Annex Nr.2

The Impact of Luminaire Type and Light Intensity on Herb Yield and Uniformity in Hydroponic Systems / Gaismekļa veida un gaismas intensitātes ietekme uz garšaugu ražu un vienmērīgumu hidroponikas sistēmās

Projekts Nr.22-00-A01612-000018

3D fotogrammetrijas pielietošana un energoefektivitāti veicinošu inovāciju ieviešana optimālāku vides apstākļu nodrošināšanai vertikālajā lauksaimniecībā / Application of 3D photogrammetry and implementation of energy efficiency-enhancing innovations to ensure optimal environmental conditions in vertical farming.

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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, making it possible to grow crops year-round regardless 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 Piovene et al. (2015) have demonstrated that the ratio of red to blue light can significantly impact the growth and nutraceutical content of plants. Furthermore, Sæbø et al. (2003) 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 or absent. Murchie et al. (2009) 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.

This study aims to compare the effectiveness of several artificial lighting systems, including a custom-developed and also commercial solutions in promoting the growth of culinary herbs like basil (*Ocimum basilicum* L.), flat-leaf parsley (*Petroselinum crispum var. Neapolitanum*), chives (*Allium schoenoprasum*), and cilantro (*Coriandrum sativum*). Unlike previous research, which often focuses on optimizing specific wavelengths, this study does not hypothesize a superior light source. Instead, it offers an objective comparison, identifying how different lighting technologies perform in a containerized growing environment.

The luminaire developed for this study was designed to deliver a precise balance of light spectrum and intensity based on the specific needs of these herbs, as informed by agricultural recommendations. Using an online modeling tool from OSRAM, the luminaire combines multiple LED diodes to achieve the desired optical parameters. We will assess each lighting system's impact on plant yield to determine which offers the most advantageous conditions for container-based plant production.

By comparing these lighting technologies, this study will provide essential insights into optimizing lighting in controlled environments, supporting the broader goal of improving the productivity and sustainability of CEA systems.

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 (Resh, 2012). 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 (Kozai et al., 2016; Al-Kodmany, 2018). 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 (Touliatos et al., 2016). As a result, hydroponics is increasingly viewed as a sustainable solution for urban food production (Germer et al., 2011).

One critical factor influencing the success of hydroponic cultivation is light quality, which significantly impacts plant growth, morphology, and yield (Kaiser et al., 2019). This literature review explores how varying light spectra affect the growth and development of key culinary herbs—specifically basil (Ocimum basilicum L.), flat-leaf parsley (Petroselinum crispum var. neapolitanum), chives (Allium schoenoprasum), and cilantro (Coriandrum sativum)—in hydroponic systems (Lin et al., 2013; Pennisi et al., 2020). By examining the ideal light conditions and the specific growth requirements of these herbs, this review aims to identify best practices for optimizing crop quality and yield in controlled environments (Paradiso & Proietti, 2020).

Container-based growing systems, commonly used for aromatic herbs, provide numerous advantages in urban contexts (Bai et al., 2020). They enable optimal space utilization, which is a crucial benefit in cities where land is limited and expensive (Al-Chalabi, 2015). Vertical farming, for example, allows multiple crop layers to be cultivated within a compact area, significantly boosting yield per square meter (Benke & Tomkins, 2017). 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 (Kozai et al., 2016). Such control over growing conditions supports the fine-tuning of factors like light intensity and nutrient delivery, contributing to enhanced crop productivity and quality (Kubota et al., 2017).

Additionally, the use of container-based systems offers flexibility in production cycles (Graham et al., 2019). 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 (Appolloni et al., 2021). 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 (Despommier, 2010).

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 (Massa et al., 2008). Understanding these dynamics is essential for optimizing hydroponic systems to support sustainable urban agriculture (Van Delden et al., 2021).

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, predominantly chlorophyll a and b, absorb specific wavelengths primarily in the blue (400-500 nm) and red (600-700 nm) regions (Wang et al., 2017). Research by Goins et al. (1999) 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, Sæbø et al. (2003) 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, Morrow (2008) 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. Koller et al. (2018) demonstrated that increasing light intensity from 200 to 400 µmol m^2 s^{-1} resulted in a 50% increase in basil biomass. Additionally, research by Jiang et al. (2019) 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, López et al. (2021) 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 L.), flat-leaf parsley (Petroselinum crispum var. Neapolitanum), chives (Allium schoenoprasum), and cilantro (Coriandrum sativum), each 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 Zhang et al. (2018) 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. Kopsell et al. (2014) 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 (Heuvelink, 1999).

Flat-leaf parsley thrives under a balanced light spectrum, with studies suggesting that a red-to-blue light ratio of 2:1 promotes optimal growth. Moustakas et al. (2019) demonstrated that using LED lights with this ratio resulted in a 50% increase in leaf biomass and a 30% increase in chlorophyll content compared to fluorescent lighting. Furthermore, parsley is sensitive to light intensity, with optimal growth occurring at approximately 300 μmol m^2 s^{-1}, where biomass can increase by up to 45% (Hernández et al., 2020). The ideal growth conditions for parsley include temperatures between 15-21 °C, relative humidity of around 60-70%, and a pH range of 6.0 to 7.0 (Sinha et al., 2015).

Chives are particularly responsive to light quality, requiring high levels of blue light for optimal growth. Liu et al. (2020) demonstrated that chives grown under a spectrum of 70% blue and 30% red light showed a 40% increase in total biomass and improved flavor intensity compared to plants grown under standard fluorescent lights. Additionally, chives benefit from higher light intensities (400 μmol m^2 s^{-1}), which can enhance growth rates and yields by up to 60%. Chives thrive at temperatures ranging from 15-25 °C, with a humidity level of about 50-60% and a pH range of 6.0 to 7.0 (Bock et al., 2019).

Cilantro, known for its sensitivity to light conditions, exhibits significant growth improvements under varied light spectra. Research by Ashraf et al. (2019) revealed that cilantro grown under LED systems with a balanced spectrum (50% red, 50% blue) yielded a 35% higher biomass compared to those under high-pressure sodium (HPS) lighting. The study also found that essential oil content increased by 20% under optimized light conditions, enhancing the herb's aromatic qualities and nutritional benefits. The ideal growth conditions for cilantro include temperatures of 20-25 °C, relative humidity between 50-70%, and a nutrient solution pH of 6.0 to 7.0 (Kumar et al., 2015).

The intersection of plant growth and nutritional quality is critical in CEA. Piovene et al. (2015) 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 (Kopsell et al., 2014). 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.

While these aromatic herbs share common growth requirements, such as temperature and humidity, they also exhibit specific needs that complicate uniform cultivation in a controlled environment. For example, 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 (Liu et al., 2020). Additionally, parsley prefers slightly cooler temperatures (15-21 °C) compared to basil (18-30 °C) (Heuvelink, 1999; Sinha et al., 2015). Cilantro's growth can be adversely affected by high temperatures, with optimal growth occurring at 20-25 °C (Kumar et al., 2015). 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 (Bai et al., 2020). 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.

Materials and methods

The growth characteristics of four plant types (basil (*Ocimum basilicum* L.), flat leaf parsley (*Petroselinum crispum var. Neapolitanum),* chives (*Allium schoenoprasum*), and cilantro (*Coriandrum sativum*)), were evaluated for the effect of three different luminaires within climate controlled 40” HQ shipping container using a hydroponic Nutrient-film technique (NFT) system. The container is equipped with 60 m^2 urban farming models at a height of 30 cm and a nursery part. Basil, parsley, and cilantro were seeded 4–7 seeds per jiffy (25mm, Jiffy Products S.L. Ltd), and chives 9–12 seeds per jiffy manually. All seedlings were kept in the same conditions (temperature, light, day/night interval, humidity, CO2) for 45 days in nursery shelves before transplanting to the system. Basil, parsley, and cilantro were transplanted into NTF hydroponic system at a density of 63 plants per square meter, and chives at 113 plants per m^2. In a system, plants grow in a completely controlled environment. The automatic system controls pH (5.8 – 6.6), and EC (1.7–2.5), every 20 minutes wind blowers provide 10 min long wind periods, RH (65-85 %), temperature (22 –24 °C) is controlled by the HVAC system, CO2 (800 –1000 ppm) is provided automatically from CO2 tank, light intensity was set before test, day/night interval set for 12 h –12 h. Lighting: Five different luminaire types were used.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 180 to 275 μmol/m^2/s at the centre of each shelf.

The effect of lights was evaluated in harvest 27 days after transplant by measurements of fresh plant length, green plant part length, roots length, total plant mass, green plant part mass, roots mass, and yield per square meter. Measurements were performed for 11 plants per square meter (shelve or grow board) based on the previously designed scheme (Figure 1).

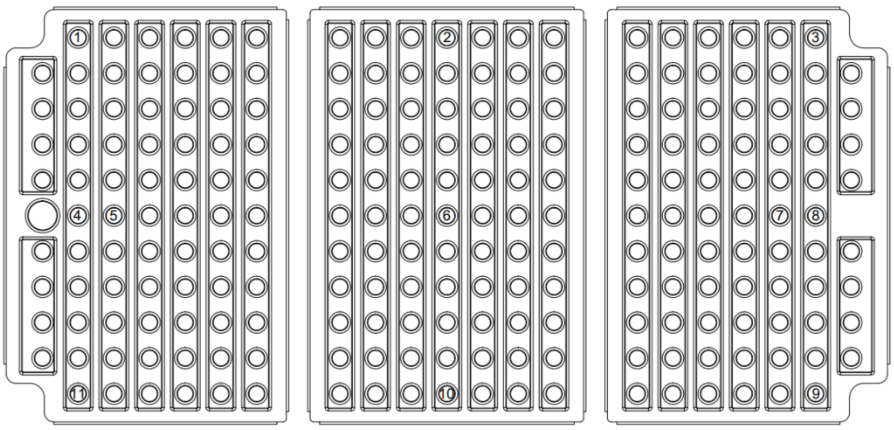


Figure 1. Marked plants per grow board

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.

