible **c)** the prototype module implemented in a grocery shop.

Nevertheless, the most important construction challenge in the proposed vertical farms is to provide plants with the most appropriate lighting and climatic conditions (Figure 4). The use of rotating towers, as opposed to classic shelves, allows not only to increase the ergonomics but also efficacy, yield and further automation.

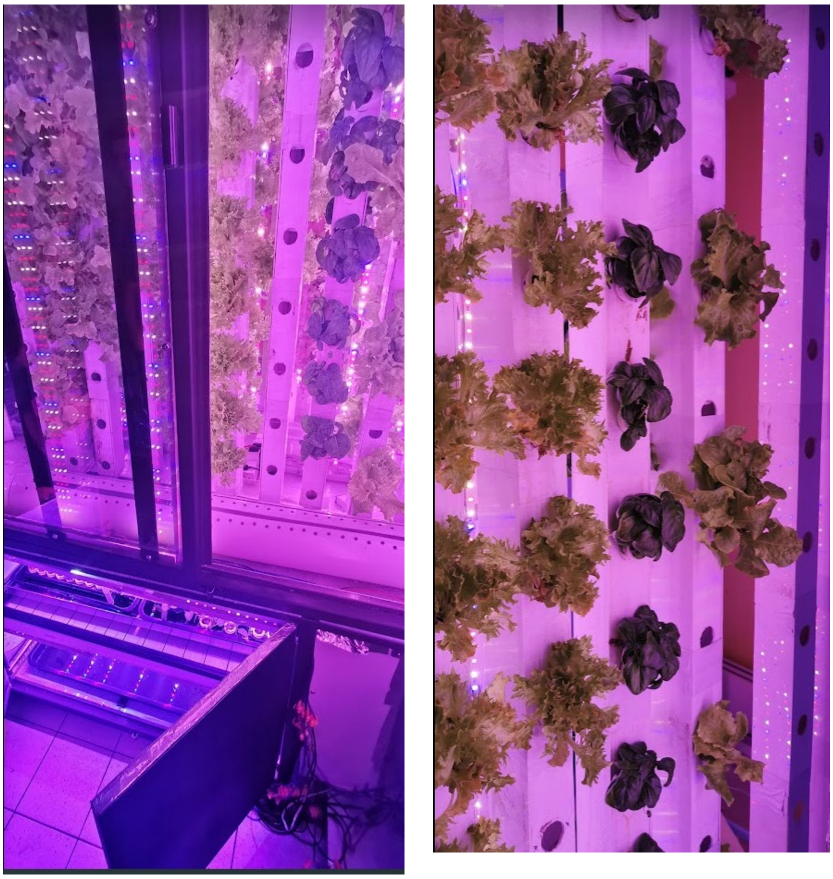

Figure 4. Testing different types of plants in a module with variable climatic parameters.

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Plants pass through successive chambers in the cultivation cycle. Each chamber is designed to optimise the entire process on the one hand and to rationalise the space and use of the necessary materials and equipment on the other. Chamber A1 (“day”) represents conditions during the day, which always lasts 16 hours. Chamber A2 (“night”) imitates night and the plants stay there for 8 hours in a 24-hour cycle. By using an airtight partition between the chambers and a suitable ventilation system, it is possible to create conditions that allow optimum variation in humidity, temperature and CO_2 concentration. The multi-chamber cultivation system gives the possibility to vary the conditions in each chamber, so that the plants receive exactly what they need at that stage of growth (Table 2). This improves both the cultivation process and optimises electricity consumption.

Table 2. Vertical farming cultivation system with the day/night chamber feature.

	Human interaction	Light	Temp.	Humidity	Irrigation	Plant position	Days in the chamber
Loading chamber	Yes	No	Fixed	Fixed	N/A	Horizontally	N/A
Germination chamber	No	No	Fixed	Fixed	Ebb&Flow	Horizontally	3-5
Propagation chamber	No	Yes	Variable	Variable	Ebb&Flow	Horizontally	20-24
A1—towers' chamber—daytime	No	Yes	Fixed	Fixed	Dripping	Vertically	20-24
A2—towers' chamber—nighttime	No	No	Fixed	Variable	Dripping	Vertically	
Exit chamber	Yes	Yes	Fixed	Fixed	NFT	Horizontally	2

The operator places new trays with the substrate in the loading chamber. There are enough of them to run continuously for at least 21 days. Robot 1 picks up the trays with substrate and moves them to the automatic sowing unit. In the next step, they are placed in the germination chamber for a period of 3 to 5 days. After germination, the robot moves the trays from the germination chamber to the propagation chamber, where they will remain for approximately 21 days. The trays are placed in cuvettes. Each cuvette holds 10 trays. After a given period, the robot picks up the tray and transfers it to the lift, which moves it above to chamber A1. In chamber A1, robot 2 takes individual plants from the tray to the cultivation towers. The plants in the cultivation towers are moved between chambers A1 and A2, with 16 hours spent in chamber A1 and 8 hours in chamber A2 during the day (Figure 5). After a certain period, the robot pulls the plants out of the cultivation towers and moves them in the dispensing chamber, where they spend another 48 hours, after which they are collected by the operator.

