Eur. J. Hortic. Sci. *89*(5) | ISSN 1611-4426 print, 1611-4434 online | https://doi.org/10.17660/eJHS.2024/024 | © ISHS 2024

Original article – Thematic Issue

Light quality and intensity modulation on yield and quality on crops grown in vertical farms

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Summary

The yield and quality of crops in vertical farms are related to the quality and quantity of light. Light quality affects crop morphology and composition. The loss of specific spectral bands in certain crops can modify the normal growth of leaves, which can compromise the visual appearance of the produce. An increase in specific parts of the spectrum, such as UV-A, UV-B, or blue light, can induce the stimulation of secondary metabolism with an increase in phenolic compounds, anthocyanins, and carotenoids. The blue:red (B:R) ratio is also very important for plant growth and development. The B:R ratio also has an impact on energy consumption; usually, R is higher than B. Besides the quality, it is important that the intensity directly influences photosynthesis, biomass accumulation, and nutrient assimilation, such as nitrogen, which affects nitrate accumulation. The intensity of the blue and red bands influences crop performance. Specific light intensity modulation within the photoperiod can affect crop yield and energy-use efficiency. LED technology allows the supply of light intensity and quality based on crop requirements. Specific recipes can be provided for each crop. The possibility of light spectrum change can allow the accumulation of bioactive compounds in crops enhancing their nutritional quality.

Keywords
antioxidant, baby leaf, energy-use efficiency, indoor environment, leafy vegetables, photoperiod

Significance of this study

What is already known on this subject?

- The artificial lighting is important in protected cultivations and different type of lamps have been used to increase the light intensity in winter. The amount of light must be carefully considered in order to avoid an excessive production cost. In indoor cultivations such as vertical farming the artificial lighting is one of the major costs and LED technology is surely the strategy to reduce the cost of lighting.

What are the new findings?

- The LED lamps can be built on demand considering the crop light requirements. The LED lamps can vary the intensity and can provide different diodes which can emit in different regions of the spectrum, mainly blue and red with different ratios. The LED technology combined with management software can create a specific light recipe for each crop.

What is the expected impact on horticulture?

- The LED technology will increase the competitiveness of vertical farming, reducing the energy lighting costs and improving yield and quality. The different lighting recipes can provide produce with higher bioactive compounds, which can have beneficial effects on human health.

Introduction

Vertical farming (VF) is extremely promising because of its technologically advanced cultivation systems. VF offers multiple benefits, including efficient local production of food and reduction in the logistics of products between the production area and the market. The global market size of VF is expected to expand from 2023 to 2030 (Al-Kodmany, 2024). Market growth is attributed to the growing adoption of environmentally friendly methods for the production of fruits and vegetables. The unprecedented growth of the world's population has increased demand for urban agriculture. The demand for fresh products in the market follows an increase in urbanisation, which is growing. It is estimated that the world population will reach 8.5 billion people by 2030 and almost 10 billion by 2050 (Al-Kodmany, 2024). Population growth is concentrated in urban and peri-urban areas, and VF is a productive system that can directly play a role in the production of food in areas of high population density (Erekath et al., 2024). VF is a production system that can overcome the problems of urban soil and air pollution, making abandoned factories and unused urban spaces usable (Appolloni et al., 2021).

VFs can restore productive activity to non-productive land subject to desertification and convert deserts into productive areas. In Arab countries such as Oman and in the extreme northern European region such as Iceland, VFs provide a real opportunity for a constant supply of fresh products (Jonathan and Magd, 2024; Jónsdóttir and Benediktsson, 2024).

VFs are energy-intensive, and high-energy consumption is necessary for environmental control (temperature, relative humidity, light, and ventilation) and crop management. Energy is essential for artificial lighting, cooling, heating and ventilation. However, the energy efficiency of VFs can vary considerably, depending on the cultivation method and technology used.

The production activity of VF must be integrated with urban needs by sharing energy costs and reducing production costs. An example of a bioeconomy associated with VF is the use of carbon dioxide emitted by methane boilers for heating as carbon fertilisation for crops, which increases their production capacity. Some examples of VF in the U.S. are present in "Plant Chicago" (https://www.plantchicago.org/), where, in addition to producing food, energy is also produced, and waste is recycled. This project demonstrated the feasibility of VF in practice and paved the way for further developments in the field.

