Analysis of LED lighting strategies in vertical urban farming for enhancement of plant productivity and energy consumption

João Miguel Rodelo Pereira

joaomirodelo@gmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal

October 2023

1. Introduction

In 2022, the global population reached 8 billion and it is expected to grow to 9.7 billion by 2050 [1]. This surge, coupled with calorie-intensive diets, presents a challenge to achieving global food security without harming the environment. This paper underscores the urgency of reevaluating agricultural practices due to their environmental impact. Agriculture contributes to 25% of global greenhouse gas emissions [2], stemming from chemical use, waste, deforestation, and biological processes. Waste management and drainage of organic soils significantly contribute to emissions and synthetic fertilizer production relies on fossil fuels and inefficient application methods. Land use and deforestation disrupt ecosystems and reduce soil fertility. Water consumption in food production is significant, with agriculture responsible for 70% of global freshwater use [3]. Inefficient irrigation methods and inadequate regulation contribute to water wastage. One alternative is Vertical Farming, which optimizes environmental conditions, reduces land and water usage, eliminates pesticide use, and enables year-round crop production. Innovative methods like Vertical Farming, alongside changes in practices, regulations, and consumer behaviour, are essential for global food security without compromising the environment. However, the elevated energy consumption of these facilities requires sustainable implementation for its benefits to be exploited.

This study focuses on developing and analysing an LED control system for a vertical farm greenhouse in Lisbon. The system integrates light sensors and LED actuators to optimize plant growth and minimize energy use by adapting LED operation to natural light conditions. The research covers hardware functionality, sensor accuracy, LED dimming precision, and dynamic responses to natural light patterns. A plant growth study evaluates different lighting strategies on two basil plant varieties – Gustosa and Pluto. The study aims to determine optimal DLI targets, assess energy consumption, and investigate natural and artificial light's impact on basil plant development in a vertical farm.

2. Literature Review

This section explores the historical context and innovations in agriculture, emphasizing the need for sustainable practices. Sustainable agriculture presents multifaceted challenges, requiring region-specific solutions within social, economic, and political contexts. Water-efficient techniques like drip irrigation and soilless systems like hydroponics, aeroponics, and aquaponics are introduced as potential solutions to reduce water consumption [4]. The advancements in agricultural machinery, digitalization, and automation are explored. Smart farming, empowered by sensors and data analytics, enhances decision-making and resource utilization. Controlled Environment Agriculture (CEA) offers climate-resilient and season-independent food production by controlling environmental conditions. Vertical farming, a major CEA form, can reduce CO2 emissions by up to 70% compared to traditional agriculture when powered by renewable energy. Challenges arise when case studies of conventional vertical farms report carbon footprints up to 10 times superior to traditional methods. To enhance sustainability, vertical farming should prioritize renewable energy use together with rational and efficient use of energy to effectively reduce associated emissions. This method excels in reducing transportation emissions, fertilizer and pesticide use, waste production, and conserving water and land resources, making it a promising option for sustainable agriculture.

In Controlled Environment Agriculture (CEA), understanding key environmental parameters like temperature, humidity, and light is essential. Basil plants thrive at 18-30°C during the day and 13-25°C at night, with a 5°C day-night temperature difference. The optimal humidity for basil falls within the 50-75% range. Light is a fundamental factor in photosynthesis and plant growth. Light quantity, measured by metrics of Photosynthetic Photon Flux Density (PPFD) and Daily Light Integral (DLI) in the botanical context, and light quality, characterized by the spectral composition of light, play critical roles in plant development. Different plant species respond uniquely to variations in light quality, with blue and red light being essential for photosynthesis and overall plant physiology. Regarding light quality, basil plants are reported to have optimal PPFD between 234 to 545 $\mu mol.m^{-2}.s^{-1}$ (DLI = 13.5 to 31.4 $mol.m^{-2}.d^{-1}$) for the generality of greenhouse crops, and DLIs around 15 are the most recommended for Basil [5][6]

Energy consumption is a significant concern in CEA, with lighting, primarily from energy-efficient LEDs, representing a substantial portion of the total energy costs. Energy use may vary based on factors like climate, equipment efficiency, and crop-specific lighting needs. The study [7] evaluates LED energy performance in a basil greenhouse with varying artificial light supplements. Energy consumption ranges from 20.25 to 162.00 kWh per growth cycle, showing biomass growth efficiency from 0.30 to 1.83 g/kWh. This metric is crucial for assessing LED effectiveness in plant yield, particularly in comparable natural light conditions.