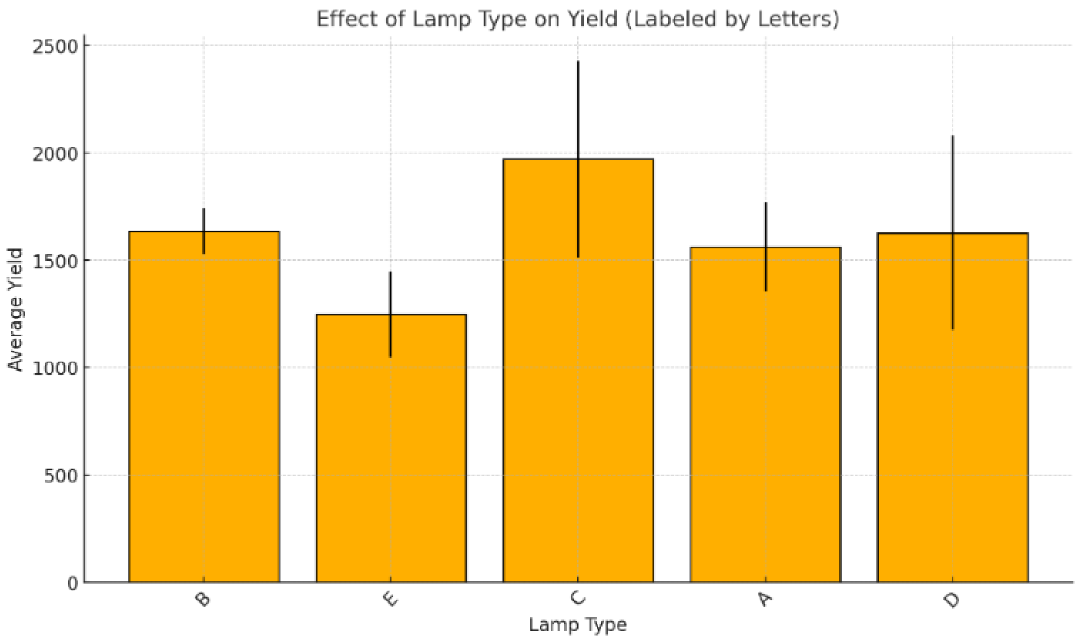
Results -Basil

The study assessed the yield responses of Ocimum basilicum L. subjected to five distinct luminaire types (labelled A through E) across a gradient of light intensities (200, 230, 250, 260, and 275 µmol/m^2/s). The experimental design incorporated measurements from 11 individual plants per growth board to ascertain the average weight for each grouping (see table below). 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: Mean values of measured plants per growth board

Light intensity 200	Mean weight	St.dev	Mean length	St.dev	Yield
A	23,2	7,8	30,6	5,1	1485,3
B	21,18	5,8	49,09	2,08	1221
C	28,5	5,88	23,14	3,12	1414,5
D	x	x	x	x	x
E	x	x	x	x	x
Light intensity 200					
A	27,55	5,58	28,36	3,44	1628
B	28,45	8,53	29,36	6,24	1637
C	32,91	8,78	30,09	2,97	1870
D	27,55	8,25	33,64	3,96	1481
E	x	x	x	x	x
Light intensity 250					
A	25,11	5,49	21,7	5,52	1757
B	26,82	6,45	27,32	4,53	1571
C	30	8,43	21,8	2,8	1852
D	22,81	5,14	26,18	5,91	1331
E	16,41	7,11	14,36	9,61	1110
Light intensity 275					
A	22,9	4	21	5,84	1595
B	23,91	8,61	24,82	5,69	1601
C	31,91	11,4	24,82	4,04	2038
D	24,27	8,82	27,09	7,01	1401

E	19,09	6,56	17,09	6,13	1154,5
Light intensity 250					
A	25,18	6,31	24,09	5,47	1711,5
B	38,13	11	31,46	5,02	1779
C	43,5	11,08	32,04	5,61	2678
D	30,49	10,36	27,99	6,88	2298
E	24,5	6,5	23,22	6,54	1477,5



Effect of Lamp Type on Yield (Labeled by Letters)

The bar graph titled "Effect of Lamp Type on Yield (Labeled by Letters)" presents the average yields of basil 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 highest average yield, which suggests its lighting conditions—possibly involving specific spectral outputs or intensity settings—are most conducive for basil growth. In contrast, Lamp Type E shows the lowest yield, indicating its lighting conditions may be suboptimal and could benefit from adjustments to enhance growth. Furthermore, the error bars depicted in the graph, which represent the standard deviation of yields, suggest 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 lighting provided or to slight variations in local growing conditions. These differences in yield consistency are critical for understanding each lamp's effectiveness and reliability.

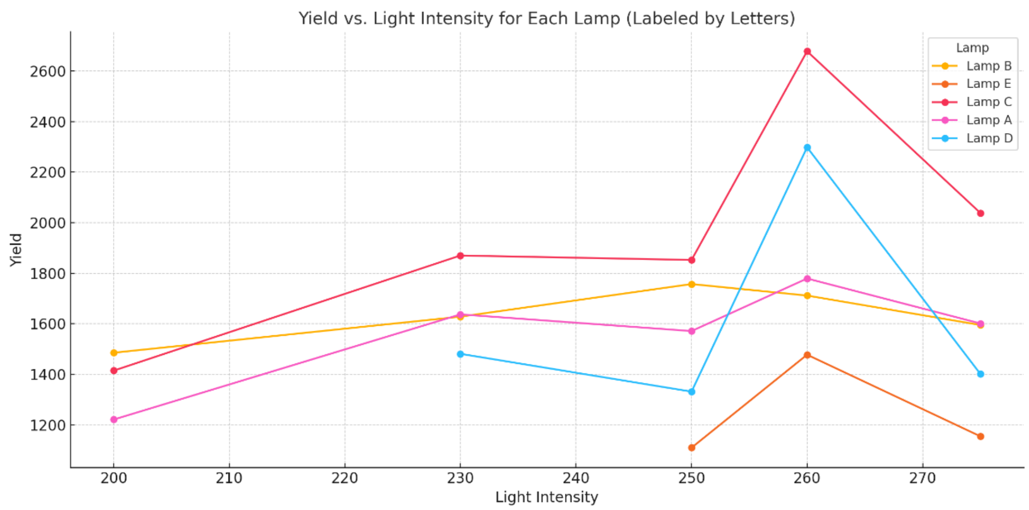


Fig. 1. Yield vs. Light intensity for each lamp

The trends indicate how different lamps perform under varying light intensities (200 to 275). 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 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. Lamp B and Lamp A demonstrate more consistent performance across the range of light intensities, with gradual changes in yield. These lamps may be more suitable for setups requiring stable output across varying conditions. 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.

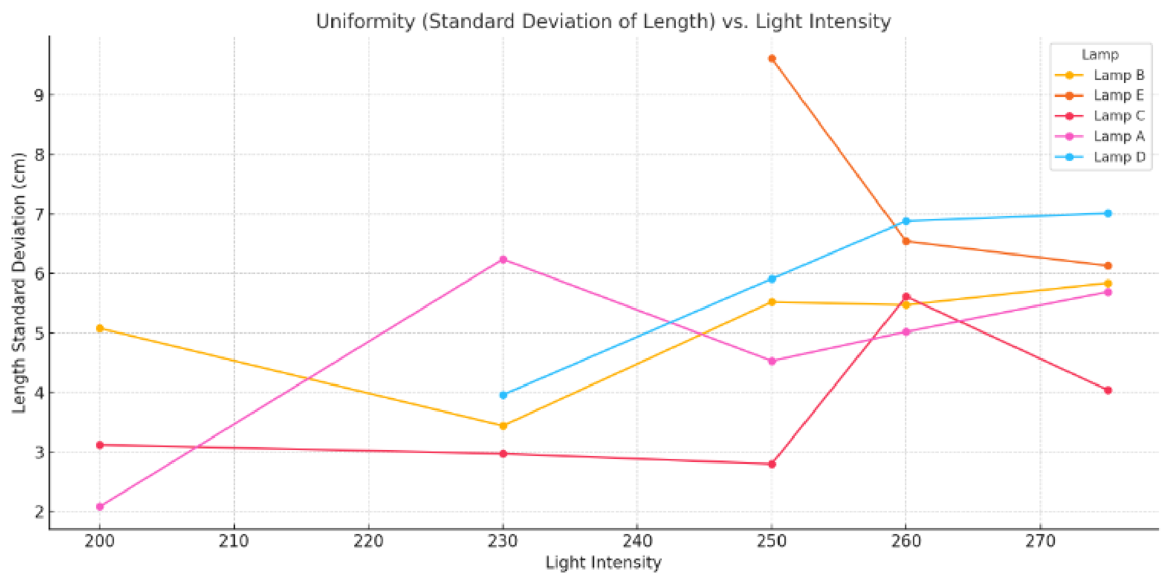


Fig. 2. Uniformity vs. Light intensity

Uniformity, measured as the standard deviation of plant lengths and weights, offered insights into the consistency of plant growth under each lighting condition: At 230 μmol/m^2/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/m^2/s, where the plants exhibited greater discrepancies in growth parameters, possibly indicating less ideal lighting conditions for uniform growth.

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 ($r = 0.25$) across all luminaires, underscoring the importance of optimized light management. A strong correlation between plant weight and yield ($r = 0.85$), indicating that healthier, heavier plants generally produced more biomass, a vital indicator for commercial basil production. Length had a weaker correlation with yield ($r = 0.13$), suggesting that factors other than sheer plant size might be more critical in determining yield, such as physiological health or leaf area. ANOVA tests further suggested that differences in yield between different lamps were not statistically significant ($p = 0.078$), indicating that while trends and preferences exist, the choice of luminaire might not critically impact yields under controlled conditions.

Conclusion - Basil

Optimizing light spectra in hydroponic systems is crucial for enhancing both plant yield and nutritional quality in controlled environments.

Container systems present a viable solution for urban agriculture in Europe, enabling efficient space utilization and promoting sustainable practices. As controlled environment agriculture (CEA) technologies continue to evolve, further research into the interplay of light quality, intensity, and plant responses will be essential for maximizing the efficiency and sustainability of urban farming.

This study aims to contribute to the growing body of knowledge by providing an objective comparison of various artificial lighting systems and their effects on culinary herbs. Ultimately, this research supports the broader goal of sustainable food production, emphasizing the importance of tailored lighting strategies to optimize growth and enhance the nutritional profile of valuable crops.

