Impact of Light Intensity and Luminaire Type on Basil Yield: Insights from a Hydroponic Urban Agriculture System

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***Abstract*— This study investigates the impact of different artificial lighting systems on the growth and yield of basil (*Ocimum basilicum L.*) within a controlled hydroponic environment. Aimed at comparing the effectiveness of several luminaire types, the research is identifying the optimal lighting conditions that enhance plant growth and productivity in an urban agriculture setting. The experiment was conducted in a 40" HQ shipping container using a Nutrient Film Technique (NFT) system. Basil plants were grown under five different luminaire types (A, B, C, D, E) at varying light intensities (200, 230, 250, 260, and 275 µmol/m²/s) with 3 repetitions. Plant growth parameters, including weight, green plant part length, and total yield per square meter, were measured from 11 plants per growth board (55 plants in each test) after a cultivation period of 27 days post-transplantation. The findings demonstrated significant variations in plant yield and growth characteristics across the different lighting setups. Luminaire C consistently provided the highest yields, particularly at the 260 µmol/m²/s intensity, suggesting its lighting configuration offers optimal conditions for basil production. In contrast, Luminaires D and B showed lower yields, indicating less favourable growth environments under their specific lighting conditions. Statistical analysis revealed that there were observable trends in yield enhancement under specific lamps. Additionally, the study highlighted variations in plant uniformity. In terms of plant uniformity, the standard deviations in length and weight were lowest under Luminaire B, emphasizing its potential for producing uniform crops, a crucial factor in commercial horticulture. The study underscores the critical role of selecting appropriate lighting technologies to maximize plant growth in controlled environment agriculture. By identifying the most effective luminaire types and light intensities, the research contributes valuable insights toward optimizing urban agricultural practices and enhancing the sustainability of food production systems.**

Keywords*— basil, hydroponics, luminaires

I. INTRODUCTION

Controlled-environment agriculture (CEA) systems, such as vertical farms and container-based operations, are emerging as vital tools to meet the growing global demand for food. These systems offer precise control over environmental variables, enabling year-round crop cultivation independent of external climate conditions. However, the success of CEA heavily depends on optimizing these controlled parameters, with lighting being one of the most critical factors. Artificial lighting directly influences photosynthesis, plant morphology, and yield, making it essential to select the most suitable light sources for maximizing plant growth.

In indoor cultivation, the spectrum, intensity, and uniformity of lighting play a crucial role in plant development. Studies such as [1] have demonstrated that the ratio of red to blue light can significantly impact the growth and nutraceutical content of plants. Furthermore, [2] highlighted that manipulating the light spectrum using LEDs can optimize growth rates and improve the nutritional quality of crops. This is especially relevant in controlled environments where natural sunlight is limited

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or absent. [3] noted that improving photosynthetic efficiency through optimal lighting is a key challenge for modern agriculture, particularly for fast-growing crops like basil, parsley, and chives.

Hydroponics, a soil-less cultivation method utilizing nutrient-rich water solutions, has become a vital approach in urban agriculture, particularly for aromatic herbs in Europe [4]. As global food demand continues to rise and arable land becomes increasingly scarce, hydroponic systems especially in closed environments like vertical farms and container-based setups are gaining prominence for their efficient use of resources, reduced water consumption, and minimized pest issues [5], [6]. These systems enable year-round crop production by incorporating Controlled-Environment Agriculture (CEA) principles, allowing for precise regulation of light, temperature, humidity, and nutrient delivery [7]. As a result, hydroponics is increasingly viewed as a sustainable solution for urban food production [8].

One critical factor influencing the success of hydroponic cultivation is light quality, which significantly impacts plant growth, morphology, and yield [9]. Container-based growing systems, commonly used for aromatic herbs, provide numerous advantages in urban contexts [10]. They enable optimal space utilization, which is a crucial benefit in cities where land is limited and expensive [11]. Vertical farming, for example, allows multiple crop layers to be cultivated within a compact area, significantly boosting yield per square meter [12]. Moreover, these systems facilitate precise monitoring and control of environmental parameters, reducing the risk of pest infestations and disease—common issues in traditional soil-based agriculture [5]. Such control over growing conditions supports the fine-tuning of factors like light intensity and nutrient delivery, contributing to enhanced crop productivity and quality [13].

