Let There Be (Optimal) Light

Nanna Kalmar

Egaa Gymnasium, Denmark

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Abstract

On average, the agricultural sector uses 70% of water withdrawals worldwide to produce crops[1] and contributes to the eutrophication of lakes by using nutrients that are leached from the soils into lakes and reservoirs[2]. Vertical farming has great potential to remedy some of these issues. By growing plants vertically in controlled environments with artificial light and reusing the water, vertical farms use op to 99% less water[3] and can produce up to 10 times the yield per square meter[4] compared to traditional greenhouses. This improved efficiency comes at a cost; on average, vertical farms use more than 600% more energy per kilogramme of crop compared to traditional greenhouses[5]. 55% of this energy use is due to the use of artificial lighting[6]. Even though a lot of research is conducted on yield optimisation of crops in vertical farming, few research articles focus on the growth efficiency of crops to reduce the energy use in vertical farms. Only a few articles have tested photoperiods under $10\ \mathrm{h} \cdot \mathrm{d}^{-1}$. This study focuses on reducing the energy costs of light use in vertical farms by finding the photoperiod with highest energy use efficiency for the leafy vegetable *rocket* (eruca sativa). Energy use efficiency is defined as fresh mass per unit of electricity input (measured in kWh). In this study, rocket plants were exposed to LED growth light, with photoperiods ranging from $0\ \mathrm{h} \cdot \mathrm{d}^{-1}$ to $24\ \mathrm{h} \cdot \mathrm{d}^{-1}$ ($0\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $4\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $9\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $12\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $14\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $24\ \mathrm{h} \cdot \mathrm{d}^{-1}$) and a PPFD of $800\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$. The photoperiod $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ had the highest energy use efficiency of all photoperiods and, if used in vertical farms, this could account for approximately a 10 percent decrease in energy per kilogramme used in vertical farms (a $4\ \mathrm{kWh}$ decrease), with the planting density of 1400 plants per m^2. This could amount to a yearly energy saving of $4{,}000{,}000\ \mathrm{kWh}$ per vertical farm (based on the yearly harvest of the vertical farm Nordic Harvest). This could help make vertical farming a more sustainable plant production for the future and in turn, help farming protect our water resources instead of consuming and polluting.

[1] (OECD, n.d.)
[2] (EPA, 2022)
[3] (Marsh, 2023)
[4] (Villazon, 2022)
[5] (McDonald, 2022)
[6] (WayBeyond & Agritecture, 2021)

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Introduction

With increasing number of droughts in the world, the need for efficient water use persists. On average, the agricultural sector uses 70% of water withdrawals worldwide to irrigate and produce crops[7]. However, less than 60% of this water is consumed by crops, the remaining is wasted[8]. Furthermore, global food production is relying on intensive use of nutrient fertilizers to increase crop yield, with the risk of nutrient leaching from the soils into lakes and reservoirs[9]. This promotes algae growth that causes harm to the fish in the lakes and can release toxins to the water, making it harmful to humans.

Vertical farming, where crops are grown vertically indoors, use up to 99% less water than traditional farms[10]. They can also produce up to 10 times more crops than traditional farms with the same area[11]. This is done by placing plants in a controlled environment with artificial lighting. In this controlled environment, the water can be reused, water evaporation is not as severe, and nutrients added to the water do not end up in lakes, etc. However, vertical farms use more than 600% energy per kilogramme of crop compared to traditional greenhouses[12] and over 120 times more energy per kg of produced lettuce, compared to conventional agriculture[13]. This is primarily due to the use of artificial lighting. This study investigates whether this energy consumption can be optimised by exposing plants to less light without reducing the growth of the plants substantially. This would reduce the energy consumption and make vertical farming a more sustainable solution for the future of plant production, thus reducing water consumption of the agricultural sector, while keeping production high.

This study investigates a research question few scientists before have investigated: Is it possible to find a more optimal photoperiod[14] for *rocket* (*eruca sativa*) with a higher energy use efficiency[15] than photoperiods with 16 hours (or higher) of light per day. The most compelling facet of this study is that I investigate photoperiods of less than 10 hours per day which few researchers have previously investigated. Therefore, this is relevant basic research that attempts to challenge the focus of wanting to expose a plant to as much light per day as the plant can absorb - can plants grow and produce a high yield with less light per day?

In this study I investigate: *What is the lowest photoperiod a plant can be exposed to where the energy use efficiency n is high and comparable to the energy use efficiency for the photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$, and how can this knowledge be applied to optimise energy consumption in vertical farming?*

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[7] (OECD, n.d.)
[8] (Marsh, 2023)
[9] (EPA, 2022)
[10] (Marsh, 2023)
[11] (Haan, n.d.)
[12] (McDonald, 2022)
[13] (WayBeyond & Agritecture, 2021)
[14] How many hours of light per day a plant is exposed
[15] Energy use efficiency is in this context defined as grams of fresh plant mass per unit of energy in kWh

Background

PPFD is a measure of light intensity and is short for "photosynthetic photon flux density". The unit for PPFD is $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. This is a measure of how many photons strike the plant per unit of area per second[16]. The term DLI, which stand for "daily light integral", is used to describe the amount of light a plant receives per day. DLI has the unit $\text{mol} \cdot \text{m}^{-2} \cdot \text{d}$ which is an expression for the number of photons per square meters per day. This is also used in the scientific literature to describe light intensity[17].

The term photoperiod is used to describe the number of hours per day a plant is exposed to light. The photoperiod for a plant is usually written as two numbers separated by a slash, e.g., 10/4, where the format is light/darkness. In this instance the plant receives 10 hours with light and 14 hours with darkness.