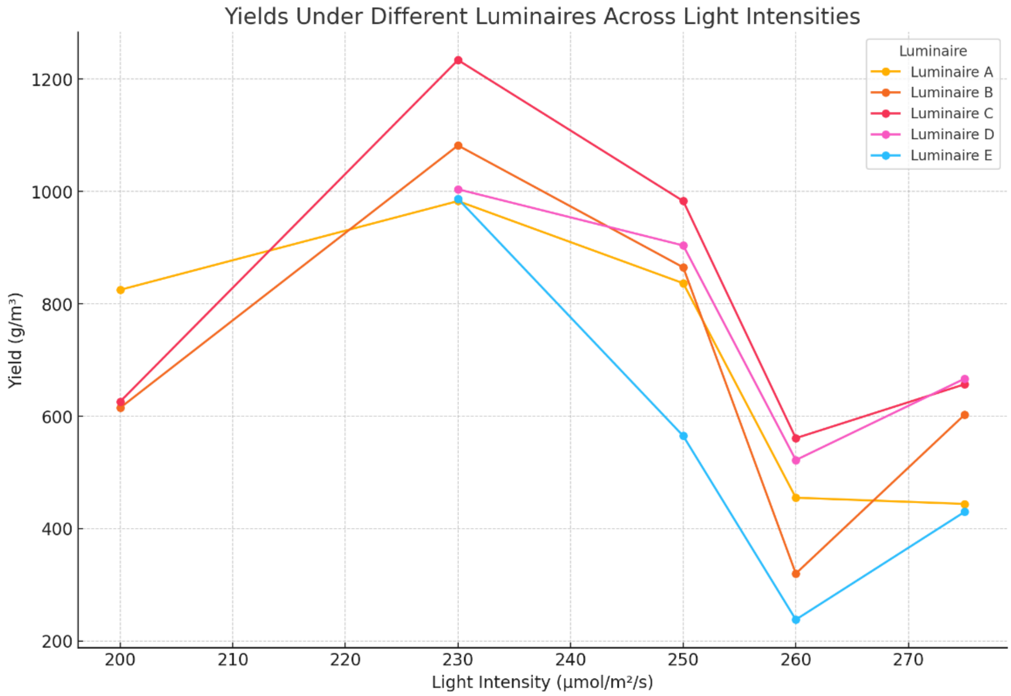
Our results indicate significant variations in yield across different luminaire types, with Lamp C consistently showing the highest yields, particularly at an intensity of 260 μmol/m^2/s. In contrast, Lamps A and D demonstrated lower yields, highlighting the sensitivity of basil to specific spectral outputs and intensity settings. Statistical analysis suggested that while there were observable trends in yield enhancement under specific lamps, differences were not statistically significant ($p>0.05$), pointing to the potential influences of other environmental or genetic factors.

These findings underscore the critical role of selecting appropriate lighting technologies in optimizing plant growth and yield in hydroponic systems. This research contributes to the evolving field of urban agriculture by providing actionable insights that can help maximize productivity in space-constrained environments. Further studies are recommended to explore the long-term impacts of these lighting conditions on secondary metabolite production and overall plant health. This study contributes valuable insights towards optimizing both yield and energy consumption, which is vital for advancing sustainable urban agricultural practices and reducing the environmental footprint of food production systems.

Results – Chives

Light intensity and luminaire type play critical roles in influencing plant growth and yield in controlled agricultural systems. Understanding how these variables impact productivity is essential for optimizing cultivation strategies, particularly in hydroponic setups where environmental conditions are meticulously regulated. This study evaluated the effects of five different luminaires across a range of light intensities on the yield and uniformity of chives (*Allium schoenoprasum*). By analyzing the data collected, we aimed to identify the most effective combinations of luminaire type and light intensity for maximizing yield while maintaining growth consistency. The results provide valuable insights into the relationship between light conditions and chive productivity, highlighting key patterns and practical recommendations for controlled environment agriculture. Below, we detail the observed trends in yield and variability, offering a comprehensive overview of the impact of each luminaire under varying light intensities.

Luminaire	Mean weight	St.dev	Mean length	St.dev	Yield g/m3	Light intensity µmol/m²/s
A	7,1	3,0	30,5	30,1	825,0	
B	5,59	1,84	28,73	3,19	615	
C	6,64	2,38	28,18	3,43	626	200
D	x	x	x	x	x	
E	x	x	x	x	x	
A	7,55	3,2	26,36	2,46	983	
B	9,27	2,05	27,64	2,23	1082	
C	9,18	4	27,82	2,21	1234	230
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	
B	7,5	2,76	26,18	3,88	865	
C	9,23	4,37	30,14	3,68	983	250
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	
B	4,73	2,14	18,82	2,69	603	
C	5,18	1,4	24,55	3,11	657	275
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	
B	4,27	2,38	27,27	2,38	320	
C	8,45	3,73	28	5,24	561	260
D	10,27	8,13	28,09	1,98	522	
E	4,27	1,42	21,91	3,6	238	



The results showed in graph indicate that **Luminaire C** is the optimal choice for maximizing yield, especially at a light intensity of 230 μmol/m^2/s. Other luminaires, such as A and B, provide reasonable alternatives but with lower overall yields. This graph visually emphasizes the importance of choosing the right luminaire and light intensity for achieving high productivity in chive cultivation.

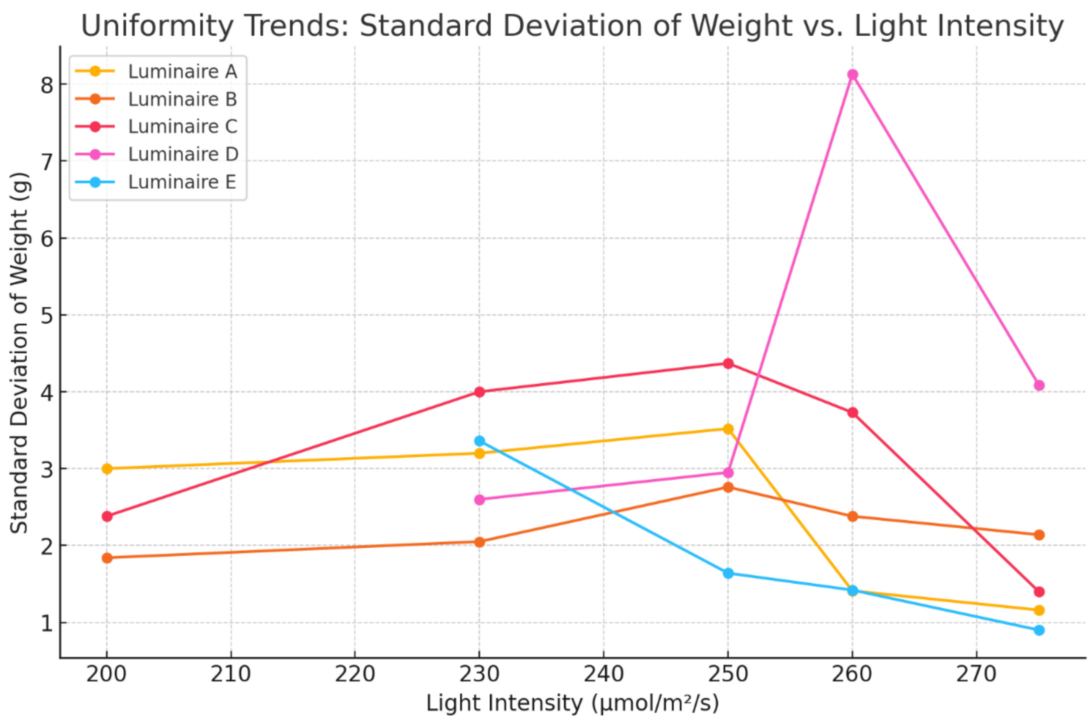
The analysis of yields under different luminaires reveals notable differences in productivity and highlights the most effective lighting conditions for chive cultivation. Luminaire C consistently performs well across a range of light intensities, achieving the highest yield of **1234 g/m^3** at 230 μmol/m^2/s. This suggests that Luminaire C provides an optimal combination of light quality and intensity for maximizing chive growth, making it the best choice for high-yield cultivation.

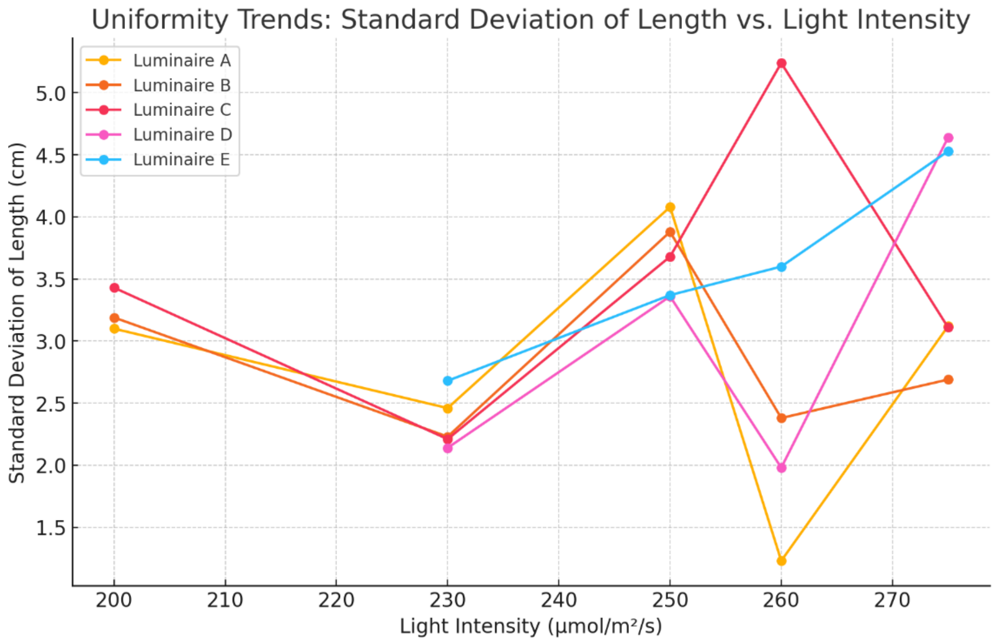
At lower light intensities of 200 μmol/m^2/s, Luminaire A achieves a moderate yield of **825 g/m^3**, while Luminaires B and C produce slightly lower yields of **615 g/m^3** and **626 g/m^3**, respectively. This indicates that Luminaire A is relatively effective under lower light conditions but does not outperform Luminaire C at higher intensities.

As light intensity increases to 250 μmol/m^2/s, Luminaire C continues to excel with a yield of **983 g/m^3**, demonstrating its adaptability and consistent productivity across conditions. Luminaire B also improves its performance at this intensity, reaching a yield of **865 g/m^3**, though it remains below that of Luminaire C.

At the highest tested intensity of 275 μmol/m^2/s, yields decline across all luminaires, with Luminaire C still leading at **657 g/m^3**. This suggests that extremely high light intensities may not be optimal for chive growth, as yields diminish and variability in growth increases. Luminaire D performs similarly to C at this intensity, achieving a yield of **667 g/m^3**, while Luminaire E falls significantly behind with a yield of only **430 g/m^3**, indicating it is less suited to high-intensity conditions.