Additionally, the use of container-based systems offers flexibility in production cycles [14]. Farmers can quickly rotate or replace crops in response to market demands, ensuring a steady supply of fresh produce with superior flavor and nutritional profiles [15]. The proximity of these systems to urban centers further reduces transportation costs and carbon emissions, aligning with the growing consumer demand for locally sourced, sustainable food [16].

This literature review will delve into the influence of light quality on hydroponically grown herbs, evaluate the ideal growth conditions for each species, and discuss the challenges of achieving uniform growth in controlled environments [17]. Understanding these dynamics is essential for optimizing hydroponic systems to support sustainable urban agriculture [18].

The Importance of Light Quality in Hydroponics

The effectiveness of photosynthesis depends heavily on light quality, defined by the spectrum of wavelengths emitted by light sources. Key photosynthetic pigments, mainly chlorophyll a and b, absorb particular wavelengths mostly within the blue range (400-500 nm) and red range (600-700 nm) regions [19]. Research by [20] demonstrated that a red-to-blue light ratio of 3:1 can significantly enhance plant growth, yielding a 25% increase in biomass for lettuce and a 30% increase for basil compared to other light ratios. This highlights the necessity of optimizing light ratios tailored to specific crops.

Light Emitting Diodes (LEDs) have revolutionized horticultural lighting due to their efficiency, longevity, and customizable spectra. For instance, [2] found that utilizing a tailored LED spectrum (60% red, 40% blue) enhanced lettuce growth rates by 40% and increased leaf chlorophyll content by 30% compared to fluorescent lighting. Furthermore, [21] noted that LED systems can reduce energy consumption by up to 75% compared to traditional high-pressure sodium (HPS) lights, making them a more sustainable choice for growers.

In addition to light quality, light intensity and uniformity are critical for plant development. Additionally, research by [22] indicated that uneven light distribution could lead to growth discrepancies, with plants receiving optimal light growing 30% larger than those in shaded areas. Several studies have aimed to compare the effectiveness of different artificial lighting systems. For instance, [23] evaluated the growth of basil and lettuce under high-pressure sodium (HPS), fluorescent, and LED systems. The study found that LED lighting resulted in a 60% increase in growth rates and a 20% increase in nutrient content compared to HPS systems. Furthermore, the energy savings from using LEDs were quantified at 50% less electricity compared to traditional HPS systems for the same light output, demonstrating both economic and environmental benefits.

Growth Conditions and Light Sensitivity of Aromatic Herbs

Aromatic herbs, such as basil (*Ocimum basilicum*), have unique growth requirements influenced by light quality and environmental conditions. Understanding these needs is crucial for maximizing growth and nutritional quality, particularly in controlled environment agriculture (CEA).

Basil is a fast-growing herb highly sensitive to light quality. Research by [24] indicates that basil plants exposed to a light spectrum rich in red wavelengths (around 620-660 nm) exhibit enhanced leaf area and chlorophyll concentration, leading to biomass increases of up to 35% compared to those grown under lower red-light conditions. [25] found that specific LED lighting (80% red, 20% blue) significantly improved the essential oil content of basil, enhancing its flavor profile and market value. Optimal growth conditions for basil include temperatures of 18-30 °C, relative humidity of 50-70%, and a nutrient solution pH of 5.5 to 6.5 [26].

The intersection of plant growth and nutritional quality is critical in CEA. [1] highlighted that manipulating light spectra can enhance both biomass production and the nutraceutical profiles of crops. For instance, basil grown under LEDs with a tailored spectrum exhibited a 35% increase in phenolic compounds compared to those grown under standard fluorescent lighting [25]. This dual focus on yield and nutritional quality is essential for maximizing the benefits of hydroponics in controlled environments, particularly in urban agriculture, where space and resources are limited.