Literature review

An article by Pennisi, et al. (2020) tried to find the optimal photoperiod for lettuce, basil, rocket, and chicory. They used red and blue LEDs and investigated three photoperiods on $16\ \text{h} \cdot \text{d}^{-1}$, $20\ \text{h} \cdot \text{d}^{-1}$ and $24\ \text{d} \cdot \text{h}^{-1}$ with a constant light intensity with a PPFD of $250\ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, which corresponds to a DLI of $14.4\ \text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, $18\ \text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and $21.6\ \text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ respectively. They found that the optimal photoperiod for lettuce and chicory was $16\ \text{h} \cdot \text{d}^{-1}$ (DLI $14.4\ \text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), since it was the photoperiod that had the highest energy use efficiency, which they calculated as the fresh plant mass per unit of energy. They also found that the dry mass of lettuce, basil and chicory had a linear relation with DLI where the dry mass increased with an increasing DLI.

Proietti, et al. (2021) tried to find a photoperiod with high energy use efficiency for rocket in order to develop CEAL-technologies[18] that is usable on the Earth and in space. They exposed rocket to two different photoperiods on 12/12 and 24/0 (hours of light/hours of darkness). They used LEDs with broad spectrum light (white, far-red, red and blue) with a high light intensity (PPFD $600\ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) at the photoperiod 12 hours per day. The photoperiod with the duration of 24 hours they split into two interventions, where they used white LEDs in one intervention, and red and blue LEDs in the other intervention. Both interventions with a photoperiod of 24 hours had a lower light intensity (PPFD $300\ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). They saw that both interventions with a photoperiod of 24 hours increased the growth of rocket more than the photoperiod of 12 hours. However, they wrote that the yield for all interventions were high. They propose that to save energy, it is optimal to expose plants in a CEAL to light 24 hours of the day with low light intensity, where the plants get a high accumulated PPFD and also reduces the number of photons per unit of time the plants are exposed to. They also wrote that they could confirm that rocket is a great candidate for vertical farming and plant production in space, based on their results.

A review article by Jin, et al. (2022) investigated a term called light use efficiency in vertical farms, greenhouses and fields. Light use efficiency (abbreviated LUE) is in their article defines as grams of dry mass per cumulative DLI (the total amount of light the plant is exposed to in the experiment) - the unit $\text{g} \cdot$

[16] (Bugbee, 2019)
[17] (Baldinger, 2022)
[18] Controlled Environments with Artificial Lighting (vertical farms)

mol^{-1}.[19] They compared LUE-values from different studies concerning vertical farming (53 studies), greenhouses (13 studies), and fields (8 studies). They found that the values for LUE in studies in vertical farming was more scattered than the LUE-values for greenhouses and fields. The average LUE-value was highest in vertical farms ($0.55\ \mathrm{g} \cdot \mathrm{mol}^{-1}$), greenhouses thereafter with an average LUE-value of $0.39\ \mathrm{g} \cdot \mathrm{mol}^{-1}$ and lastly fields with a value of $0.23\ \mathrm{g} \cdot \mathrm{mol}^{-1}$). The reason for the generally higher LUE-values in vertical farming is due to the very controllable light intensity due to the use of artificial light, in comparison to greenhouses and fields where the light intensity varies greatly each day. They also mention the high planting density as a factor of why vertical farms have a higher LUE - more plants per square meter means less light wasted (e.g., photons that doesn't strike plants).

Kang, et al. (2013) investigated the influence of different photoperiods and light intensities on lettuce. They conducted experiments where they investigated the following light intensities: $200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $230\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $260\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $290\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ combined with the photoperiods 18/6, 9/3 (2 cycles per day) and 6/2 (3 cycles per day)[20]. The light intensity $290\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ produced good resultas at all photoperiods. Combined with the photoperiod 9/3 it produced the highest plant height and fresh mass, combined with the photoperiod 18/6 it produced the highest root fresh mass, plant dry mass and root length, while combined with the photoperiod 6/2 it resulted in the biggest leaf width, root dry weight and maximum number of leaves. Besides growth they also investigated the anthocyanin[21] content in lettuce. The anthocyanin content was highest at the light intensity $290\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and the photoperiod 6/2 and lowest at the light intensity $200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and photoperiod 6/2. In the article, they conclude that a high light intensity ($290\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$) and a long photoperiod (9/3 or 18/6) produce a high fresh and dry mass.

The four articles abowe all focused on photoperiods, light intensity and efficiency regarding light or energy. Pennisi, et al. (2020) found that the lowest photoperiod they tested, had the highest energy use efficiency. Furthermore, Proietti, et al. (2021) found that by giving a plant lower light intensity during a longer photoperiod they could optimise growth. This is very interesting results since it shows that exposing a plant (in this case, lettuce) to as much light as possible is not always the best option since it can reduce the energy use efficiency and growth of the plant. Kang, et al. (2013) found that scattering the light throughout the day, giving a 3 hour break between light emissions (instead of 6 hours) resulted in a higher growth. And Jin, et al. (2022) found that vertical farming has the highest light use efficiency compared to greenhouses and fields.

In an article by Knight & Mitchell (1983) they exposed four lettuce plants ("Salad Bowl", "Bibb", "Ruby" and "Grand Rapids") to light intensities with PPFD's of $261\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $452\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $644\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $932\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and photoperiods on $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $24\ \mathrm{h} \cdot \mathrm{d}^{-1}$. They found that the growth of all plants (except Grand Rapids) was highest at the light intensity of $932\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$. They also found that the dry mass of all plants was highest at the beforementioned light intensity and photoperiod. They also saw that plants exposed to the light intensity $932\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ had more leaves than at other intensities. However, they found that all plants experienced symptoms of

[19] Not to be confused eith the unit for molar mass M that also is $\mathrm{g} \cdot \mathrm{mol}^{-1}$
[20] Every plant therefore received $18\ \mathrm{h} \cdot \mathrm{d}^{-1}$ but with different intervals
[21] Anthocyanin is a red and blue pigment in plants that for example is increased at high light intensities (Scheller, 2022)

stress at this high light intensity ($932\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$), e.g. purplish leaves. These stress symptoms were reduced by doubling the amount of nitrogen in the ground. This didn't have a large effect on the dry mass.