In summary, **Luminaire C** is the best-performing option for chive cultivation, especially at a light intensity of **230 μmol/m^2/s**, where it achieves the highest yield. Luminaire A is a viable alternative for low-intensity conditions, while Luminaires B and D offer moderate performance. Luminaire E consistently underperforms and may not be an ideal choice for maximizing yield. These results emphasize the importance of selecting both the right luminaire and the optimal light intensity to achieve the best results in controlled chive production.

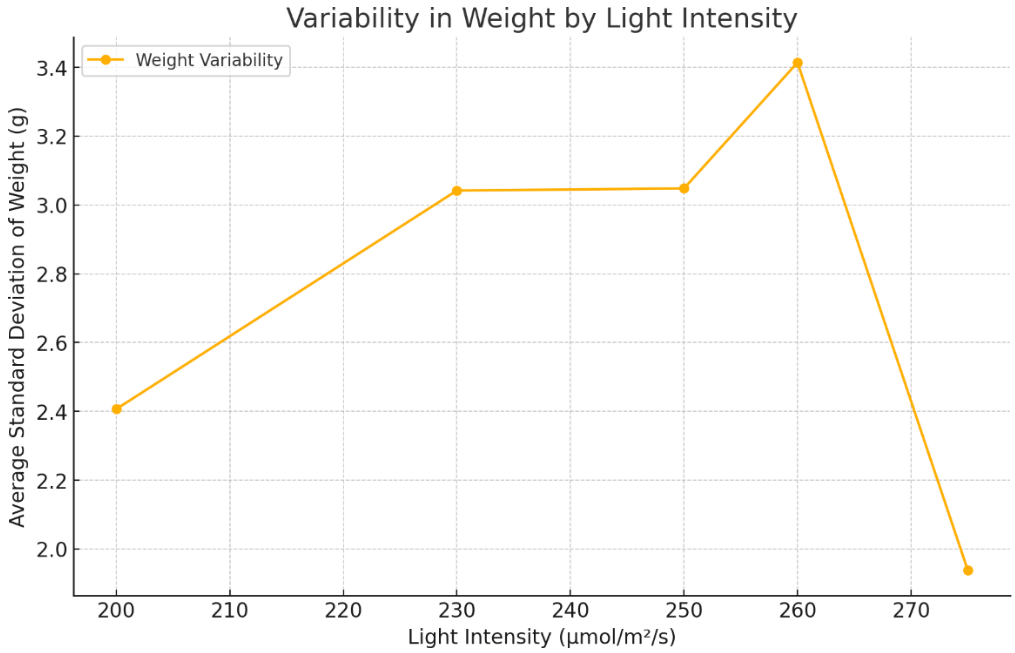




The graphs provide a clear visualization of the uniformity trends in chives under varying light intensities and luminaires. The first graph, which depicts the standard deviation of weight against light intensity, highlights how variability in chive weight changes for each luminaire. Luminaire D shows a noticeable increase in variability at higher light intensities, particularly between 250 and 260 μmol/m^2/s, indicating less consistent weight growth. In contrast, Luminaire A maintains a relatively stable and low variability across light intensities, suggesting it supports more uniform weight growth.

The second graph focuses on the standard deviation of length versus light intensity, showcasing the changes in variability in chive length across luminaires. At higher intensities, Luminaires C and D experience significant spikes in variability, indicating inconsistent length growth under these conditions. On the other hand, Luminaire A demonstrates consistent performance with lower variability, even at higher intensities, highlighting its ability to produce uniform chive lengths.

Overall, the graphs reveal a trade-off between light intensity and growth uniformity. While some luminaires achieve higher yields, their variability increases, affecting the uniformity of the crop. Luminaire A stands out as a reliable choice for maintaining uniform growth in both weight and length under a range of light intensities. This analysis provides valuable insights for optimizing light conditions to balance yield and uniformity in chive cultivation.



The analysis of variability by light intensity reveals how different levels of light affect the consistency of chive growth. For weight variability, the standard deviation starts relatively low at 200 μmol/m^2/s, indicating consistent growth at this intensity. As the intensity increases, variability also rises, peaking at 260 μmol/m^2/s. This suggests that higher light intensities may introduce factors that lead to more uneven growth, such as localized stress or competition for resources. However, at the highest intensity of 275 μmol/m^2/s, variability in weight decreases significantly, indicating more uniform growth under these conditions.

For length variability, a similar trend is observed. At 200 μmol/m^2/s, the standard deviation is high, indicating some inconsistencies in length. The variability drops sharply at 230 μmol/m^2/s, where length growth is most uniform. However, as the intensity continues to rise, variability increases again, reaching a peak at 250 μmol/m^2/s. At 275 μmol/m^2/s, length variability remains high, suggesting that very high intensities may not promote uniform length growth, even though weight becomes more consistent.

These findings highlight that lower light intensities, particularly around 230 μmol/m^2/s, support the most uniform growth in both weight and length. Higher intensities, while potentially boosting yield, introduce variability, particularly in length. This suggests that growers seeking uniformity should prioritize moderate light intensities, while those focusing on maximizing yield may consider higher intensities with careful management of potential inconsistencies.

Conclusion- chives

This study highlights the critical influence of luminaire type and light intensity on the yield and uniformity of chives in a controlled hydroponic environment. The results demonstrate that selecting the appropriate combination of these factors can significantly enhance productivity while maintaining consistent growth.

Luminaire C emerges as the optimal choice for maximizing yield, particularly at a light intensity of **230 μmol/m^2/s**, where it achieved the highest yield of **1234 g/m^3**. This combination provides a superior balance of light quality and intensity for promoting chive growth, making it the best option for growers aiming to maximize productivity. While Luminaire C also performs well across other intensities, its yield diminishes slightly at higher light intensities, indicating the need for careful optimization.

Luminaire A, on the other hand, offers consistent and uniform growth, with low variability in both weight and length across light intensities. This makes it a reliable choice for growers prioritizing crop uniformity, particularly at moderate light intensities. **Luminaire D** also shows competitive performance at higher light intensities, but it exhibits greater variability in growth, which may be less desirable for consistent crop production. **Luminaires B and E** consistently underperform, with Luminaire E showing the lowest yields and high variability, making it unsuitable for chive cultivation.

The analysis of variability reveals a trade-off between light intensity and growth consistency. While higher light intensities, such as **260 μmol/m^2/s**, can increase yield, they also introduce more variability, especially in length. Moderate light intensities, particularly around **230 μmol/m^2/s**, support the most uniform growth in both weight and length, highlighting the importance of balancing intensity to achieve both yield and uniformity.

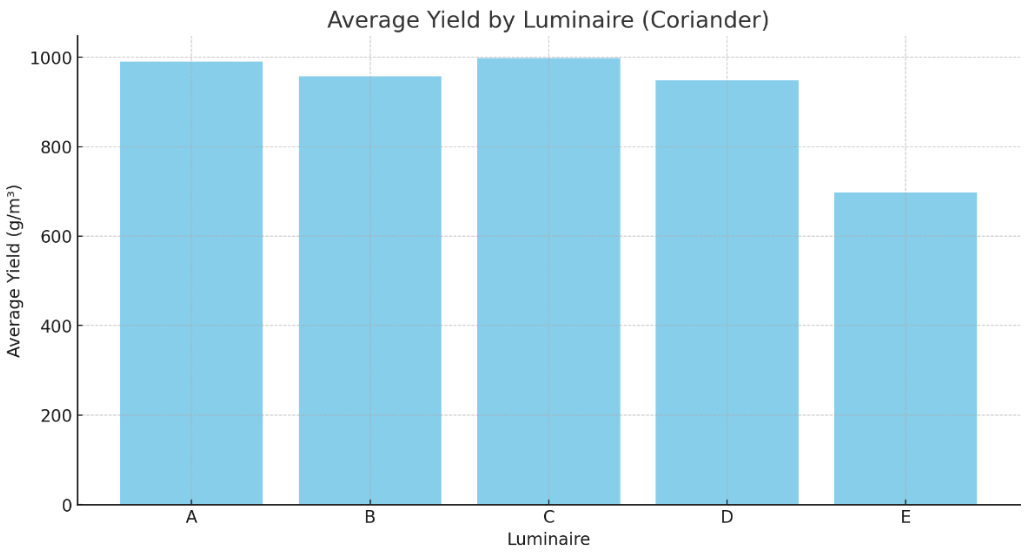
In conclusion, optimizing chive production requires careful consideration of luminaire type and light intensity. **Luminaire C at 230 μmol/m^2/s** is recommended for maximizing yield, while **Luminaire A** provides a stable option for achieving uniform growth. This study underscores the importance of tailored lighting strategies in controlled environment agriculture, offering actionable insights to enhance both productivity and consistency in chive cultivation. Further research into the long-term effects of these conditions and their impact on other growth parameters, such as nutrient uptake and secondary metabolite production, could provide additional valuable insights for sustainable hydroponic practices.

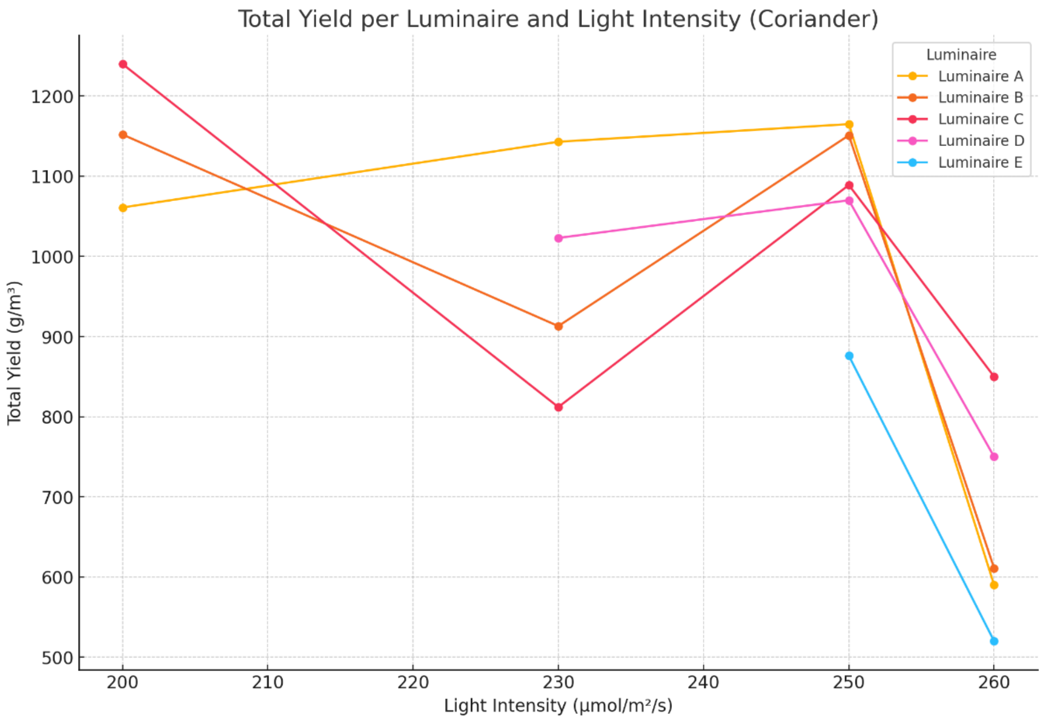
Results-coriander

Coriander is a widely cultivated herb, known for its culinary and medicinal uses. In controlled environment agriculture, understanding the interplay between light intensity and luminaire type is crucial for optimizing both yield and uniformity. This study evaluated the effects of different luminaires across a range of light intensities (200 to 260 µmol/m^2/s) on the growth and productivity of coriander grown in a hydroponic system. Key parameters such as yield, weight, and length were measured, alongside their respective variabilities, to assess how different conditions impact growth consistency and overall productivity.