Basil thrives under higher red-light ratios, whereas chives perform best under increased blue light levels, showing a preference for a spectrum comprising 70% blue and 30% red light [27]. Additionally, parsley prefers slightly cooler temperatures (15-21 °C) compared to basil (18-30 °C) [26], [28]. Cilantro's growth can be adversely affected by high temperatures, with optimal growth occurring at 20-25 °C [29]. This variability presents challenges in creating an optimal growing environment that simultaneously meets the diverse needs of these herbs. Strategies to mitigate these challenges may include zoning the growing area by crop type or employing adjustable lighting systems that cater to the specific requirements of each herb.

Despite advancements in hydroponic systems and lighting technologies, challenges remain. Integrating energy-efficient lighting solutions while maintaining optimal growth conditions is a significant hurdle. The high initial costs of advanced LED systems can pose barriers for small-scale producers [10]. Moreover, the long-term effects of continuous exposure to artificial lighting on plant health and productivity are still not fully understood. Future research should focus on conducting long-term studies to evaluate the sustained effects of different lighting systems on plant health and yield over multiple growth cycles. Additionally, exploring the synergistic effects of combined environmental factors (e.g., temperature, humidity) alongside light spectrum will help optimize overall plant performance in closed systems. Finally, assessing the economic feasibility of advanced lighting systems in various hydroponic setups, particularly in terms of energy costs and return on investment, will be critical for widespread adoption.

II. Materials and Methods

The growth characteristics of basil (*Ocimum basilicum*) were investigated within a climate-controlled 40" HQ shipping container retrofitted for urban agriculture. The study utilized a hydroponic Nutrient Film Technique (NFT) system, strategically arranged over a 60 m² area segmented into growing and nursery sections. The nursery section was positioned at a height of 30 cm above the ground, optimized for early-stage plant development.

Basil was seeded into peat pellets (25mm, Jiffy Products S.L. Ltd). Seeding densities were adjusted to species-specific requirements: 4–7 seeds per pellet for basil, these seedlings were uniformly cultivated under controlled conditions temperature, light exposure, day/night intervals, and humidity levels for a 45-day period in the nursery shelves.

Post-nursery, basil plants were transplanted into the main hydroponic NFT system at a density of 63 plants per square meter. This system maintained precise control over environmental parameters to ensure optimal plant growth:

pH and EC: Automatically adjusted within the ranges of 5.8–6.6 and 1.7–2.5, respectively.

Ventilation: Wind blowers activated every 20 minutes, providing 10-minute wind cycles to simulate natural conditions.

Humidity and Temperature: Regulated between 65-85% and 22-24 °C by an HVAC system.

CO_2 Enrichment: Levels maintained at 800–1000 ppm via automated CO_2 tank systems.

Lighting: Five different luminaire types were utilized: A, B, C, D, E. The main difference between each of the used luminaires is the spectral composition of an emitted light (Fig. 1.). Lamps A and D mostly utilize only red and blue light, which results in a dark pink spectrum. Lamp E includes more green light than the two previously stated lamps, which results in a lighter pink spectrum, but Lamps B and C include a full wavelength band with a peak in the green light region, thus resulting in a white light spectrum.

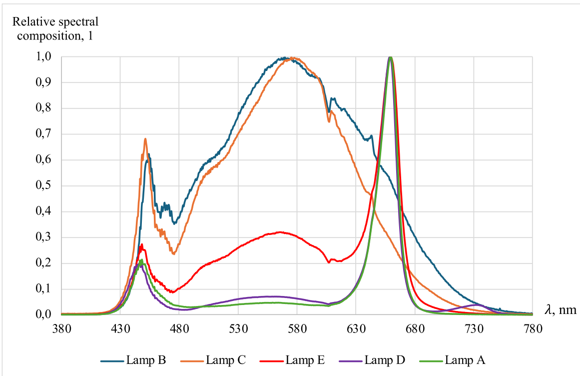

Fig. 1. Relative spectral composition of all 5 used luminaires

Light intensity, controlled via the Control Panel for luminaire A and the "Casambi" app for luminaires B, C, D, and E, was consistently set across all units for each test, ranging from 200 to 275 µmol/m²/s at the centre of each shelf.

The effectiveness of the lighting systems was assessed 27 days post-transplantation by measuring various growth parameters of 11 previous selected plants per square meter of each grow board (see Figure 2). Measurements included:

Plant Dimensions: Total plant length, green part length, and root length.