In another article Knight & Mitchell (1982) they exposed lettuce plants to light intensities $444\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $889\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ with a photoperiod of $20\ \mathrm{h} \cdot \mathrm{d}^{-1}$. Besides light intensities, they also varied temperature during the day and night. They found that the highest fresh mass was reached by a high light intensity and high temperature, and the lowest dry mass at low light intensity and low temperature. They explain this results by the fact that the temperature increase the leaf expansion rate. This makes the leaves larger, so they in turn can more efficiently absorb the increasing light. They also mention that the temperature variance during the day was not necessarily the most important parameter for the increased growth, and that light intensity is more important than temperature.

Both articles Knight & Mitchell (1983) and Knight & Mitchell (1982) focused on growth and mass optimisation of lettuce. Both articles investigated the influence of high intensity light on lettuce and found that this can lead to increased growth. This shows that even though plants have an upper threshold on how much light they can absorb, which also increases growth, this threshold is very high.

Elmardy, et al. (2021) exposed rocket to light with different light intensities, colour-compositions and photoperiods. They investigated the light intensities $160\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $190\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $220\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, light with red:green:blue-ratio of 7:0:3, 3:0:7 and 5:2:3, and photoperiods on 10/14, 12/12 and 14/10. They compared this to a control they exposed to white flourescent light with a light intensity of $190\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and photoperiod of 12/12. They saw that a combination of photoperiod 14/10 and r:g:b-ratio 7:0:3 produced the highest growth, regardless of light intensity. They also saw that rocket exposed to light intensity $220\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, photoperiod 10/14 and r:g:b-ratio 7:0:3 was highest, had the highest leaf are and root length.

Yan, et al. (2019) studied which effect light quality (colour of the light) and DLI had on growth, energy use efficiency and nutritional quality in lettuce. They studied five different DLIs on $5.04\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$, $7.56\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$, $10.08\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$, $12.60\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$ and $15.12\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$ [22] and four different LEDs with white light and different mixtures of blue and red light (red:blue-ratio on 0.9, 1.8, 2.7 and 3.6, respectively). They saw that the fresh mass increased somewhat linearly with an increasing DLI, except $12.60\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$ and $15.12\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$, where a significant difference on the mass at the two different DLIs didn't occur. They found that LUE and energy use efficiency decreased linearly with an increasing DLI. In a nutritional perspective they saw that DLI and light quality had great impact on nitrate concentration, anthocyanin concentration and vitamin C conventration. A higher DLI produced a lower nitrate concentration and a higher anthocyaning and vitamin C concentration. Yan, et al. (2019) recommends LED with a red:blue-ratio of 2.7, with a DLI of $12.60\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$ as the optimal light conditions for lettuce production in vertical farming.

Shimizu, et al. (2011) tried to optimise light conditions in vertical farming by focusing on light quality. They studied the growth of lettuce and exposed lettuce plants for six different light qualities - 5 was LED-based while the last was flourescent light. The five LED light qualities was red light, blue light, red and blue light, light imitating sunlight and light imitating flourescent light. In all experiments they exposed lettuce for

[22] The corresponding PPFD-values for the DLIs are $100\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $150\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $250\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $300\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$

different light qualities with the photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$. They found that the light quality with highest fresh mass was red light followed by flourescent light.

The articles Elmardy, et al. (2021), Yan, et al. (2019) and Shimizu, et al. (2011) focused primarily on the quality (colour) of the light. They found that the light quality had great impact on plant growth - especially red LED light increased plant growth. However, Yan, et al. (2019) saw that the change in light quality did not have an impact at low DLIs. There are therefore indications that the light quantity (DLI and PPFD) have greater importance than light quality (colour of the light) in a growth context. This is also why I am using growth light that has mulitple colours (blue, red and white) to get the most optimal growth.

The article Chia & Kubota (2010) investigated if light treatments at the end of the day could change the height and other growth parameters of tomatoes. They used incadescent light with different red:far-red-ratios on 0.05 and 0.47 respectively, and durations of the treatmens from 3-24 minutes. In total they exposed plants to light treatments with DLIs from $1\text{-}8\ \mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$. They found that the fresh and dry mass of leaves were not influenced significantly by the treatments. They saw, however, that the fresh mass of the stem was greater at both light treatments and that the length of the lowest part of the stem (hypocotyl) became longer by increasing the intensity of the far-red exposure at a lower duration. They also write that there are indications that the light dosage can reach a saturation point for the plant - e.g. the highest light intensity $40\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and the shortest duration (3 minutes) produced the same hypocotyl length as the other treatments.

Brazaitytė, et al. (2019) studied the usage of UV-A-LED as a supplemental light in a LED setup and if it could influence the growth and the nutritional quality of mustard microgreens. Their LED setup consisted of LEDs with light peaks at the wavelengths $447\ \mathrm{nm}$, $683\ \mathrm{nm}$, $665\ \mathrm{nm}$ and $731\ \mathrm{nm}$. They investigated two durations of the light supplement at $10\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$, investigated the wavelengths $366\ \mathrm{nm}$, $390\ \mathrm{nm}$ and $402\ \mathrm{nm}$ with a PFD[23] of $300\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$. They found that the supplemental lighting did not change the mass of the mustard microgreens but that a supplemental light treatment at $402\ \mathrm{nm}$ increased the leaf area of the plants (regardless of duration). They also found that the nitrate concentration in the plants were highest at light treatments of $366\ \mathrm{nm}$ and $390\ \mathrm{nm}$ (at both durations) and was the lowest at treatment at $402\ \mathrm{nm}$ (at the duration $10\ \mathrm{h} \cdot \mathrm{d}^{-1}$). However, they emphasised that the concentration of nitrate was not high enough to be harmful to humans. They also found that the mineral concentration (except iron) was increased during longer wavelenghts ($390\ \mathrm{nm}$ and $402\ \mathrm{nm}$) at the duration of $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$. They conclude that UV-A supplemental lighting can improve the nutrient concentration of mustard microgreens without having adverse effects on the growth.