The objective of this analysis was to identify the most effective lighting conditions for maximizing yield while ensuring uniform growth. The results offer insights into how light intensity and luminaire selection influence coriander cultivation, providing actionable recommendations for controlled agricultural systems. Below, we present a detailed analysis of the observed trends in yield and growth uniformity under varying light intensities and luminaires.

Luminaire	Mean weight	St.dev	Mean length	St.dev	Yield g/m3	Light intensity µmol/m²/s
A	21,4	11,4	19,5	3,4	1061,0	200
B	22,6	8,7	21,3	3,1	1152	
C	25,2	6,4	22,5	3,9	1240	
D	x	x	x	x	x	
E	x	x	x	x	x	
A	29	7,47	25,64	4,1	1143	230
B	14,27	6,35	19,73	2,89	913	
C	12,73	6,73	16,09	2,97	812	
D	18,27	4,86	22,64	3,34	1023	
E	x	x	x	x	x	
A	21,86	5,52	21,95	2,91	1165	250
B	23,64	4,39	24,24	2,57	1151	
C	23,87	7,5	23,23	4,74	1089	
D	17,09	6,39	23,01	5,06	1070	
E	14,82	2,62	18,82	3,01	876	
A	9,45	3,14	15,36	3,42	590	260
B	10,09	2,71	15	4,57	611	
C	13,18	7,76	16,55	3,58	850	
D	11,82	3,3	19,82	5,2	750	
E	8,45	3,31	15,2	5,79	520	





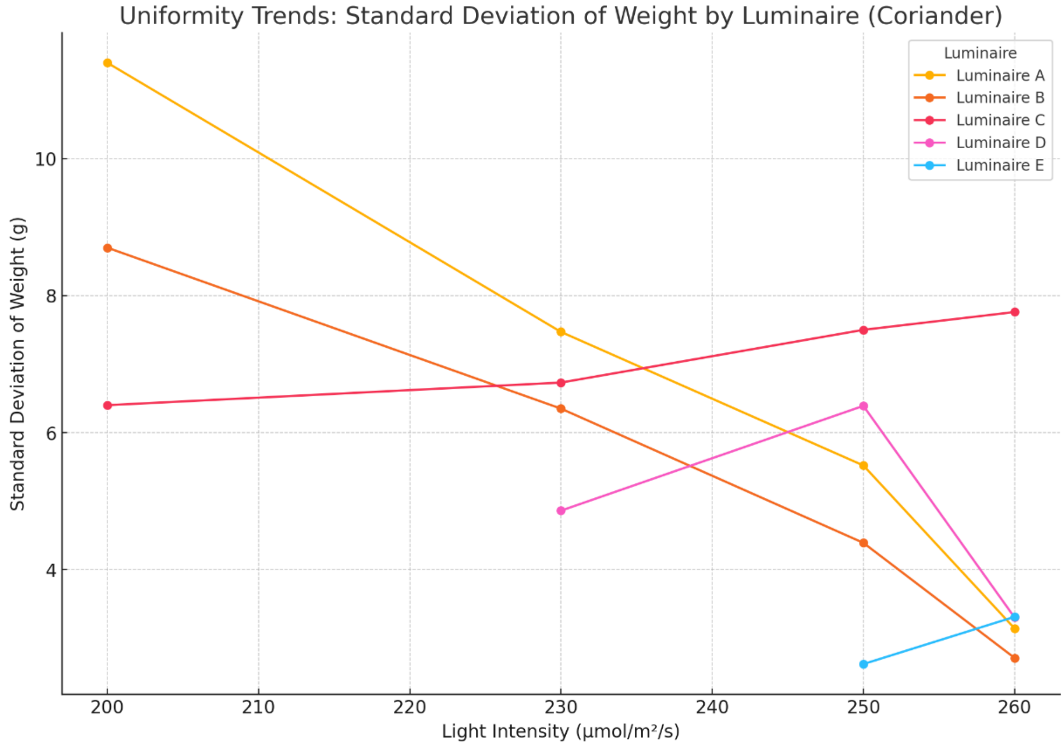
The graph above illustrates the total yield of coriander per luminaire across different light intensities. At a light intensity of 200 μmol/m^2/s, **Luminaire C** achieves the highest yield, producing **1240 g/m^3**, followed by Luminaire B with **1152 g/m^3**, and Luminaire A with **1061 g/m^3**. This indicates that Luminaire C is most effective under low light intensity conditions.

As the light intensity increases to 230 μmol/m^2/s, **Luminaire A** surpasses the others, producing a yield of **1143 g/m^3**, with a significant drop in yields for Luminaire B and Luminaire C. At this intensity, Luminaire D also shows improved performance, producing a yield of **1023 g/m^3**.

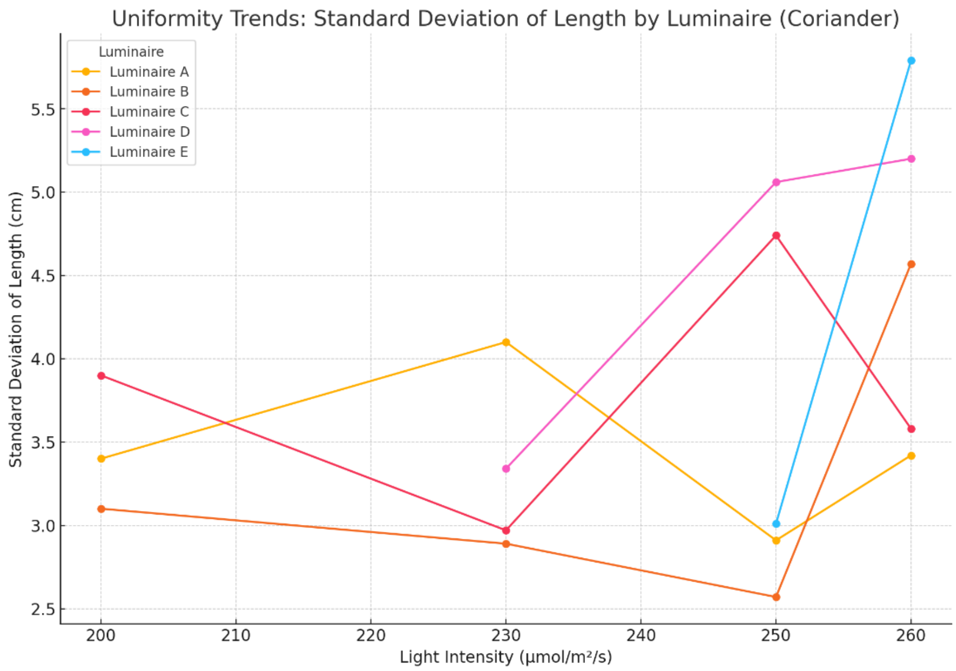
At 250 μmol/m^2/s, **Luminaire A** continues to excel with the highest yield of **1165 g/m^3**, slightly outperforming Luminaire B at **1151 g/m^3**. Luminaire C and Luminaire D also perform well at this intensity but remain below the yields of A and B.

Finally, at 260 μmol/m^2/s, yields decline sharply across all luminaires. Luminaire C achieves the highest yield at this intensity with **850 g/m^3**, while Luminaires A, B, D, and E show reduced performance, indicating that such high light intensity is less suitable for coriander cultivation.

This analysis demonstrates that Luminaire C is highly effective at lower intensities, while Luminaire A becomes more efficient as the intensity increases to moderate levels (250 µmol/m²/s). However, at very high intensities (260 µmol/m²/s), yield declines across all luminaires, emphasizing the need for optimized light conditions.



The first graph shows how the variability in coriander weight (as measured by the standard deviation) changes with light intensity for each luminaire. At lower intensities (200 µmol/m²/s), Luminaires A and C exhibit higher variability in weight, indicating inconsistent growth. As the light intensity increases, variability generally decreases for most luminaires. At 260 µmol/m²/s, Luminaires A, B, and D demonstrate better weight uniformity with reduced variability, while Luminaire C shows a slight increase in variability, indicating its reduced consistency at higher intensities.



The second graph depicts the variability in coriander length under the same conditions. At lower intensities (200–230 µmol/m²/s), Luminaires A, B, and C demonstrate relatively low variability, with Luminaire B achieving the most consistent length growth. However, as light intensity increases to 250–260 μmol/m^2/s, variability in length spikes sharply for Luminaires D and E, suggesting a decline in uniformity under high-intensity conditions. Luminaires A and B maintain relatively stable length uniformity across all intensities.

Conclusion- coriander

This study highlights the significant impact of luminaire type and light intensity on the growth and productivity of coriander in a controlled hydroponic system. The findings provide valuable insights into how these variables influence yield, weight, length, and growth uniformity, offering actionable recommendations for optimizing cultivation practices.

Yield Trends: Luminaire C demonstrates the highest yield at lower light intensity (200 μmol/m^2/s), achieving 1240 g/m^3, making it the most effective luminaire for maximizing productivity under such conditions. However, as the light intensity increases, Luminaire A becomes the top performer, peaking at 1165 g/m^3 at 250 μmol/m^2/s. Luminaire B also shows consistent performance, producing competitive yields at moderate intensities but underperforming compared to Luminaire A and C. At the highest intensity (260 μmol/m^2/s), all luminaires exhibit reduced yields, with Luminaire C retaining a slight edge. This indicates that very high light intensities are suboptimal for coriander cultivation.