Biomass: Total plant mass, green part mass, and root mass.

Yield: Calculated per square meter to evaluate the productivity under each lighting condition.

All plants were sourced from identical seed stock and germinated under equivalent conditions to ensure uniformity. Data collection was synchronized, conducted by the same researcher using standardized methods to guarantee comparability.

Results were analysed to determine the impact of different light treatments on plant growth and yield. Graphical representations of yield across varying light intensities for each luminaire type were prepared facilitating a visual assessment alongside statistical evaluations to discern significant differences and trends.

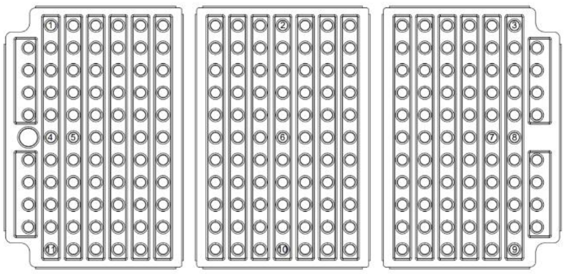

Fig. 2. Marked plants per grow board.

To summarize, in all of the comparative shelves, the plants growing under different luminaire types were sourced from the same seed stock, and the seeds germinated in the same conditions and same time. All of the seedlings were transplanted from the nursery to the hydroponic NFT system at the same time and all of the measurements, and data collection at the harvest were done at the same time, with the same instruments and by the same responsible person. To be able to ensure that data is comparable.

III. Results and Discussion

The study assessed the yield responses of *Ocimum basilicum* subjected to five distinct luminaire types (labeled A through E) across a gradient of light intensities (200, 230, 250, 260, and 275 μmol/m²/s). The experimental design incorporated measurements from 11 individual plants per growth board to ascertain the average weight for each grouping (see table 1). Subsequently, the standard deviation was computed for these values to quantify variability within each sample set. Furthermore, the average length of the green plant part was determined along with its corresponding standard deviation, providing insights into growth uniformity across treatments. Ultimately, the total yield per square meter was calculated, encapsulating the overall productivity of the hydroponic system under each lighting condition.

Table 1 Mean values of measured plants per growth board

Luminaire	Measurements					
	Mean weight	*St. dev*	*Mean length*	*St. dev*	*Yield g/m2*	*Light intensity μmol/m²/s*
A	7,1	3,0	30,5	3,1	825,0	
B	5,59	1,84	28,73	3,19	615	200
C	6,64	2,38	28,18	3,43	626	
D	x	x	x	x	x	
E	x	x	x	x	x	
A	7,55	3,2	26,36	2,46	983	230
B	9,27	2,05	27,64	2,23	1082	
C	9,18	4	27,82	2,21	1234	
D	9,73	2,6	29,73	2,14	1004	
E	8,36	3,36	26,91	2,68	987	
A	7,09	3,52	27	4,08	836,75	250
B	7,5	2,76	26,18	3,88	865	
C	9,23	4,37	30,14	3,68	983	
D	7,02	2,95	27,8	3,36	904	
E	4,36	1,64	23,85	3,37	565	
A	2,91	1,16	17,09	3,12	444	275
B	4,73	2,14	18,82	2,69	603	
C	5,18	1,4	24,55	3,11	657	
D	5,27	4,09	23,55	4,64	667	
E	2,09	0,9	19	4,53	430	
A	5	1,41	29,55	1,23	455	260
B	4,27	2,38	27,27	2,38	320	
C	8,45	3,73	28	5,24	561	
D	10,27	8,13	28,09	1,98	522	
E	4,27	1,42	21,91	3,6	238	

The bar graph titled "Effect of Lamp Type on Yield (Labeled by Letters)" presents the average yields of *Ocimum basilicum* achieved under five distinct lighting conditions, identified as A, B, C, D, and E. Each bar signifies the average yield measured per square meter for each respective luminaire during the experimental evaluation. Notably, Lamp Type C demonstrates the