Viršilė, et al. (2019) investigated the influence of light on growth and nitrate concentration in lettuce. They exposed lettuce to the photoperiods $12\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$, $18\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $24\ \mathrm{h} \cdot \mathrm{d}^{-1}$, and the light intensities $100\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $200\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $300\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, $400\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ and $500\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$. They found that the light intensity had great impact on the nitrate concentration and saw that the nitrate concentration in lettuce was very high at $100\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$. This concentration decreased with an increasing light intensity (however, no sigificant difference on nitrate concentration at $300\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ to $500\ \mathrm{\mu mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$). They also found that the light intensity had greater impact

[23] Since they use ultraviolet light, they use the term PFD (photon flux density) and not PPFD (photosynthetic photon flux density) to describe light intensity

on the growth of the lettuce than photoperiod. They saw that light intensities between $300\text{-}400\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ produced the highest fresh mass, leaf area and height in lettuce.

Both Chia & Kubota (2010) and Brazaitytė, et al. (2019) focused on improving light conditions by either supplementing with UV-A light or exposing the plants to light treatments at the end of the day; Viršilė, et al. (2019), however, had a larger focus on the influence of light on nitrate concentration in lettuce. Chia & Kubota (2010) found that plants probably have a saturation point - a point where the plant cannot absorb any more photons - which therefore further emphasises the importance of finding the point where the plant can convert the light energy most efficiently without bombarding it needlesly with light. Brazaitytė, et al. (2019) and Viršilė, et al. (2019) found that the light conditions can actually change the nutrient concentration and nitrate content in microgreens and salad which also adds a nutrient dimension, which one should pay attention to in the optimisation and improvement of light conditions in vertical farming.

In a review article Ahmed, et al. (2019) they investigated different factor that could influence the growth of lettuce plants in a CEAL (Controlled Environments with Artificial Lighting). The factors they studied were light, air velocity (air circulation), temperature, relative air humidity and concentration of $\mathrm{CO_2}$. Light is one of the most important factors for plant growth and LED lighting was pointed out to be a great source of light since LED light is energy conserving, easy to control and emit minimal heat. Ahmed, et al. (2019) mentions that the optimal light intensity can increase the rate of the photosynthesis of the plant and increase the dry plant mass. They indicate that the most optimal light intensity is between $200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ to $250\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ with a photoperiod between $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$ to $18\ \mathrm{h} \cdot \mathrm{d}^{-1}$ in lettuce plants. They also mention that the photosynthesis can be influenced negatively by a light intensity that is too high. Lastly, they write that the most effective combinations of LED colours is red and blue since they are the best at improving plant growth. They found that an air velocity of between $0.3\ \mathrm{m} \cdot \mathrm{s}^{-1}$ and $0.7\ \mathrm{m} \cdot \mathrm{s}^{-1}$, a temperature between 22-25 ℃, a relative air humidity between 70-80% and a $\mathrm{CO_2}$ concentration of $1000\text{-}1500\ \mu\mathrm{mol} \cdot \mathrm{mol}^{-1}$ is the most effective combination in a CEAL in relation to the growth of lettuce plants.

Generally, these articles show some tendencies in growth and energy use efficiency in a vertical farming perspective. Articles like Ahmed, et al. (2019), Pennisi, et al. (2020) and Brazaitytė, et al. (2019) found that a long photoperiod not necessarily mean a high growth or energy use efficiency. They point to a tendency that there is a maximum amount of light a plant can efficiently absorb and convert to growth - a saturation point. This point can, however, be very high which Knight & Mitchell (1983) found. Therefore, it makes sense to investigate different photoperiods to find the most optimal and energy use efficient photoperiod for rocket. Artikles like Yan, et al. (2019), Shimizu, et al. (2011) and Elmardy, et al. (2021) also found that light quality (the colour of the light) had a great impact on plant growth. Yet, Yan, et al. (2019) found that a change of light quality didn't have an effect on plant growth at low DLI's. Therefore it seems that light quantity (DLI and PPFD) has greater impact than light quality (colour of light) in a growth context.

All articles (except Chia & Kubota (2010) and Brazaitytė, et al. (2019)) had lettuce plants as their primary focus. Almost all articles focused on the optimisation of yield for lettuce plants in vertical farming, regardless of energy costs. This yield optimisation, however, does not always make sense in a vertical farming perspective, where energy costs and consumption also play a huge part in the profitability of the business. Few articles investigated the term energy use efficiency, which is why I intended to research that term. The articles that investigated light conditions in vertical farming, have not investigated photoperiods under $10\ \mathrm{h} \cdot \mathrm{d}^{-1}$. My research therefore stands out, since I both investigate long photoperiods like $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$ but also short photoperiods like $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $4\ \mathrm{h} \cdot \mathrm{d}^{-1}$, and I try to investigate if they have an energy use efficiency that is higher or lower than the photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$. The mentioned articles also debate a common result in experiments on energy use efficiency: it is not necessarily good to give a plant as much light as possible. It is more energy use efficient to give lettuce plants a specific amount of light - not too much or too little - and it is this exact amount I am trying to find.