In summary, understanding the intricate interplay between light quantity (and quality), alongside energy-efficient lighting practices, is paramount for successful plant growth in CEA. These factors are essential considerations for maximizing productivity while minimizing energy consumption and environmental impact.

The study seeks to establish how different light (DLI) target quantities, achieved through a combination of natural sunlight and supplementary LED lighting, influence plant performance. Additionally, the project aims to design, set up, and optimize an automated light control system with sensors and LED dimmers for efficient and precise light management within the greenhouse. This research intends to enhance energy efficiency and plant productivity in vertical urban farming by demonstrating the practicality and effectiveness of this system, using cost-effective materials and tuning techniques.

3. Case Study - Raiz Vertical Farm®

Raiz Vertical Farms® is a pioneering vertical farming startup (Figure 1) located in Beato, Lisbon. Its innovative concept farm, established in 2021, serves as a proof of concept for urban agriculture, showcasing that food can be grown efficiently with minimal water and land resources within city limits. The farm caters to local restaurants and markets, with plans to expand its smart farming solutions to communities and organizations globally. This study aims to assess the impact of Daily Light Integral (DLI) on basil plant growth within Raiz's greenhouse facility, where natural light is combined with LED lighting. The research also involves designing and implementing an automated light control system for optimal energy efficiency and plant productivity, contributing to the development of urban vertical farming. The greenhouse's strategic location in Lisbon benefits from abundant sunlight and favourable climatic conditions throughout the year, promoting year-round crop cultivation. The farm utilizes hydroponic systems with water circulation to efficiently nurture plant growth. A variety of plants have been successfully cultivated, but the focus is on herbal plants. The study addresses the basil varieties, "Sweet" Gustosa basil and Pluto basil.

Figure 1 - Raiz Vertical Farms® concept farm

Raiz Vertical Farms® uses an array of equipment for environmental control, including one AC, a dehumidifier and LEDs which can be seen in Figure 2 top view scheme of the growing container with six cultivation barrels in total.

The system employs three light sensors, one microcontroller for data processing and three LED blades for artificial light complements, which will be installed on each of the three barrels used for the experimental campaign.

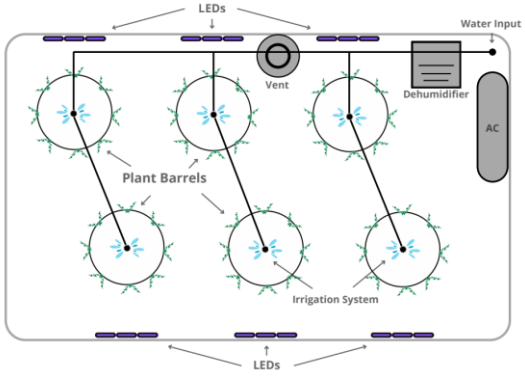

Figure 2 - Schematic representation of the growing container of Raiz's concept farm (top view).

The farm's energy consumption encompasses the operation of all the equipment mentioned. AC space cooling is the most energy-intensive

operation due to high indoor temperatures during the day. However, LED operation also significantly contributes to overall energy consumption, along with ventilation and dehumidification. Energy consumption data were collected using the Shelly Plus 1PM electrical metering device, which was connected to the LEDs, dehumidifier, ventilation fan, and pumps.

This study addresses challenges faced by Raiz Vertical Farms® related to manual labour in farm operations and the limitation in the control of LED operation. To enhance efficiency and reduce human errors, the focus is on automating the LED lighting system. Currently, equipment like LEDs, can be controlled remotely but lack the ability to adjust light intensity and adapt to natural light. By implementing a dynamic lighting control system, operations can become automated, catering to individual plant lighting needs and optimizing energy use. The study also aims to determine optimal lighting requirements by testing different lighting strategies and assessing energy consumption, while considering a mix of natural and artificial light exposure. This innovative approach promises to streamline farming processes and improve productivity at Raiz Vertical Farms®.

4. LED Control System Assembly and Tunning

This section introduces a dynamic LED control system designed to address limitations in the farm's existing lighting system. The new system is represented in Figure 3 and aims to automatically adjust artificial light based on daily weather conditions, allowing for customizable daily light integral (DLI) targets and enhancing energy efficiency. The study will explore different DLI levels (12.5, 15, and 17.5 mol.m^{-2}.d^{-1}) using the new control system in three barrels. Each barrel is equipped with light sensors (AS7341), Horti-Blade LED strips, and a Raspberry Pi Zero 2W microcontroller to measure natural light intensity and control artificial lighting. The entire system's components, including multiplexers, PWM-to-Voltage converters, LED drivers, and Shelly digital switches, work together to adjust the light intensity.