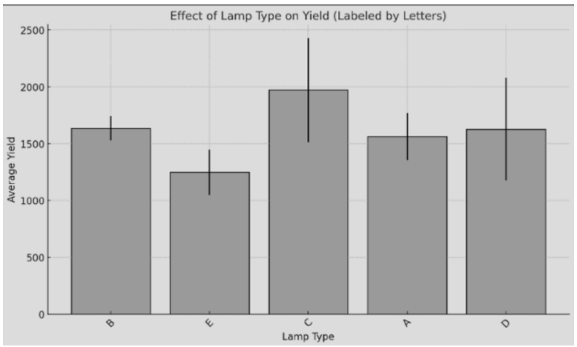

Fig. 3. Effect of Lamp Type on Yield (Labeled by Letters).

highest average yield, which suggests its lighting conditions characterized by a full wavelength band with a peak in the green light region are most conducive for basil growth. This result aligns with findings from [1], who demonstrated that manipulation of light spectra can significantly enhance plant biomass and nutraceutical profiles, supporting the efficacy of targeted spectral optimization in controlled environments.

In contrast, Lamp Type B, despite having a similar full-spectrum output, shows the lowest yield, indicating that other factors, such as spectral balance, may be suboptimal and could benefit from adjustments to enhance growth.

Lamps A and D, which primarily emit red and blue light, creating a dark pink spectrum, may influence plant growth differently due to the absence of a broader spectral range. Similarly, Lamp E, which includes more green light than A and D and produces a lighter pink spectrum, could contribute to a distinct growth response.

Furthermore, the error bars in the graph, representing the standard deviation of yields, highlight variability in plant responses. This variability is more pronounced with Lamp Types C and D, indicating a broader range of yield outcomes that could be attributed to individual plant sensitivities to the provided light spectrum or slight variations in local growing conditions. These differences in yield consistency are critical for understanding each lamp's effectiveness and reliability.

The trends indicate how different lamps perform under varying light intensities (200 to 275) (Fig.2.). Lamp C demonstrates the highest yield at a light intensity of 260, while other lamps like Lamp B and Lamp A exhibit more consistent performance across intensities. These insights can guide the optimization of light setups for maximum yield under specific conditions. Lamp C shows the most dramatic increase in yield with rising light intensity, peaking at 260 before experiencing a decline at 275.This phenomenon corresponds to previous studies, such as [9], suggesting that plants experience a peak efficiency at certain intensities, beyond which additional light becomes counterproductive or even detrimental to growth. This indicates its optimal performance at this specific intensity. Lamp D and Lamp E exhibit more variable performance, with sharp increases or decreases at specific intensities. These trends highlight the potential sensitivity of these lamps to changes in light conditions.

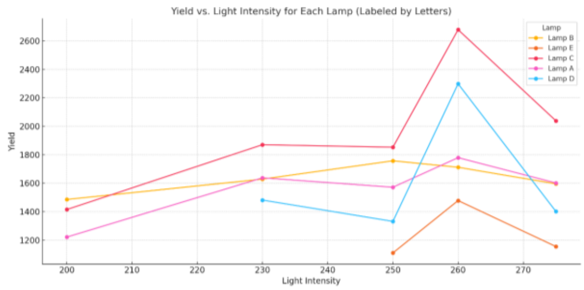

Fig. 4. Yield vs. Light intensity for each lamp.

Lamp B and Lamp A demonstrate more consistent performance across the range of light intensities, with gradual changes in yield. Moreover, lamps primarily emitting red and blue wavelengths (Lamp Types A and D) were observed to produce intermediate yields. These findings support earlier conclusions by [24], [30] which found that red and blue light strongly influence plant morphogenesis and phytochemical profiles but may not necessarily optimize biomass production compared to fuller-spectrum lights.

The comparison emphasizes that light intensity significantly impacts yield, but the optimal intensity varies depending on the lamp. This analysis provides actionable insights for optimizing light setups in controlled environments, helping to maximize yield by choosing the right lamp and light intensity combination.