Methods and procedures

To ensure variable control, an experimental setup is devised where the rocket is exposed to light in a light-isolated box so that external light doesn't interfere with the experiment:

- The intervention box is a 47 cm x 34 cm x 27 cm transparent plastic box (32 L)
- The outside of the box is covered by blackout fabric
- The light source is a 12 W LED growth lamp (red:blue:white relation 9:2:1)
- The height from lamp to bottom of box is approximately 25 cm
- Light intensity is measured in lux with a Vernier light sensor at different distances and is converted to $\mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ with an online converter[24], since this convertion is not simple and varies depending on the type of light
- A thermometer is placed on the innermost edge in all intervention boxes to control temperature. It samples 6 times per hour.

In the experiments 54 rocket plants is germinated in 7-8 days under a growth lamp[25] (see figure 1).

Figure 1. Germination of the rocket sprouts[26]

Each pot has 3 plants and a 2 cm layer of moler for optimal drainage. After the germination, the 16 most uniform seedlings is chosen and these are used in the experiments. The rocket plants is exposed to different

[24] Link https://www.waveformlighting.com/horticulture/convert-lux-to-ppfd-online-calculator
[25] FLUORA fluorescent light 30 W, 1000 lm
[26] Own work

photoperiods with 4 plants in each intervention. Each intervention is exposed to a light intensity with a PPFD of $800\ \mu mol \cdot m^{-2} \cdot s^{-1}$ and is exposed to one photoperiod[27]. The photoperiod 16/8 is chosen as the control, since this is a commonly used photoperiod in the scientific literature. Every 2-4 day the plants are watered, the amount of water is noted, and pictures of each intervention is taken. The experiments run over approx. 35 days after which the height h (at the highest point), width w (at the widest and narrowest point), length l (at the widest and narrowest point), fresh weight m_f and dry weight m_d of the plants is measured. To measure the fresh mass the roots of the plants are cut off and the plants are measured on a scale (± 0.001 g). After this the plants are dried in a heating cabinet at 70°C for 72 hours, and afterwards the dry mass is measured.

Eventually the measured parameters for the plants is compared, the used energy E_{day} in kWh per day and the total used energy E_{total} (at each intervention) is calculated and the energy use efficiency n, measured in g fresh mass per kWh is calculated.

Results

4 experiment series, consisting of 14 experiments in total is conducted. In table 1 you can see the results of the experiments (where T_{photo} is the photoperiod). Experiment series 1 is not incorporated since the interventions in this experiment series where overwatered and thus crop failure occurred.

Exp. No.	T_{photo}	h / cm	m_f / g	m_d / g	l / cm	w / cm
2.1	0/24	0.0	0.000	0.000	0.0	0.0
2.2	1/23	0.5	0.001	0.000	0.1	0.1
2.3	4/20	6.0	0.372	0.019	4.6	3.0
2.4	16/8	10.7	3.914	0.414	9.0	5.8
3.1	7/12	9.5	2.468	0.220	8.3	7.1
3.2	12/12	8.1	3.120	0.514	8.6	6.0
3.3	2/1[28]	8.4	2.942	0.267	9.1	7.6
3.4	16/8	7.4	2.095	0.402	5.9	4.6
4.1	9/15	9.9	3.022	0.332	9.7	7.5
4.2	14/10	10.1	3.156	0.587	8.2	6.3
4.3	16/8	9.5	3.188	0.614	8.4	5.7
4.4	24/0	8.6	2.265	0.521	7.2	5.4

Table 1. Data from experiments (average values)[29]

To compare results between the experiment series, the relative fresh mass m_{frel} and the relative dry mass m_{trel} is calculated. This is done by the following formula

$$m_{rel} = \frac{m - m_c}{m_c}$$

[27] See table 1
[28] 6 cycles - total photoperiod $12\ h \cdot d^{-1}$ (alternating photoperiod)
[29] Made in Excel, own work

where m_{rel} is the relative fresh or dry mass, m is the dry or fresh mass of the intervention and m_c is the dry or fresh mass of the control in the experiment series (the photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$).

These calculated values are inserted in a graph, and the masses for the experiment series are compared. The graphs containing the relative fresh and dry mass can be seen in figure 2 and 3.

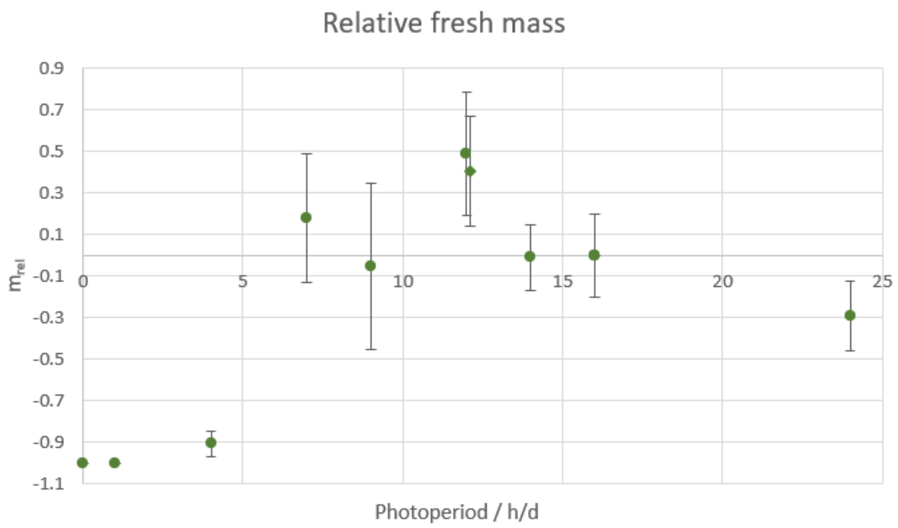

Figure 2. Graph containing the relative fresh mass as a function of photoperiod in hours per day (the diamond is the alternating photoperiod 2/1)[30,31]