Uniformity in Weight: Weight uniformity improves with increasing light intensity for most luminaires. At lower intensities, particularly at 200 μmol/m^2/s, Luminaires A and C show greater variability, reflecting inconsistent growth in weight. At higher intensities, such as 260 μmol/m^2/s, Luminaires A, B, and D exhibit reduced variability in weight, signifying more uniform growth. However, Luminaire C experiences a slight increase in variability at high intensities, suggesting its reduced consistency in weight under these conditions.

Uniformity in Length: Length uniformity remains stable and relatively low in variability at lower and moderate light intensities (200–230 μmol/m^2/s) for Luminaires A, B, and C, with Luminaire B providing the most consistent results. At higher intensities (250–260 μmol/m^2/s), variability in length increases significantly, particularly for Luminaires D and E, highlighting their reduced effectiveness in promoting consistent growth. Luminaires A and B maintain stable length uniformity even at higher intensities, reinforcing their reliability.

Optimal Conditions for Coriander Cultivation: Luminaire C is the optimal choice for maximizing yield under lower light intensities (200 μmol/m^2/s), making it suitable for setups requiring high productivity with minimal energy input.

Luminaire A is most effective at moderate intensities (250 μmol/m^2/s), offering the best combination of high yield and growth uniformity.

Luminaire B provides consistent performance across various intensities and excels in maintaining length uniformity, making it a viable alternative for achieving balanced results.

High light intensities (260 μmol/m^2/s) lead to reduced yields and increased variability, particularly for Luminaires D and E, which are less suitable for coriander cultivation under these conditions.

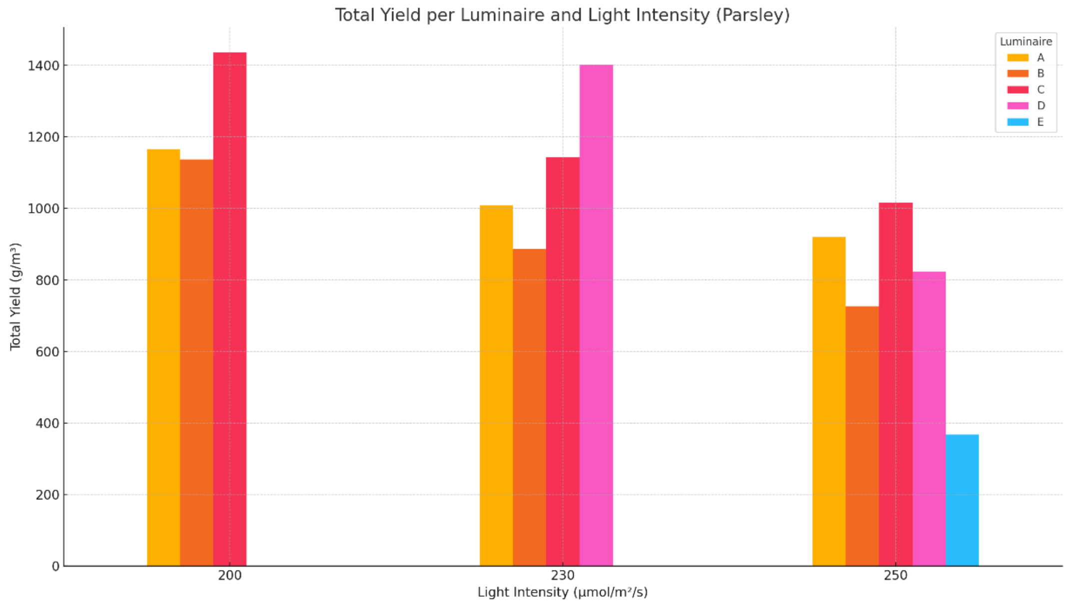
Results- parsley

Parsley is a versatile herb widely used for its culinary and medicinal properties. As with other crops, the growth and productivity of parsley are influenced significantly by environmental factors such as light intensity and luminaire type, particularly in controlled environment agriculture. These factors are critical for optimizing both yield and growth uniformity, which are essential for commercial success in hydroponic systems.

This study investigates the effects of varying light intensities (200 to 250 µmol/m^2/s) and luminaire types on the growth and yield of parsley. Key parameters such as weight, length, and their respective standard deviations were measured to evaluate overall productivity and consistency. By understanding the interplay between light conditions and luminaire performance, this analysis aims to identify optimal strategies for maximizing parsley production while maintaining growth uniformity.

Below, we present the results of this analysis, highlighting the trends in yield, weight, and length across different luminaires and light intensities, along with insights into variability and uniformity.

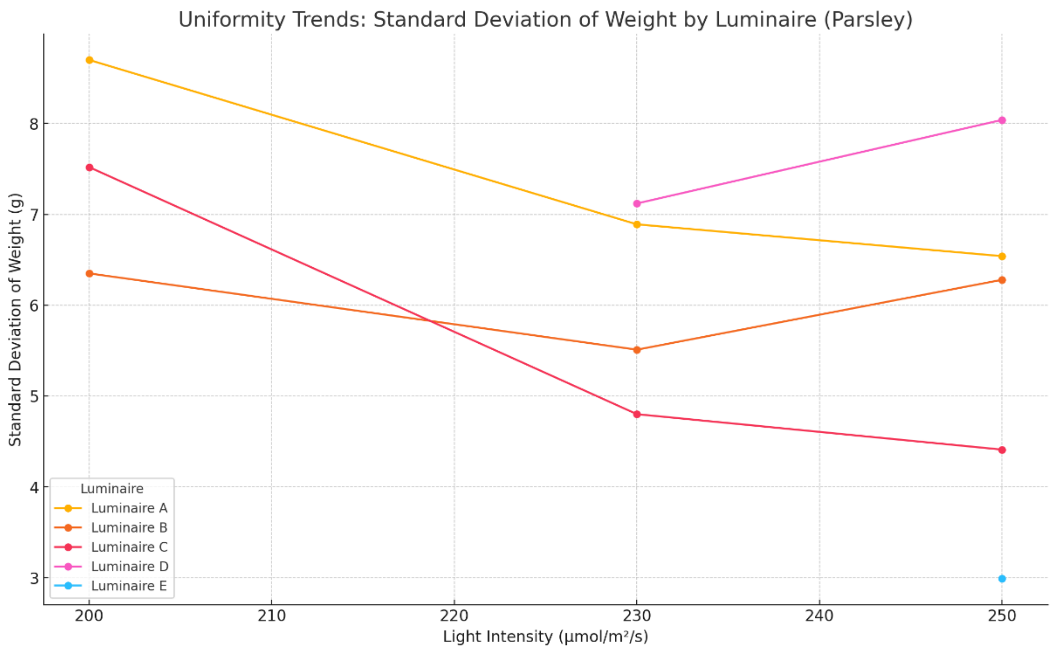
Luminaire	Mean weight	St.dev	Mean length	St.dev	Yield g/m3	Light intensity µmol/m²/s
A	17,9	8,7	24,3	3,8	1166,0	200
B	19,68	6,35	27,82	3,6	1137	
C	23,73	7,52	31,32	3,97	1435	
D	x	x	x	x	x	
E	x	x	x	x	x	
A	17,82	6,89	25,91	2,84	1008	230
B	14,18	5,51	25,45	2,57	886	
C	19,45	4,8	23,27	3,57	1143	
D	23,27	7,12	27,91	5,14	1402	
E	x	x	x	x	x	
A	14,85	6,54	23,82	3,36	920	250
B	11,23	6,28	18,86	3,96	726	
C	16,77	4,41	22,77	3,92	1017	
D	15,55	8,04	23,09	4,13	823	
E	10,36	2,99	16,45	3,65	368	

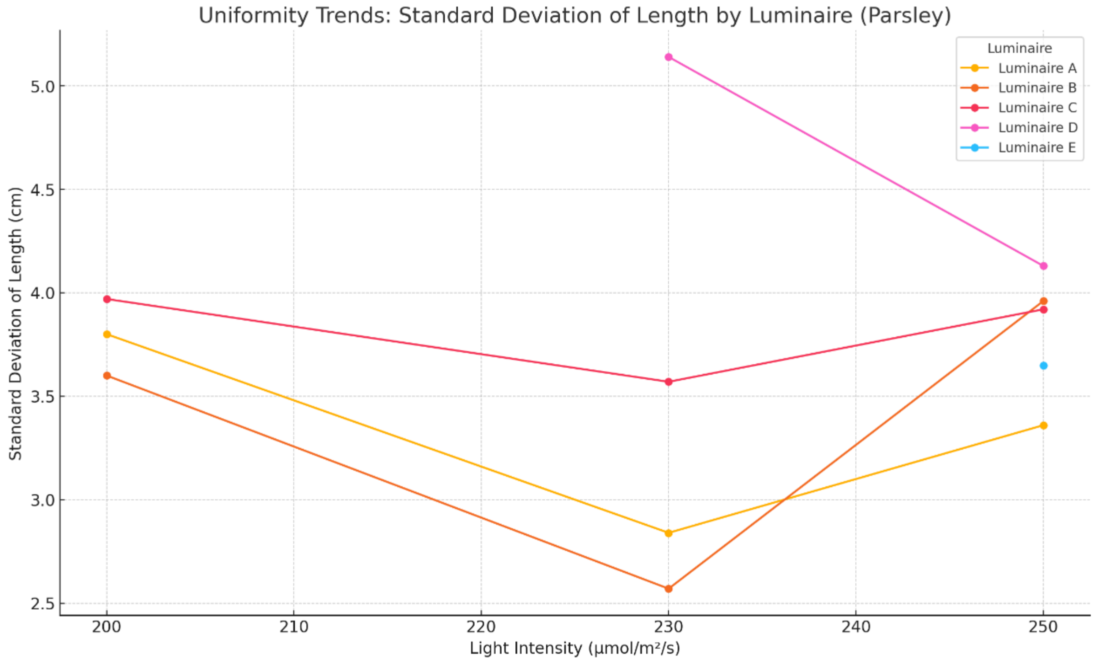


The bar graph illustrates the total yield of parsley under various luminaires and light intensities. Each set of bars represents a specific light intensity, with individual bars corresponding to the yield achieved by each luminaire. At a light intensity of 200 μmol/m^2/s, Luminaire C produces the highest yield, indicating its superior performance under low light conditions. Luminaire A follows closely, with Luminaire B also showing competitive yields.