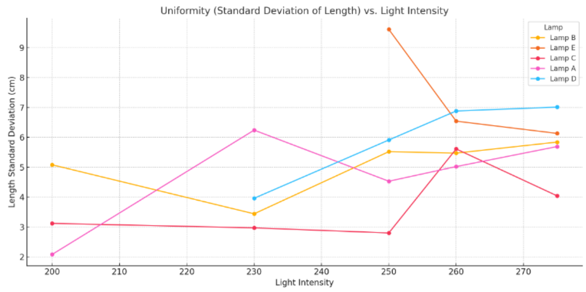

Fig. 5. Uniformity vs. Light intensity

Uniformity, measured as the standard deviation of plant lengths and weights, offered insights into the consistency of plant growth under each lighting condition (Fig.3.): At 230 μmol/m²/s, Lumianire B showed the lowest standard deviation in plant lengths and weights, indicating high uniformity and consistent growth outcomes. In contrast, Luminaire D and E displayed higher variability, particularly at 275 μmol/m²/s, where the plants exhibited greater discrepancies in growth parameters, possibly indicating less ideal lighting conditions for uniform growth. This finding aligns with observations by [22], who noted that excessive or improperly distributed artificial lighting can lead to uneven plant growth, thereby complicating management and reducing marketability**.**

These results suggest that while higher light intensities can drive greater yields, they may also introduce variability in plant growth, affecting overall crop uniformity and potentially marketability in commercial operations.

Statistical analyses reinforced these observations: A moderate positive correlation between light intensity and yield (r = 0.25) was observed across all luminaires, underscoring the importance of optimized light management. Notably, lamps with a full-spectrum output, such as Lamp Types B and C, provided a more balanced light composition, which may have contributed to better overall growth conditions. However, despite this broader spectrum, Lamp B exhibited the lowest yield, suggesting that factors beyond spectrum alone, such as light intensity or spectral ratios, play a role in plant development.

A strong correlation between plant weight and yield (r =0.85) indicates that healthier, heavier plants generally produced more biomass, a key factor for commercial basil production. This finding aligns with the spectral influence, as Lamp Type C, which provided a full-spectrum light with a peak in the green region, supported the highest average yield, potentially due to its balanced wavelengths enhancing photosynthetic efficiency. In contrast, Lamps A and D, which primarily emit red and blue light and create a dark pink spectrum, may have promoted specific growth responses but did not necessarily maximize overall biomass production.

Plant length had a weaker correlation with yield (r = 0.13), suggesting that sheer plant size is not the primary determinant of yield. Instead, physiological health, leaf area, or light absorption efficiency factors influenced by spectral composition may be more critical. The presence of more green light in Lamp E's spectrum compared to A and D could have contributed to differences in light penetration and absorption, potentially influencing plant morphology.

However, the observed differences in spectral composition and plant responses highlight the need for further investigation into optimizing light quality for commercial basil production. The variability seen in yield outcomes, particularly with certain lamps, suggests that refining spectral ratios or intensity settings could enhance consistency and maximize production efficiency.

IV. Conclusion

Lamp C, which provides a full-spectrum light with a peak in the green region, resulted in the highest average yield, particularly at 260 µmol/m²/s. This suggests that a balanced light spectrum enhances photosynthetic efficiency and promotes basil biomass production. Lamps A and D, which primarily emit red and blue light, produced lower yields, indicating that the absence of a broader spectral range may limit overall biomass accumulation. A moderate positive correlation (r = 0.25) between light intensity and yield was observed, reinforcing the importance of optimizing light management.

Yield peaked at 260 µmol/m²/s under Lamp C but declined at 275 µmol/m²/s, suggesting that excessive intensity might not further enhance growth.

A strong correlation (r = 0.85) between plant weight and yield was identified, confirming that heavier plants produce more biomass, an essential metric for commercial basil cultivation.

Plant length had a weaker correlation with yield (r = 0.13), suggesting that size alone is not a critical determinant of productivity. Instead, factors like leaf area, light absorption efficiency, and physiological health play more significant roles.

However, the variability in plant responses suggests that further refinements in spectral ratios and intensity levels could improve consistency and optimize yield efficiency.

The study reinforces the importance of selecting the appropriate lighting technologies for hydroponic systems, as spectral composition and intensity significantly influence yield and uniformity.

The findings support the use of full-spectrum lighting, particularly with a peak in green light, to enhance biomass production in basil cultivation.

Further studies are recommended to explore the long-term impacts of these lighting conditions on secondary metabolite production and overall plant health.

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