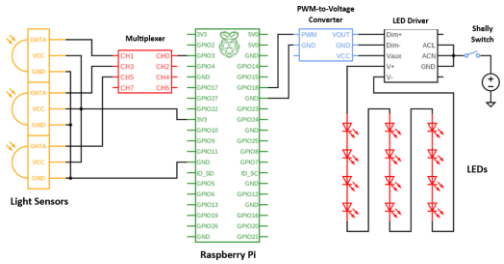

Figure 3 – Electrical Diagram of the entire LED control system including main components light sensors (yellow), Raspberry Pi (green), LED load (red) and driver (black), and secondary components multiplexer (red), PWM-to-voltage Converter (blue) and Shelly Plus 1PM (blue).

The LEDs operate after sunset, ensuring a minimum of 7 hours of darkness for plant development. The LED intensity varies to meet the targeted DLI for optimal plant growth based on both natural and artificial light exposure, with daily variations in photoperiod accounted for. The schematic of the LED operation is shown in Figure 4.

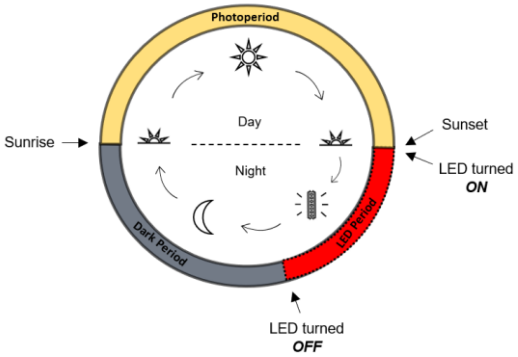

Figure 4 – Schematic of the LED control system operation for an example day

A detailed account is provided of the installation and setup of components in the LED control system. Central to this system are Raspberry Pi microcontrollers, which manage sensors and LED control. Three Raspberry Pi units were utilized for different plant barrels, enabling wireless access via SSH. These run on Linux operative system, were programmed using Python and allow data transfer to Google Cloud Platform. Figure 5 shows a picture of the control system installed in front of the testing section of one barrel with 3 LED blades, 3 sensors and the microcontroller (inside the top box)

Figure 5 – Light sensor positioning on a testing barrel.

To facilitate the analysis of light's impact on plant productivity, Photosynthetic Photon Flux Density (PPFD) was employed as the unit of measurement after conversion. A 3D-printed housing box was also designed to protect the sensor and filter part of the light to avoid sensor saturation. To convert the multiple sensor channel readings into a single PPFD value, a multiple input linear regression (MLR) approach was employed. A total of 198 measurements were collected from the AS7341 sensor and a reference smartphone app called "Photone." This reference app accurately measures PPFD and was used to establish a reliable conversion method with high accuracy (R^2 = 0.982) with a maximum error of 13%.

The LED control system employs PWM (Pulse Width Modulation) to regulate light intensity. This method involves sending pulsed signals with varying ON/OFF cycles, with the ON duration determining the light output level. PWM signals are converted to an analogue 0-10V signal to control the LED driver's output voltage, which, in turn, affects light intensity. The LED driver allows dimming between 10% and 100% of maximum intensity. To ensure linearity, tests were conducted, and the results demonstrated a highly linear relationship between PWM duty cycle and voltage output (Vout), LED light intensity (PPFD), and electrical power consumption. The limitation of dimming levels between 10% and 100% was addressed by applying a simple conversion, allowing precise control within this range. The duty frequency of PWM signals was also found to influence the outcomes. Higher frequencies were recommended for improved control. However, the highest frequency that didn't result in substantial dimming loss was 500Hz.

5. Experimental Procedure and Performance Indicators

The experimental setup involves cultivating two basil plant species, Gustosa "Sweet" Basil and Pluto Basil, in three separate barrels, each with its own independent LED control system. Each barrel houses 15 plants, consisting of nine Gustosa and six Pluto basil plants. Environmental conditions, including temperature, humidity, and lighting, are monitored and controlled using air conditioning, dehumidification, and ventilation. The average temperature during the

experiment is maintained at 25°C, and relative humidity averages 61%. Irrigation is standardized across the barrels, ensuring equal water flow per plant of 0.039 L/h. Seeds are initially sown in jiffy pallets, and seedlings are transplanted into the hydroponic barrels after 2 weeks of germination. During harvest, plants are cut at the stem's base, separating them from the roots and remaining jiffy material. The plant mass considered for sale comprises the stems and leaves (edible part).