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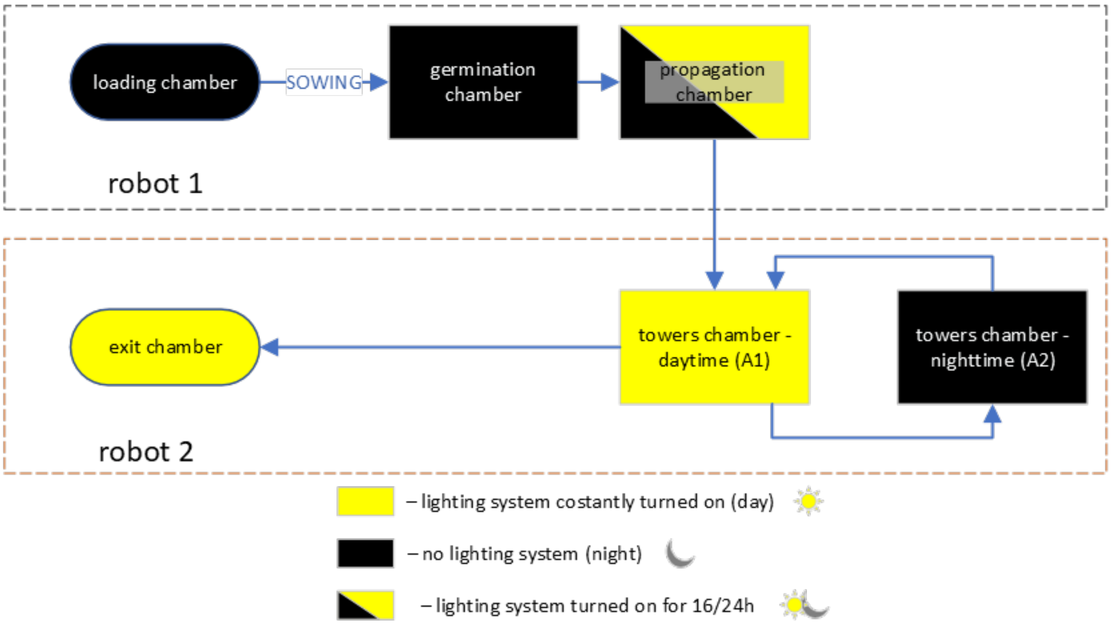

Figure 5. Cultivation process devided into operational zones of robot #1 and #2.

3. Discussion

Traditional agricultural practices face numerous challenges, including limited land availability, water scarcity, climate change, and a growing global population. Vertical farming offers a promising solution by enabling the cultivation of plants in a vertically stacked or inclined arrangement, typically in indoor environments. This approach maximizes space utilization and optimizes resource efficiency while reducing the environmental impact of agriculture. Vertical farming offers several advantages over traditional agriculture. Firstly, it allows year-round cultivation, independent of weather conditions, making it less vulnerable to climate change and ensuring a continuous food supply. Secondly, it significantly reduces land usage, as multiple layers of plants can be grown in a single vertical structure. Thirdly, it conserves water by recycling and reusing it within the system. Additionally, vertical farming minimizes the need for pesticides and herbicides, promotes efficient energy usage, and minimizes transportation distances, leading to reduced carbon emissions. However, the additional value of the presented Muke system is a multi-chamber cultivation system, which allows for:

1. A reduction in initial investment costs mainly due to a 30% reduction in the lighting installation needed compared to other vertical farming solutions.
2. Efficient use of the available cultivation space, allowing an increase in the total production in a given space. This is particularly important where space is limited and expensive.
3. A reduction in the amount of materials and equipment needed for construction.

Table 3. Key features of the vertical farming Muke system with day/night chambers.

Feature	Description
Device Overview	The system consists of a tower structure divided into two modules: day and night, in a 2:1 ratio, aligning with natural plant growth patterns by providing 16 hours of light followed by 8 hours of darkness. The day module is illuminated 24/7 to extend the lifespan of the lighting system.
Climate Control	The day and night modules create distinct climate conditions, with the day module simulating daytime (lighting, temperature, humidity) and the night module simulating post-sunset conditions. This ensures plants receive optimal conditions throughout their growth cycle.
Water Efficiency	Features a closed ventilation and irrigation circuit, leading to a 95% reduction in water consumption compared to traditional farming methods. The closed-loop system recirculates water, minimizing wastage and promoting sustainable agriculture.

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Accessibility and Ergonomics	The module has been constructed based on three principles: a. Modularity and ease of transportation—the semi-prepared farm is assembled on-site by a team of 2 within 1 day. b. Comfort of handling—the feeding zone, located in the lower front part, allows quick and easy loading of new trays with substrate and removal of used ones. The dispensing zone, located at the front of the module at a height of 100 to 180 cm, allows easy collection of plants ready for sale, without any need for ladders or platforms. c. Ease of ongoing maintenance and repair—the replacement of any technical device in the module can be carried out by 1 technician in no more than 3 hours.