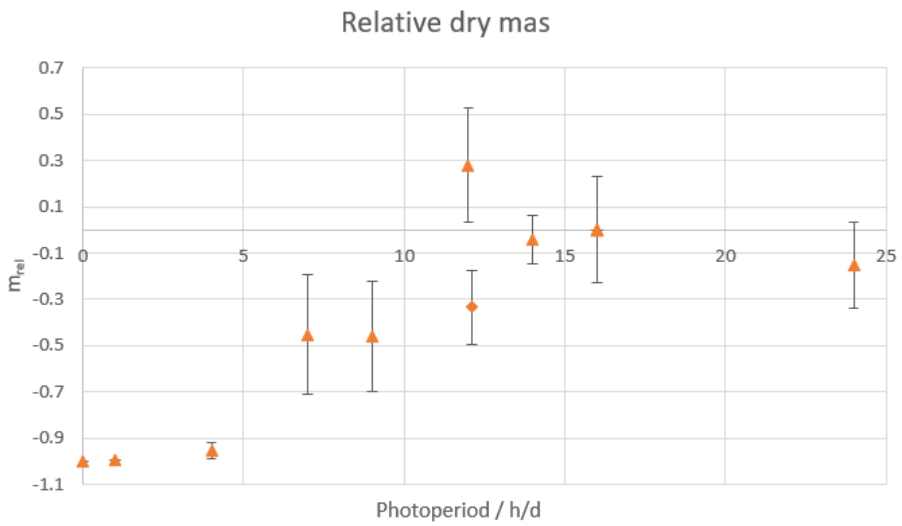

Figure 3. Graph containing the relative dry mass as a function of photoperiod in hours per day (the diamond is the alternating photoperiod 2/1)[32,33]

The intervention with the photoperiod 12/12 has the highest relative fresh and dry mass. Subsequently, the intervention 2/1 (photoperiod $12\ \mathrm{h} \cdot \mathrm{d}^{-1}$) has the next-highest relative fresh mass.

[30] Made in Excel, own work
[31] Error bars based on standard deviation - only mean values displayed in graph
[32] Made in Excel, own work
[33] Error bars based on standard deviation - only mean values displayed in graph

The energy consumption per day E_{day}, measured in $\mathrm{kWh} \cdot \mathrm{d}^{-1}$, the total energy consumption over the entire experiment E_{total}, measured in kWh and the energy use efficiency n, measured in $\mathrm{g} \cdot \mathrm{kWh}^{-1}$ is calculated.

E_{day} is calculated by the following formula

$$E_{day} = P \cdot T_{photo} \cdot 10^{-3}$$

where P is the wattage of the light bulb in W and T_{photo} is the fotoperiod in $\mathrm{h} \cdot \mathrm{d}^{-1}$. The factor 10^{-3} convert the unit of E_{day} to $\mathrm{kWh} \cdot \mathrm{d}^{-1}$.

E_{total} is calculated by the following formula

$$E_{total} = E_{day} \cdot \Delta t$$

where Δt is the number of days the experiment lasted, where the germination period is deducted.

n is calculated by the following formula

$$n = \frac{m_f}{E_{total}}$$

where m_f is the fresh plant mass in g.

To compare the energy use efficiency between interventions, the relative energy use efficiency n_{rel} is calculated by

$$n_{rel} = \frac{n - n_c}{n_c}$$

where n is the energy use efficiency for the intervention and n_c is the energy use efficiency for the control (photoperiod $16\ \mathrm{h} \cdot \mathrm{d}^{-1}$). The graph containing values of relative energy use efficiency can be seen in figure 4.

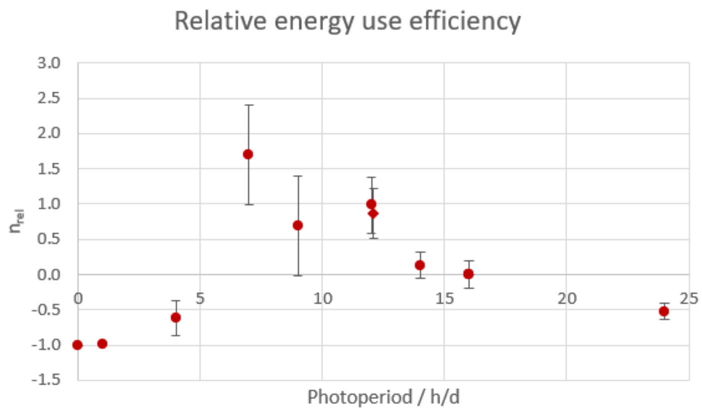

Figure 4. Graph containing the relative energy use efficiency as a function of photoperiod in hours per day (the diamond is the alternating photoperiod 2/1)[34,35]

[34] Made in Excel, own work
[35] Error bars based on standard deviation - only mean values displayed in graph

The graph shows that the intervention $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ has the highest relative energy use efficiency, compared to all inteventions. However, there is a statistical overlap with the energy use efficiency of the photoperiod $9\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and the photoperiod $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ which would be interesting to investigate further.

Discussion

A substancial point to discuss is whether the energy use efficiency n is directly proportional to the photoperiod (in number of hours light per day). The article Pennisi, et al. (2020) found that the smallest photoperiod they tested ($16\ \mathrm{h} \cdot \mathrm{d}^{-1}$ had the highest energy use efficiency. Therefore, you could discuss if the energy use efficiency of different photoperiods can reach a maximum and decrease afterwards, since the plant may not be able to absorb more light after a specific point. I found this in my results since the energy use efficiency was highest at $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and decreased with higher light intensity.

A parameter I haven't investigated is whether this change of photoperiod can change other factors e.g., taste, viability, the plant's resistance towards illness, etc. It is not known if the taste of the plant can change if the plant receives less light, since the light influences the growth which, in turn, can influence the intake of nutrients (that are important for taste). This is discussed further in *Contact to scientists*. Yan, et al. (2019) and Kang, et al. (2013) both found that the anthocyanin concentration in lettuce changed with DLI and Kang, et al. (2013) found a decreasing nitrate concentration and a rising vitamin C concentration when DLI was increased, which also underlines that the amount of light can change the nutritional content of lettuce. It is not investigated in this project if the viability of the plant could be influenced by less light; if the plant may be more susceptible to illness if it is exposed to an excessive amount of light, since it may be focusing all its energy on growth and photosynthesis.