Another example is the "Growing Underground" project in London. Located in an old bomb shelter under London's streets, VF produces herbs and vegetables. This project demonstrated that VFs can be implemented even in limited urban spaces, thereby increasing the food resilience of cities.

Light intensity and quality play crucial roles in crop cultivation on vertical farms. The light intensity is directly related to photosynthesis. A higher light intensity, higher yield, and shorter growing cycles can be achieved. The annual yield production is directly related to light availability. This is the result of the use of the energy provided by artificial lighting. In vertical farming, light is a major production cost that must be carefully evaluated. The light or radiation spectrum that must be considered for photosynthesis ranges from 400 to 700 nm (Figure 1). However, within this range, crops have higher light absorption at specific peaks associated with the leaf pigments responsible for light harvesting (Moss and Loomis, 1952). The light-harvesting complex (LHC) in leaves refers to a network of proteins and pigments that captures and transfers light energy to the reaction centre of photosystems during photosynthesis (Iwai et al., 2024). The primary role of LHC is to efficiently absorb light energy and transfer it to the photosynthetic machinery, where it can be converted into chemical energy. The LHC is composed of various pigment-protein complexes called antenna complexes. These complexes contain chlorophyll and other accessory pigments such as carotenoids, which absorb light of different wavelengths. The pigments in LHC have unique absorption spectra, allowing them to capture light energy across a broad range of wavelengths. In vertical farming, the measurement of light absorption spectra is crucial for optimisation and increases the light use efficiency in crops. Light conditions in the cultivation environment can induce small changes in the light absorption spectrum (Loconsole et al., 2019). Therefore, lamps with spectrum emissions that overlap with light absorption molecules provide a higher light-use efficiency for cultivation.

Lamps and lighting energy requirements

Artificial lighting is necessary for plant growth; it can be performed using Light-Emitting Diodes (LED) lamps or High-Intensity Discharge (HID) lamps, which are commonly used for plant cultivation. HID lamps include metal halides (MD) and high-pressure sodium (HPS) lamps. There are several differences between these lamps that must be evaluated for their applications (Rea et al., 2009).

Light spectrum

LED lamps provide a highly specific light spectrum that can be tailored to the needs of plants at different growth stages. They can emit narrow wavelengths of light in the red and blue spectra, which are crucial for photosynthesis and the different stages of plant growth. However, based on plant needs, emission can be improved by adding additional diodes such as UVA, green, or far-red (Figure 2). Some LEDs can modify emission within a specific range, and the intensity can be modified during cultivation. HID lamps have a broader spectrum that includes more yellow and green lights, which is less efficient for photosynthesis (Cocetta et al., 2023). The spectrum emission is fixed and cannot be modified and depends on the construction materials and gas composition inside the lamp bulbs (Giese et al., 2002).