The element that will distinguish Muke farm system from the competition is a system of the automated tower modules which allows the towers to be moved between the A1 (day) and A2 (night) chambers. In the analysing module, there are 39 towers, of which 26 are in chamber A1 and 13 in chamber A2 at any one time. The towers, together with the plants, are moved every 8 hours, ensuring that the 16/8 cultivation cycle is maintained, which is optimal for most of the leafy greens and fresh herbs studied and provides the best quality to growth rate ratio. By moving the towers 3 times a day and performing a full cycle during this time, there are no dead zones where unwanted microorganisms, pathogens or molds can develop. This also reduces the risk of shading from one plant to another, which can consequently lead to uneven growth and suboptimal cultivation. In addition, by moving the towers, it is possible to photograph each plant once a day and based on image analysis, estimate its welfare, weight and size. Ultimately, the system will, based on this information, decide whether the plant is ready to be harvested or removed in the event of problems or underperformance.

Table 4. Retail VF Muke 39W140h vs FreightFarms Greenery S—the data obtained directly from Muke's documents, which refers to the 8-month pilot project of Muke Retail Farm 39W140H and [25,26].

	Muke 39W140h	**Greenery S**
Energy per 1 kg of produce	7.95 kWh	14.20 kWh (approx)
Annual yield of lettuce (heads approx. 150g) per $1m^3$	2240	595 (approx)
Monthly labour hours required to operate a farm	4	140

A comparison of two small-scale vertical farm solutions, similar in their approach to the cultivation itself. In both cases, the plants are grown horizontally in trays in the first phase of their growth, before being transplanted into cultivation towers and grown vertically. What is apparent from the table is the significant differences in efficiency between the two solutions. Muke's optimised solution not only uses around half the energy required to produce the same weight of plants while uses smaller space. The FreightFarms solution requires 3.75 times more space to achieve the same yield. In cities, with dense and expensive space, this aspect of efficient space use is particularly important. A comparison of the time required to operate the farms on a monthly basis clearly shows that automated cultivation appears to be the only sensible solution in areas where labour is limited and expensive.

4. Limitations

High initial capital investment, operational costs, and energy requirements are significant barriers to the widespread adoption of vertical farming systems [27,28]. Technical challenges, such as optimizing lighting, temperature, humidity, and nutrient delivery systems must be addressed for optimal plant growth. Additionally, the limited variety of crops suitable for vertical farming and the lack of standardized industry practices pose challenges to its scalability. Vertical farming systems are currently the most suitable for certain types of crops, such as leafy greens, herbs, and microgreens. The limited variety of crops that can be economically cultivated using this approach poses a challenge for achieving agricultural diversity. Moreover, an important issue is to ensure appropriate operating parameters, process repeatability and functional reliability while ensuring ergonomic layout that facilitates operation and service. The arrangement of components must take into account the role and impact of individual elements on other elements of the system. However, ongoing research and development efforts are expanding the range of crops suitable for vertical farming, including fruits, vegetables, and even certain root crops. Establishing consistent regulatory frameworks, quality standards, and industry certifications are essential for promoting the widespread adoption and commercial viability of vertical farming systems. Collaboration between academia, industry stakeholders, and policymakers is crucial in developing these standards.

5. Conclusions

Vertical farming has emerged as a sustainable approach to plant cultivation, offering numerous advantages over traditional farming methods. By maximizing resource efficiency, reducing land usage, and providing year-round crop production, vertical farming has the potential to revolutionize food production and address the challenges of a growing global population. However, vertical farming faces significant challenges, primarily high energy consumption. Existing solutions for vertical plant cultivation are limited to functioning in a single climate, which leads to frequent on-off cycles of the lighting system, reducing its lifespan. Additionally, the continuous need to modify the module's climate results in economically inefficient water and energy usage. Thus, the device for tower plant cultivation introduced in this publication addresses key challenges in this area. We proposed a solution which is a system of vertical farms with modular rotating towers, in which plants are grown in strictly controlled physical and chemical conditions and move from one chamber (day) to the second one (night) on the rotating towers. A multi-chamber approach includes a day-night system, optimizing climate conditions, conserving water resources, and enabling the cultivation of multiple plant species, allowing this solution to significantly enhance crop efficiency. Furthermore, the extended lifespan of the lighting system and improved ergonomics make this device a promising tool for sustainable and diverse agricultural production. The device holds great potential in advancing agriculture towards a more sustainable and efficient future.

The practical importance of the research results from the growing population, ongoing urbanization processes, degradation of the natural environment, shrinking areas used for agriculture and ongoing climate changes. Mobile, dispersed cultivation modules produce food regardless of the surrounding natural environment, and their compact dimensions, high efficiency and automation of cultivation allow them to be placed in places of final sale or consumption of food i.e., food supermarkets or restaurants. The need for sustainable agricultural practices has led to increased interest in vertical farming. The proposed vertical farming system offers significant advantages in resource conservation and year-round cultivation, thus takes vertical farming to the next level by addressing key limitations of existing systems.

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