Pennisi, et al. (2020) found that a change in DLI (and therefore also photoperiod) could influence different plant species in different ways. Even though they found that the dry mass of almost all plants they tested (basil, chicory, lettuce, and rocket) increased linearly with DLI, it was not the same linear relationship for all plant species. Thus, the optimal photoperiod for all plants isn't necessarily the same as the optimal photoperiod for a specific plant since different plant species have different light needs.

Another point valid to discuss is variable control in biological experiments with plants; it is very difficult to keep all variables constant because so many variables in play in these experiments are hard to control. For example, the temperature, air humidity and the CO_2-content in the air can all change during the day, which may influence the growth of the plants. Therefore, it is also a question how much variable control one can maintain, since many of these variables can only be controlled under very controlled conditions (e.g., in a growth chamber). This is why I only compare experiment series by their relative mass and energy use efficiency because the conditions for the different experiment series could be different since they were conducted at different times of year.

Contact to scientists

I have contacted several scientists to discuss specific questions I have encountered while conducting my literature review and my experiments: Bruce Bugbee, professor of Environmental Plant Physiology at Utah State University, Carl-Otto Ottosen, professor at Aarhus University at Department of Food Science, Dorthe Horn Larsen, research assistant at Copenhagen University at Department of Plant and Environmental Sciences, and Kasper Reitzel Jensen, associate professor at University of Southern Denmark at Department of Biology. Carl-Otto Ottosen, Dorthe Horn Larsen and Kasper Reitzel Jensen responded to my inquiries. Carl-Otto Ottosen sent two articles on the influence of light on the growth of rocket[36]. These are included in my literature review. I consulted Kasper Reitzel Jensen, and he provided me with general feedback on my project. Dorthe Horn Larsen invited me to a video conference where we discussed the questions, I sent her. She pointed out that the research in energy use efficiency and vertical farming is sparse, which is why my research is very relevant.

An important perspective we talked about was the influence of light on the taste of rocket. Since I use a high light intensity in my experiments, she mentioned that rocket could generate more secondary metabolites (e.g., anthocyanins and bitter substances). This could result in a stronger taste in the rocket. If rocket gets a low light intensity it will not form as much bitter substances, which will make it have a less strong taste.

Finally, we talked about light and how to apply optimal light to plants. Dorthe Horn Larsen said that some of her colleagues are investigating the use of fluctuating light - light that changes its intensity during the day or the production period. You could start with a low light intensity, where the plants are small and can't absorb as many photons and gradually turn up the intensity when the plants grow bigger and can absorb more light. We also talked about other characteristics of light one could optimise, e.g., the colour of the light (light quality), the light use efficiency and the usage of far-red light[37].
I have also contacted the Danish vertical farm Nordic Harvest. Nordic Harvest is one of the largest vertical farms in Europe. I asked them which light intensity and which photoperiod they expose their plants to and if they have tried to optimise different parameters in their vertical farm.

They replied that they expose their plants to different photoperiods depending on the plant species. Their photoperiods range from $12\ \mathrm{h} \cdot \mathrm{d}^{-1}$ to $18\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and they typically use a light intensity of $150\text{-}250\ \mu\mathrm{mol} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$. Furthermore, they try to optimise different parameters in their farm. Light wise they have tried to optimise light spectres (the colour of the light) and light intensity. They have also optimised on nutrients in the water, air velocity (the rate of circulation) and $\mathrm{CO_2}$-levels.

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[36] Proietti, et al. (2021) and Elmardy, et al. (2021)
[37] Light in the far end of the red spectrum

Energy saving

In this section a quantitative answer as to how much energy is saved by using the discovered energy use efficient photoperiods compared with data from (McDonald, 2022) is presented.

Firstly, the number of plants one lamp is irradiating is calculated by calculating the area one lamp can illuminate. It is stated by the manufacturer that the lamp can cover a circle with a radius of $r = 25\ \mathrm{cm}$ if it is placed in a height of $h = 50\ \mathrm{cm}$. Since we know the height h_l of the lamp in the experiments ($h_l = 25\ \mathrm{cm}$) the radius r_l is calculated by the following

$$\frac{h}{h_l} = \frac{r}{r_l}$$

⇕ *The equation is solved for r_l by WordMat.*

$$r_l = \frac{h_l \cdot r}{h} = \frac{0.25\ \mathrm{m} \cdot 0.25\ \mathrm{m}}{0.50\ \mathrm{m}} = 0.125\ \mathrm{cm}$$

The area the lamp illuminates A_l is calculated by the formula for the area of a circle

$$A_l = r_l^2 \cdot \pi = (0.125\ \mathrm{m})^2 \cdot \pi = 0.049\ \mathrm{m}$$

The number of plants the lamp is irradiating is calculated using data for the planting density of rocket ρ (the number of plants per m^2). The planting density for rocket plants is disclosed from the vertical farm Nordic Harvest to be 1400 plants per m^2. The lamp is therefore irradiating

$$n_{lamp} = \rho \cdot A = 0.049\ \mathrm{m}^2 \cdot 1400 \frac{\mathrm{plants}}{\mathrm{m}^2} = 68.6\ \mathrm{plants}$$

Next the calculated values for total amount of energy used in experiments E_{total} in kWh and values for the average fresh mass m_{favg} measured in kg is used.