The initial trials of the implemented system allowed the investigation of the light conditions experienced inside the farm. Natural light conditions revealed variations in sunlight exposure throughout the day with a decrease of intensity in the afternoon due to the testing surface orientation at southeast (-2º). Artificial light intensity received by the plants varies non-linearly with the distance to the light source, thus an average PPFD value of 750 $\mu mol.m^{-2}.s^{-1}$ is considered for the determination of LED operation. Sowing, germination, and harvesting procedures are also explained. Additionally, the study defines daily light integral (DLI) targets for each barrel and the associated LED control algorithm.

The primary indicators for plant growth include fresh mass, size, and the total mass of the plant, which is measured weekly. The fresh mass is particularly important, as basil is sold based on its edible weight. The analysis also covers the "green profile area," which describes the plant's size by considering its height, width, and profile orientation. Plant development is monitored over four weeks until harvest.

The energy consumption of the LEDs in the dynamic control system under different daily light integral (DLI) targets is another key parameter of interest. The study aims to assess the energy required for artificial lighting under different DLI targets and to determine how much of these targets can be met passively by sunlight in a greenhouse setting.

The LED operation and DLI are monitored using Shelly meters connected to each set of LEDs. The plant yield and total energy consumption per harvest cycle are analysed, as well as the energy efficiency in biomass growth [g/kWh]. The study also formulates a relationship between plant growth and DLI regime targets (g/DLI), providing insights into the most effective DLI regimes for basil cultivation.

6. Results and Discussion

This section analyses the reliability of the lighting system by examining PPFD measurements for both natural and artificial light. It focuses on understanding daily light patterns and how the LEDs are controlled to maintain ideal lighting conditions. The results for representative days in September and October are presented, highlighting the influence of cloud cover and farm orientation on natural light patterns.

The paper then explores the limitations of the system by comparing days with varying natural light conditions, emphasizing the need for artificial light to meet optimal DLI levels for plant growth. It also provides insights into how the LED control system works and its role in ensuring plants receive sufficient light for their growth.

6.1 Representative Days

Figure 6 shows the natural light captured by one of the installed systems for a clear sky (top) and overcast day (bottom) in October. It can be observed that, as expected, both PPFD and DLI are much higher on a clear sky day. Moreover, the PPFD distribution through the clear sky day shows a pattern of high intensity in the morning period and a significant decrease in the afternoon since the analysed farm façade is Southeast oriented.

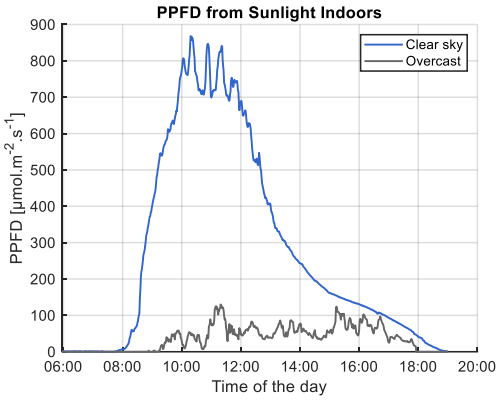

Figure 6 – Solar PPFD (top) and DLI (bottom) recorded indoors (Barrel 6) for a day with clear sky, October 8th, (blue) and overcast, October 17th, (grey) conditions.

Figure 7 represents the PPFD and DLI distributions of another representative day with the LED operation active. It clearly illustrates the sunlight presence during the day and the LED complement after sunset delivering the required light to meet the defined DLI target of 15 mol.m^{-2}.d^{-1}.