As the light intensity increases to 230 μmol/m^2/s, Luminaire D emerges as the top performer, achieving the highest yield among all luminaires. Luminaire C remains competitive at this intensity, while Luminaire A provides moderate yields. However, at 250 μmol/m^2/s, there is a noticeable decline in yield across all luminaires. Despite this drop, Luminaire C continues to perform the best, followed by Luminaire A. In contrast, Luminaires B and D exhibit reduced effectiveness at this higher intensity.

This analysis highlights the importance of selecting the appropriate luminaire and matching it with the optimal light intensity to maximize parsley yields. Luminaire C demonstrates consistent performance across different intensities, making it a reliable choice, while Luminaire D shows particular strength at moderate intensities. These findings provide valuable insights for optimizing parsley cultivation in controlled environments.





The graphs above illustrate the uniformity trends in parsley growth under varying light intensities and luminaires, focusing on the standard deviation of weight and length. The first graph shows how variability in parsley weight changes with light intensity for each luminaire. At a light intensity of 200 µmol/m^2/s, Luminaire C demonstrates relatively low variability, indicating consistent growth in weight. As light intensity increases to 230 µmol/m^2/s, most luminaires show reduced variability, reflecting improved uniformity. However, at 250 µmol/m^2/s, variability rises again, particularly for Luminaires D and A, suggesting that higher light intensities introduce inconsistencies in weight growth.

The second graph highlights the variability in parsley length across the same conditions. At 200 µmol/m^2/s, Luminaires A, B, and C show moderate variability in length, with Luminaire D exhibiting higher inconsistency. When the light intensity reaches 230 µmol/m^2/s, variability decreases across most luminaires, with Luminaire C achieving the most consistent length growth. However, at 250 µmol/m^2/s, variability increases significantly for Luminaires D and B, indicating challenges in maintaining uniform growth at higher intensities.

Overall, the results reveal that lower and moderate light intensities (200–230 µmol/m^2/s) support better uniformity in parsley growth, with Luminaire C consistently performing well in both weight and length. In contrast, higher light intensities (250 µmol/m^2/s) tend to increase variability, particularly in length, highlighting the importance of optimizing light conditions for achieving uniform growth in parsley cultivation.

Conclusions- parsley

This study highlights the significant impact of light intensity and luminaire type on the growth, yield, and uniformity of parsley (*Petroselinum crispum*) in a controlled hydroponic system. The results provide key insights into how these factors influence productivity and growth consistency, offering valuable guidance for optimizing parsley cultivation.

Yield Trends: Luminaire C consistently outperformed other luminaires in terms of yield, particularly at lower light intensities (200 µmol/m^2/s), where it achieved the highest yield of **1435 g/m^3**. This indicates its effectiveness under low light conditions, making it an ideal choice for energy-efficient setups.

At **230 μmol/m²/s**, **Luminaire D** emerged as the top performer with a yield of **1402 g/m³**, demonstrating its suitability for moderate light intensities. Luminaire C remained competitive at this intensity, while Luminaire A provided moderate yields.

At **250 μmol/m²/s**, yields declined across all luminaires, but Luminaire C continued to perform the best with a yield of **1017 g/m³**, followed by Luminaire A. Luminaires B and D showed reduced effectiveness at this higher intensity, and Luminaire E consistently underperformed across all intensities.

Uniformity in Weight: Weight variability, measured as the standard deviation, was lowest for Luminaire C at lower light intensities, indicating consistent weight growth. As light intensity increased to 230 μmol/m²/s, uniformity improved for most luminaires, reflecting enhanced consistency. However, at **250 μmol/m²/s**, variability increased, particularly for Luminaires D and A, suggesting challenges in maintaining uniform weight growth at higher intensities.

Uniformity in Length: Length variability followed a similar pattern, with moderate variability at lower light intensities for most luminaires. Luminaire C demonstrated the most consistent length growth at **230 μmol/m²/s**, while Luminaires D and B exhibited increased variability at higher intensities, particularly at **250 μmol/m²/s**.

Optimal Light Conditions: Lower and moderate light intensities (200–230 μmol/m²/s) supported better uniformity and higher yields, with Luminaire C performing consistently well across these conditions. Higher light intensities (250 μmol/m²/s) resulted in reduced yields and increased variability, suggesting that this intensity may not be optimal for parsley cultivation.

Practical Implications: Luminaire C is a reliable choice for maximizing both yield and uniformity, particularly at lower intensities, making it suitable for energy-efficient and consistent parsley production. Luminaire D shows promise at moderate intensities, achieving the highest yield at 230 μmol/m²/s but with slightly increased variability. To achieve consistent and high-yield parsley cultivation, growers should prioritize light intensities between 200 and 230 μmol/m²/s while selecting luminaires that balance productivity and uniformity.

These findings underscore the importance of tailoring light conditions to the specific growth requirements of parsley, ensuring a balance between high yields and uniformity for commercial success in controlled environment agriculture.

Conclusions

Overall Comparison of Luminaires Across All Herbs

This study evaluated the performance of five luminaires (A, B, C, D, and E) across a range of light intensities (200–260 μmol/m^2/s) on four key culinary herbs: basil, parsley, coriander, and chives. Parameters such as yield, weight, length, and growth uniformity were analyzed to assess each luminaire's effectiveness. The following conclusions provide a comprehensive overview of luminaire performance and their suitability for optimizing plant growth and yield in controlled environments.

Luminaire C – Best for Yield and Versatility

- Key Strengths: Luminaire C consistently achieved the highest yields for all crops, particularly at lower light intensities (200–230 μmol/m^2/s). Its performance was particularly strong with basil and parsley, achieving peak yields of 1435 g/m^3 and 2678 g/m^3, respectively.
- Versatility: Luminaire C was effective across a range of light intensities and crops, demonstrating adaptability and reliability for maximizing yield.
- Challenges: While Luminaire C performed well at moderate intensities, its variability in growth (especially in weight) increased slightly at higher light intensities (250–260 μmol/m^2/s). This suggests that it may not be the best choice for growers prioritizing uniformity at high intensities.
- Overall Recommendation: Luminaire C is the most versatile and productive luminaire, making it ideal for growers aiming for maximum yields across various crops. It is particularly effective for crops like basil, parsley, and chives under moderate to low light intensities.

Luminaire A – Best for Uniformity

- **Key Strengths**: Luminaire A consistently exhibited the lowest variability in both weight and length, ensuring uniform growth across all crops. This uniformity was evident across all light intensities, making it a reliable option for growers prioritizing consistency.
- **Top Performances**: Luminaire A performed particularly well for parsley and coriander, achieving competitive yields at moderate light intensities (230–250 μmol/m^2/s). It achieved the highest uniformity in coriander, supporting balanced growth in weight and length.
- **Challenges**: Luminaire A's overall yields were lower than Luminaire C's at most intensities. It also showed reduced performance at higher light intensities (260 μmol/m^2/s), with declining yields across all crops.
- **Overall Recommendation**: Luminaire A is the best choice for growers who prioritize uniformity over maximum yield. It is particularly suited for crops like coriander and parsley, where consistency in weight and length is a critical factor.

Luminaire B – Consistent Performer

- **Key Strengths**: Luminaire B demonstrated stable and reliable performance across all crops and intensities. While it did not achieve the highest yields, it consistently delivered moderate yields and strong uniformity in length.

- **Top Performances**: Luminaire B performed well with coriander and parsley, particularly at light intensities of 200–230 μmol/m^2/s, where it achieved competitive yields while maintaining low variability.
- **Challenges**: Luminaire B's yields were consistently lower than Luminaire C, and its performance declined more sharply at higher light intensities (250–260 μmol/m^2/s). Variability in weight increased significantly for crops like parsley at higher intensities.
- **Overall Recommendation**: Luminaire B is a reliable option for growers seeking a balance between yield and uniformity. It is particularly suited for crops like coriander and parsley, where moderate yields and consistent growth are sufficient.

Luminaire D – Strong at Moderate Intensities

- **Key Strengths**: Luminaire D showed strong performance at moderate light intensities (230 μmol/m^2/s), particularly for parsley and chives. It achieved competitive yields while maintaining acceptable variability levels.
- **Top Performances**: Luminaire D's standout performance was at 230 μmol/m^2/s, where it achieved the highest yield for parsley (1402 g/m^3) and competitive yields for chives (667 g/m^3).
- **Challenges**: At lower and higher light intensities, Luminaire D exhibited increased variability in growth, particularly in weight. Its performance declined significantly for coriander and parsley at higher intensities.
- **Overall Recommendation**: Luminaire D is suitable for growers focusing on specific crops like parsley or chives at moderate light intensities. However, its variability and reduced performance at other intensities make it less versatile than Luminaires C and A.

Luminaire E – Least Effective

- **Key Strengths**: Luminaire E demonstrated low variability in some crops (e.g., coriander) at lower light intensities. However, its overall performance was poor compared to other luminaires.
- **Challenges**: Luminaire E consistently underperformed across all crops and light intensities, achieving the lowest yields and the highest variability at most intensities. For example, it produced only 430 g/m^3 for chives and 368 g/m^3 for parsley at 260 μmol/m^2/s.
- **Overall Recommendation**: Luminaire E is not recommended for hydroponic cultivation of these herbs due to its low yield and high variability. Growers should prioritize other luminaires for more productive and consistent results.

Overall Conclusions

- **Best for Maximum Yield**: Luminaire C emerges as the top performer for yield across all crops, particularly at light intensities of 200–230 μmol/m^2/s. It is highly effective for basil, parsley, and chives, making it the most versatile option for growers focused on productivity.
- **Best for Uniformity**: Luminaire A stands out for its ability to maintain uniform growth in weight and length across all crops. It is ideal for growers prioritizing consistency, particularly in coriander and parsley cultivation.

- **Balanced Performance**: Luminaire B offers a balance of yield and uniformity, making it a reliable choice for coriander and parsley under moderate light intensities.
- **Moderate Intensity Specialist**: Luminaire D performs best at 230 μmol/m^2/s, particularly for parsley and chives, but its increased variability and reduced performance at other intensities limit its versatility.

Underperformer: Luminaire E consistently achieved the lowest yields and highest variability, making it unsuitable for efficient hydroponic herb cultivation.

These findings highlight the importance of selecting luminaires based on the specific goals of cultivation. For growers aiming to maximize yield, Luminaire C is the clear choice. For those prioritizing uniformity, Luminaire A offers reliable results. Meanwhile, Luminaire B serves as a balanced option for moderate performance, and Luminaire D can be considered for specific crops at moderate light intensities. Luminaire E is not recommended for commercial hydroponic cultivation due to its poor overall performance.