The energy E measured in $\mathrm{kWh} \cdot \mathrm{kg}^{-1}$ is calculated by

$$E = \frac{E_{total}}{m_{favg} \cdot n_{lamp}}$$

(McDonald, 2022) states that vertical farms on average use $38.8\ \mathrm{kWh} \cdot \mathrm{kg}^{-1}$. In the report (McDonald, 2022) refers to it is reported that 55% of the energy use is light (on average)[38]. The average light energy use is therefore equivalent to $21.34\ \mathrm{kWh} \cdot \mathrm{kg}^{-1}$.

The energy saved in percent $E_{\%}$ for the photoperiod $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ is calculated by

$$E_{\%} = \frac{E_{avg} - \left(E + \left(E_{avg} - E_{lightavg}\right)\right)}{E_{avg}} \cdot 100\%$$

where E is the energy used, E_{avg} is the average energy used in vertical farms and $E_{lightavg}$ is the average light energy usage in vertical farms. It is calculated that the photoperiod $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ can save 10% energy per

[38] (WayBeyond & Agritecture, 2021)

kg of crops ($4\ \text{kWh}$). If this saving is implemented in the vertical farm Nordic Harvest, a saving of $4{,}000{,}000\ \text{kWh}$ a year could be reached since Nordic Harvest produces 1,000 tonnes of lettuce a year.

Sources of error

Sources of error in my experiments could be the fact that I didn't measure light intensity on all 4 LED-bulbs but only measured the light intensity of one bulb and presumed the same light intensity at the other bulbs. The amount of water given to the plants is not measured in the first two experiment series, which is also a source of error. The amount of water given to the interventions is different, since the amount of light has an influence on the amount of water the plants need. The height of the bulb (as related to the bottom of the box) is also a minor source of error because small differences between the intervention boxes could occur. Another small source of error is the nutrient concentration in the soil I used, since it may not be the exact same in each pot. Finally, a source of error could be small local temperature differences in the different intervention boxes. From experiment series 3 I measured the temperature in the different intervention boxes and saw a difference at up to $2\ ^{\circ}\text{C}$ between the boxes.

Perspective

The optimisation of the photoperiod in vertical farming can be used to reduce the energy consumption. This could save energy and in turn, money for the vertical farms. My project has also gained additionally relevance due to the increasing energy prices world-wide. Apart from the perspective of saving money, a reduction of the energy use will also make vertical farming more sustainable. Vertical farms, as mentioned earlier, use over 600% more energy per kg of crops produced than traditional greenhouses. A reduction of the energy consumption would therefore make vertical farming a more sustainable alternative to traditional greenhouses, so that we in the future can optimise use of space for producing crops and increase the amount of crops we produce per m^2. This could also reduce water consumption in agriculture and prevent nutrients from leaching into lakes and reservoirs and promote algae growth. It is worth noting that vertical farms cannot fully replace traditional agriculture, but vertical farming could reduce this massive water consumption of traditional agriculture by supplementing some of the high-water intake farms. This is due to the fact that vertical farms can recycle water.

The technology for finding the optimal photoperiod, most energy efficient for a specific plant is also usable to grow food for astronauts. NASA works on developing vertical farming technologies to grow crops in space so that astronauts can be self-sufficient with food[39]. Growing plants in space requires optimising all factors related to water usage, growth, and energy consumption. My project is therefore one perspective, out of many, on how to fine-tune and optimise vertical farming to grow food as effective as possible by using as few resources as possible.

In my project I have focused on optimising the photoperiod regarding energy use efficiency. As mentioned in the discussion, this change of photoperiod can have other consequences related to taste, nutritional

[39] (Pierce, 2021)

value, etc. It would therefore be interesting to investigate further whether these consequences occur if a change of photoperiod with gain for energy use efficiency is conducted.

Conclusion

Vertical farming is a way to increase the efficiency of farmland usage by growing plants vertically. This method of cultivation uses a lot less water than traditional greenhouses and produces a lot more crops per area, due to a more controlled growth where artificial lighting is used. However, vertical farms use over 600% more energy per kg of crops than traditional greenhouses, where 55% of this energy is due to the use of artificial light instead of natural sunlight. In this research project I have tried to optimise the energy use efficiency in plant growth using artificial light, by investigating which photoperiod is the most energy use efficient for the plant rocket (eruca sativa). This is conducted in a vertical farming perspective to save energy in vertical farms. I have conducted 4 experiment series consisting of 14 interventions in total, where the following photoperiods are investigated: 0/24, 1/23, 2/1 (6 cycles), 4/20, 7/17, 9/15, 12/12, 14/10, 16/8 (control) and 24/0.

All interventions where exposed to a light intensity with a PPFD of $800\ \mu\mathrm{mol} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-1}$. The intervention exposed to the photoperiod $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ had the highest energy use efficiency of all interventions. This can lead to an energy saving of 10 % with a planting density of 1400 plants per m^2 (compared to the average energy consumption of a vertical farm). There are indications that the energy use efficiency increases until a maximum point and thereafter decreases with longer photoperiods.

The primary focus of the scientific literature in this research field has been to optimise growth and yield for lettuce plants in a vertical farming perspective, regardless of energy consumption. Few scientists have done research into the energy use efficiency. Interesting results from scientists are that a long photoperiod does not necessarily bring a large yield. Scientific articles in my literature review have not investigated photoperiods under $10\ \mathrm{h} \cdot \mathrm{d}^{-1}$. I have complemented this lack in research by investigating photoperiods like $7\ \mathrm{h} \cdot \mathrm{d}^{-1}$ and $4\ \mathrm{h} \cdot \mathrm{d}^{-1}$.

Aside from the amount of light a plant receives per day, other parameters are important to ensure an efficient growth. The wavelength of the light has great importance since photons in the red wave spectrum is most efficient regarding photosynthesis. Furthermore, other parameters play a part like the $\mathrm{CO_2}$-concentration in the air, temperature, and nutrient concentration in the soil.

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