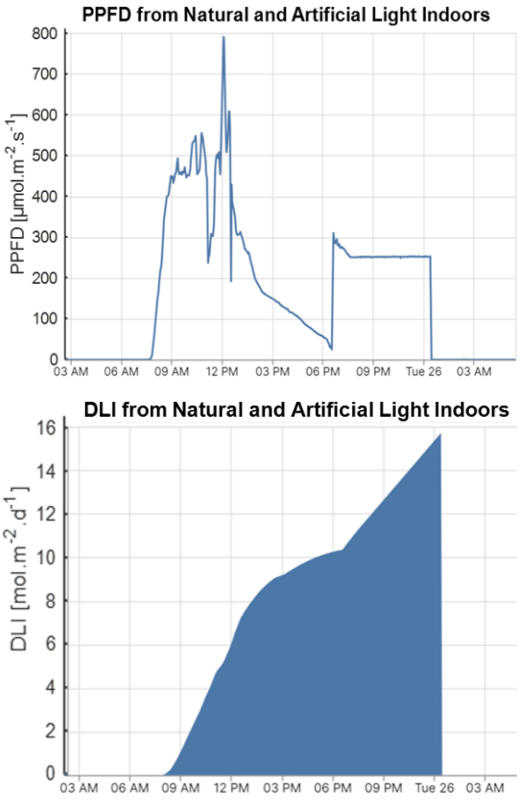

Figure 7 – Natural and artificial light PPFD (top) and DLI (bottom) for a day with mostly clear sky conditions, September 25th (Barrel 4).

6.2 Experimental Campaign

6.2.1 Solar DLI

This section analyses the critical factor in the report, Daily Light Integral (DLI). Figure 8 displays the average DLI values in mol.m^{-2}.d^{-1} recorded for all three barrels around sunset time over the 28 days of the experiment, from September 11th to October 8th. During this period, the average solar DLI from all barrels averaged 10.92 mol.m^{-2}.d^{-1}. These levels were relatively high compared to the optimal DLI target of 15 mol.m^{-2}.d^{-1} recommended in the literature. This suggests that, on average, during September and October, sunlight provided more than 2/3rds of the recommended optimal DLI.

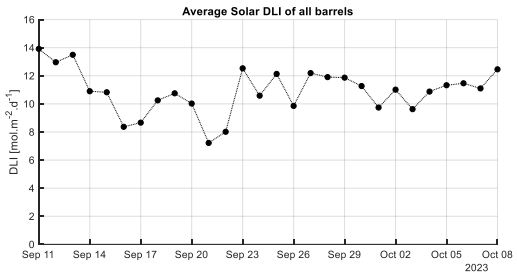

Figure 8 – Solar DLI average levels of all barrels registered during the experiment.

In summary, the experiment benefited from relatively high average DLI levels. However, variations in DLI were influenced by cloud cover and differences in sunlight exposure between barrels, especially between the corner and middle barrels.

6.2.2 DLI Target and Consumption

This section assesses the supplemental Daily Light Integral (DLI) provided by LED artificial light. The LED system dynamically adjusted light based on sunlight conditions. For Barrel 2, which had a demanding DLI regime of 17.5 $mol.m^{-2}.d^{-1}$, the LED system generally met the target, but occasional inaccuracies occurred due to various factors. Barrel 4, with a DLI target of 15 $mol.m^{-2}.d^{-1}$, also showed dynamic LED control based on sunlight conditions, with occasional inaccuracies. In this case, LED light met the intended target. Barrel 6, with a 12.5 $mol.m^{-2}.d^{-1}$ target, experienced issues like excessive sunlight and dimming malfunction. Despite these, it achieved a slightly higher DLI than the target. The LED energy consumption varied with the DLI requirement for each barrel, with Barrel 2 having the highest daily consumption. The total energy consumption for Barrels 2, 4, and 6 over the 28 days was 13.75, 12.43, and 4.48 kWh, respectively.

6.2.3 Pluto Basil

This section evaluates the growth of two basil varieties, Gustosa and Pluto, across three barrels with different light conditions. Measurements of plant fresh mass and green profile area were taken weekly, starting from the transplanting on September 11th (week 0) until the harvest on October 9th (week 4). Barrel 2 had the highest DLI target of 17.5 $mol.m^{-2}.d^{-1}$, Barrel 4 had a target of 15 $mol.m^{-2}.d^{-1}$, and Barrel 6 had a target of 12.5 $mol.m^{-2}.d^{-1}$. In the first week, there was minimal growth in terms of plant mass for all barrels. During the second week, there was a slight increase in mass and some development in terms of leaf area. By the third week, there was a substantial growth rate, with Barrel 2 showing the most significant increase in mass and a marked difference compared to Barrels 4 and 6. In the last week, the trends continued, with Barrel 2 experiencing faster growth, while Barrels 4 and 6 also saw an increase in mass. Barrel 2 produced the highest average plant edible mass of 47.5g, followed by Barrel 6 with 35g and then Barrel 4 with 32.5g. The green profile areas followed the same trend. However, it's noted that there was a large discrepancy in plant size within each barrel, with some plants appearing underdeveloped compared to others. Despite having the lowest DLI target, Barrel 6's plants achieved higher fresh mass and green profile areas than those in Barrel 4, despite its lower target due to discrepancies of natural in the farm space unaccounted by the system directed only to the farm wall. Figure 9 illustrates Pluto plant’s final form.