Future research

Explore the Impact of Light Spectra on Secondary Metabolite Production

Investigate how different light spectra influence the production of secondary metabolites such as essential oils, antioxidants, or other phytochemicals in basil and other herbs. This can help assess not just yield but also the quality and nutritional value of the crops, which is important for commercial and health-focused agriculture.

Long-term Effects of Lighting Conditions

Conduct studies to examine the long-term impact of specific light conditions on plant health, disease resistance, and productivity across multiple growth cycles. Determine whether certain luminaires lead to cumulative stress or benefits when used repeatedly.

Energy Efficiency and Cost Analysis

Assess the energy efficiency of the different luminaires over time and analyze their cost-effectiveness in relation to the yield they produce. Include renewable energy integration, such as solar-powered systems, to evaluate sustainable lighting solutions.

Comparison of Additional Light Intensities

Explore intermediate light intensity ranges (e.g., 210, 240, 270 $\mu mol/m^2/s$) to refine the optimal intensity for specific luminaires like Lamp C, which peaked at 260 $\mu mol/m^2/s$. This would help fine-tune recommendations for growers seeking maximum efficiency.

Multi-Crop Studies

Extend the study to include other economically important crops, such as leafy greens (e.g., lettuce, spinach) or fruiting plants (e.g., tomatoes, strawberries). Compare their responses to the same lighting conditions to generalize findings across multiple crop types.

Impact of CO_2 and Light Interaction

Investigate how varying levels of CO_2 concentration interact with light intensity and spectrum to influence yield and growth uniformity. Controlled experiments could reveal optimal combinations of CO_2 and light for specific crops.

Plant Morphology and Root Development

Examine in greater depth how lighting affects root morphology and nutrient uptake, which are critical for optimizing hydroponic systems. Use imaging or root scanning technologies to quantify root growth under different lighting conditions.

Lighting Effects on Nutrient Use Efficiency

Study how different lighting spectra and intensities influence the uptake of specific nutrients and water use efficiency in plants. This could be particularly useful for developing hydroponic systems with minimal resource consumption.

Microbial Interactions in Hydroponic Systems

Explore how lighting affects the microbial environment within hydroponic systems, such as beneficial microbial communities or pathogenic microbes. Analyze whether certain light conditions promote healthier plant-microbe interactions.

Consumer Preferences and Sensory Analysis

Conduct sensory analysis and consumer testing to assess how lighting conditions affect the flavor, aroma, and appearance of the herbs. Correlate sensory data with secondary metabolite profiles to identify consumer-preferred lighting conditions.

Exploration of Stress Responses

Investigate whether certain light conditions induce beneficial stress responses, such as mild photoinhibition, which can enhance secondary metabolite production without compromising yield.

Scaling Up to Commercial Production

Conduct large-scale trials to determine how findings from controlled environments translate to commercial hydroponic farms. Evaluate scalability and economic feasibility, particularly in urban agriculture settings.

Climate-Specific Adjustments

Test the same lighting conditions under different climate scenarios (e.g., varying temperature and humidity) to determine the adaptability of these lighting setups for different geographic locations.

Literature

Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability? *Sustainable Cities and Society, 18*, 74-77. https://doi.org/10.1016/j.scs.2015.06.003

Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. *Buildings, 8*(2), 24. https://doi.org/10.3390/buildings8020024

Appolloni, E., Pennisi, G., & Orsini, F. (2021). Sustainable production of baby leaf vegetables through hydroponics and light-emitting diodes. *Sustainability, 13*(3), 1163. https://doi.org/10.3390/su13031163

Ashraf, M. Y., Nadeem, M., & Ali, F. (2019). Influence of light quality on the growth and essential oil content of coriander (*Coriandrum sativum* L.). *Saudi Journal of Biological Sciences, 26*(6), 1366-1373. https://doi.org/10.1016/j.sjbs.2018.12.006

Bai, H., Guo, Y., & Zhang, Y. (2020). Prospects for the development of containerized vegetable production in urban agriculture. *Horticultural Plant Journal, 6*(2), 111-119. https://doi.org/10.1016/j.hpj.2019.12.003

Bai, S. H., Trueman, S. J., & Xu, Z. (2020). Vertical farming for herbaceous crops: New developments for food security. *Trends in Plant Science, 25*(12), 1224-1227. https://doi.org/10.1016/j.tplants.2020.09.003

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice, and Policy, 13*(1), 13-26. https://doi.org/10.1080/15487733.2017.1394054

Bock, W. J., Hoyer, A., & Jäkel, H. (2019). Influence of different light spectra on the growth of chives (*Allium schoenoprasum*). *Journal of Plant Growth Regulation, 38*(4), 1095-1102. https://doi.org/10.1007/s00344-019-10067-0

Despommier, D. (2010). The vertical farm: Controlled environment agriculture carried out in tall buildings would create a sustainable urban food supply. *Journal of Consumer Protection and Food Safety, 5*, 233-236. https://doi.org/10.1007/s00003-010-0654-3

Germer, J., Sauerborn, J., Asch, F., de Boer, J., Schreiber, J., & Weber, G. (2011). Skyfarming an ecological innovation to enhance global food security. *Journal für Verbraucherschutz und Lebensmittelsicherheit, 6*(2), 237-251. https://doi.org/10.1007/s00003-011-0691-6

Goins, G. D., Yorio, N. C., & Brown, C. S. (1999). Photomorphogenic response of lettuce to red and blue light ratios. *HortScience, 34*(3), 551-554. https://doi.org/10.21273/HORTSCI.34.3.551

Graham, C., Palmer, J., & Edwards-Jones, G. (2019). The local food sector: Development and economic impact in the urban context. *Urban Forestry & Urban Greening, 39*, 64-71. https://doi.org/10.1016/j.ufug.2019.01.002

Graham, T. H., Silva, J. A., & DeLuca, A. (2019). The sustainability of urban agriculture: Environmental and economic benefits of local food production. *Urban Agriculture & Regional Food Systems, 4*(2), 1-7. https://doi.org/10.1017/auc.2018.22

Heuvelink, E. (1999). Crop production in controlled environments. In G. C. van der Meer & E. Heuvelink (Eds.), *Controlled Environment Agriculture* (pp. 211-239). Wageningen Academic Publishers.

Hernández, J., De Castro, E., & Pacheco, R. (2020). Effects of light intensity on the growth and quality of parsley (*Petroselinum crispum* var. *Neapolitanum*) under controlled conditions. *Acta Horticulturae, 1283*, 71-78. https://doi.org/10.17660/ActaHortic.2020.1283.7

Jiang, Z., Liu, J., & Xu, J. (2019). Effects of light distribution on the growth of basil in hydroponic systems. *Journal of Horticultural Science and Biotechnology, 94*(1), 123-129. https://doi.org/10.1080/14620316.2018.1473718

Kaiser, E., Ouzounis, T., Giday, H., Schipper, R., Heuvelink, E., & Marcelis, L. F. (2019). Adding blue to red supplemental light increases biomass and yield of greenhouse-grown tomatoes, but only to an optimum. *Frontiers in Plant Science, 9*, 2002. https://doi.org/10.3389/fpls.2018.02002

Kopsell, D. A., Kopsell, J. K., & Randle, W. M. (2014). Effects of LED light quality on the growth and essential oil composition of basil. *HortTechnology, 24*(3), 364-370. https://doi.org/10.21273/HORTTECH.24.3.364

Kozai, T., Niu, G., & Takagaki, M. (2016). *Plant factory: An indoor vertical farming system for efficient quality food production*. Academic Press. https://doi.org/10.1016/C2014-0-04689-0

Kumar, P., Singh, M., & Kaur, R. (2015). Influence of different environmental factors on the growth and essential oil content of coriander (*Coriandrum sativum* L.). *International Journal of Chemical Studies, 3*(6), 39-45. https://www.chemijournal.com/archives/2015/vol3issue6/PartB/3-6-9.pdf

Liu, Y., Zhan, Y., & Wang, L. (2020). The effect of light quality on growth and development of chives (*Allium schoenoprasum* L.) in hydroponics. *Horticulture Research, 7*(1), 1-10. https://doi.org/10.1038/s41438-020-0263-2

López, S., Medina, M., & Álvarez, J. (2021). Growth of basil and lettuce under different artificial lighting systems: An evaluation of high-pressure sodium, fluorescent, and LED lighting. *Plants, 10*(5), 1007. https://doi.org/10.3390/plants10051007

Morrow, R. C. (2008). LED lighting in horticulture. *HortTechnology, 18*(4), 491-495. https://doi.org/10.21273/HORTTECH.18.4.491

Moustakas, K., Tzivras, D., & Xanthopoulos, P. (2019). Impact of LED light quality on the growth and photosynthetic performance of parsley (*Petroselinum crispum*). *Agronomy, 9*(9), 520. https://doi.org/10.3390/agronomy9090520

Piovene, C., Maggio, A., & Barbagallo, R. P. (2015). Manipulation of light spectra enhances plant biomass and nutraceutical profile of basil (*Ocimum basilicum* L.). *Scientific Reports, 5*, 11952. https://doi.org/10.1038/srep11952

Sæbø, A., Rognan, R., & Abrahamsen, A. (2003). The effects of different LED light spectra on growth and quality of lettuce. *Acta Horticulturae, 609*, 129-136. https://doi.org/10.17660/ActaHortic.2003.609.12

Sinha, A., Sinha, S., & Chatterjee, C. (2015). The effects of environmental factors on the growth and yield of flat-leaf parsley (*Petroselinum crispum* var. *Neapolitanum*). *Agricultural Science, 6*(4), 477-485. https://doi.org/10.4236/as.2015.64047

Van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J. A., Heuvelink, E., & Marcelis, L. F. M. (2021). Vertical farming: Cautiously optimistic for a sustainable future. *Trends in Plant Science, 26*(8), 742-752. https://doi.org/10.1016/j.tplants.2021.04.010

Wang, Z., Li, Y., & Lu, J. (2017). Photosynthesis and plant growth under different light quality in hydroponics. *Plant Physiology and Biochemistry, 115*, 299-307. https://doi.org/10.1016/j.plaphy.2017.04.017

Zhang, H., Zhang, H., & Zhang, Y. (2018). Effects of light spectrum on the growth of basil. *Frontiers in Plant Science, 9*, 223. https://doi.org/10.3389/fpls.2018.00223