Figure 9 – Pluto basil plants at the end of the experiment period (Week 4) in Barrel 2 (top), Barrel 4 (middle) and Barrel 6 (bottom) with DLI targets of 17.5, 15 and 12.5 mol.m^{-2}.d^{-1}, respectively.

6.2.4 Gustosa Basil

In the first week, there was minimal mass change. The second week saw slight growth in mass and leaf size, with no significant differences between barrels. During the third week, all barrels showed substantial growth, with Barrel 6 surpassing Barrel 4. In the fourth week, growth rates peaked, with Barrel 6 outperforming Barrel 4. The results showed an edible mass of 25.2g for Barrel 4 and 31.2g for Barrel 6 (Barrel 2 plants were lost), indicating 24% higher productivity in Barrel 6. Key aspects of growth were branch elongation and increased leaves, resulting in tall basil plants with large, heavy leaves. Green profile areas supported these trends, with Barrel 6's plants averaging 392cm^2, while Barrel 4's averaged 347cm^2. Figure 10 showcases the final green profile areas, emphasizing Barrel 6's taller and "bushier" plants. In summary, Barrel 6 achieved higher fresh mass and green profile areas than Barrel 4, despite a lower DLI target, due to similar reasons of previous.

Figure 10 - Gustosa basil plants at the start of the fourth week of the experiment period (Week 3) in Barrel 4 (top), and Barrel 6 (bottom) with DLI targets of 15 and 12.5 mol.m^{-2}.d^{-1}, respectively.

7 Conclusion

This study analysis revealed significant improvements in basil plant productivity with higher DLI targets. For Pluto basil, the highest DLI regime of 17.5 mol.m^{-2}.d^{-1} resulted in a 36% increase in yield compared to the lower DLI regimes, with an additional energy consumption of 10 kWh. The lowest DLI regime

was the most energy-efficient, meeting 91% of its requirements through natural light and consuming approximately one-third of the energy of the highest DLI regime. Regarding the energy efficiency in biomass, each DLI regime of 12.5, 15 and 17.5 $mol.m^{-2}.d^{-1}$ represented an average per plant of 3.45 g/kWh, 2.61 g/kWh and 7.81 g/kWh, respectively.

This study recommends targeting Daily Light Integral (DLI) regimes above 17.5 $mol.m^{-2}.d^{-1}$ for year-round farm operations to maximize plant productivity. Further research on natural light conditions throughout different seasons is advised for a comprehensive understanding of their impact on system energy consumption.

References

[1] *World population to reach 8 billion this year, as growth rate slows | UN News* (no date) *United Nations*. Available at: https://news.un.org/en/story/2022/07/1122272 (Accessed: 30 October 2023).

[2] *A five-step plan to feed the world* (2022) *Feeding 9 Billion - National Geographic*. Available at: https://www.nationalgeographic.com/foodfeatures/feeding-9-billion/ (Accessed: 30 October 2023).

[3] *Water in agriculture* (no date) *World Bank*. Available at: https://www.worldbank.org/en/topic/water-in-agriculture (Accessed: 30 October 2023).

[4] Dupuis, A. (2023) *Hydroponics vs. traditional farming: 10 major differences*, *Eden Green*. Available at: https://www.edengreen.com/blog-collection/hydroponics-vs-traditional-farming (Accessed: 3 October 2023).

[5] Avgoustaki, D.D. (2019) Optimization of photoperiod and quality assessment of basil plants grown in a smallscale indoor cultivation system for reduction of energy demand, MDPI. Multidisciplinary Digital Publishing Institute. Available at: https://www.mdpi.com/1996-1073/12/20/3980 (Accessed: January 3, 2022).

[6] Larsen, D.H. et al. (2020) Response of basil growth and morphology to light intensity and spectrum in a vertical farm, Frontiers. Frontiers. Available at: https://www.frontiersin.org/articles/10.3389/fpls.2020.597906/full (Accessed: December 20, 2023).

[7] Hunter, A. and Dean, A. (2023) Application timing and duration of LED and HPS supplements differentially influence yield, nutrient bioaccumulation, and light use efficiency of greenhouse basil across seasons. dissertation. frontier. Available at: https://doi.org/10.3389/fpls.2023.1174823 (Accessed: November 26, 2023).