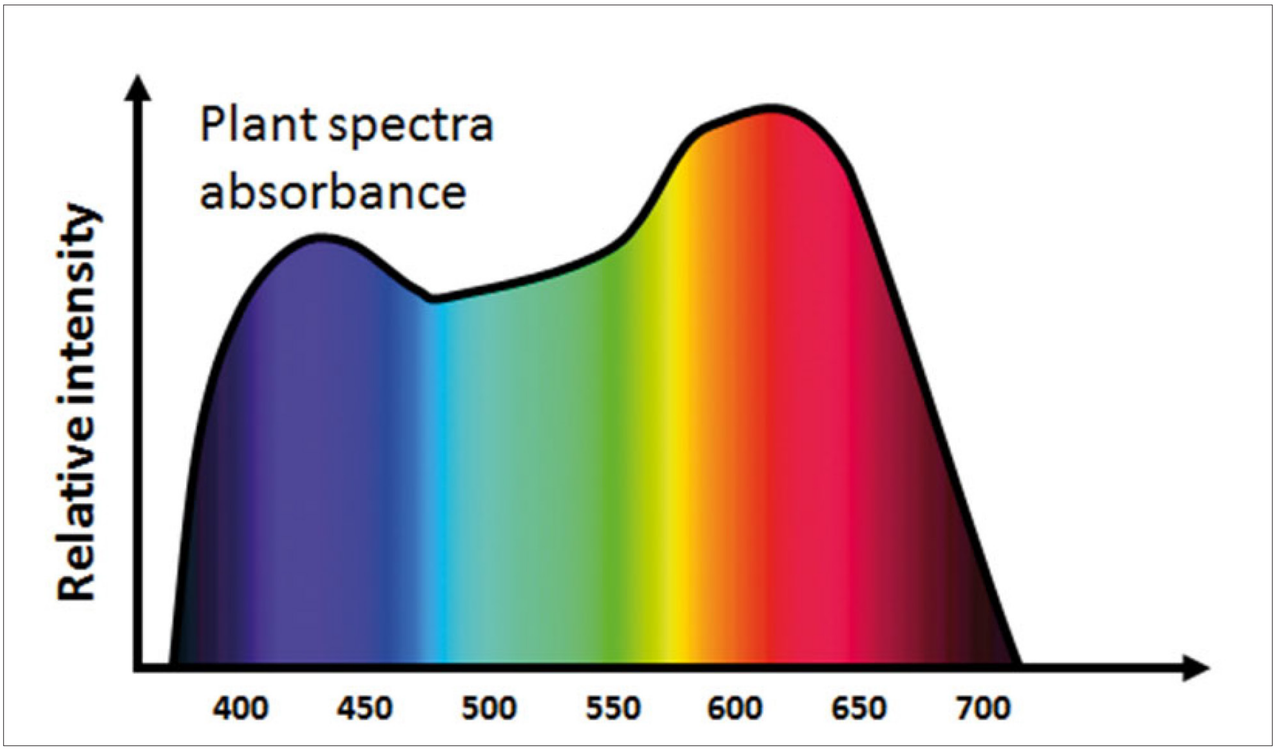

Figure 1. Photosynthetically active radiation from to 400–700 nm, with peaks in blue and red. The absorption spectrum varies among plant species (Cocetta et al., 2017).

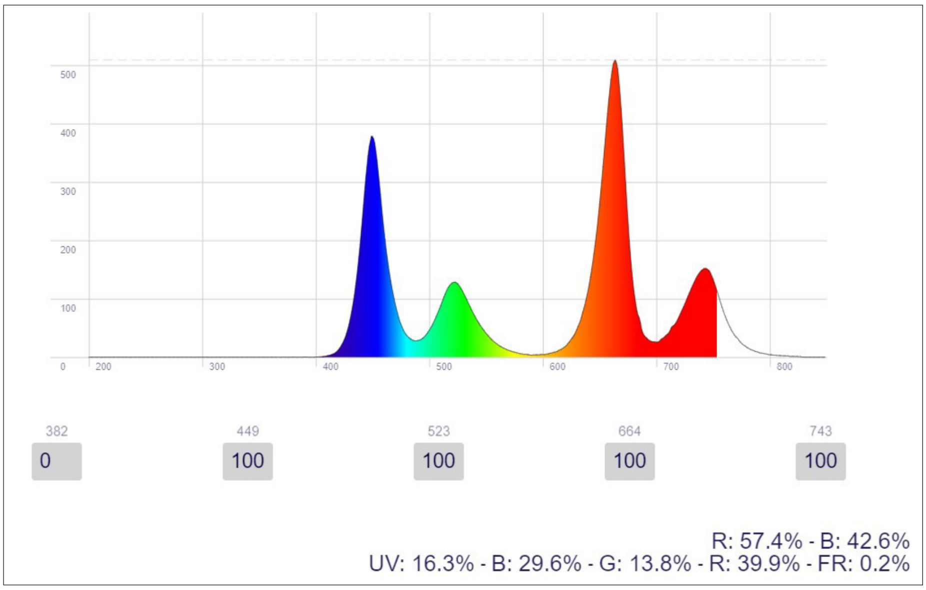

FIGURE 2. Example of LED lamp light spectrum in the blue (449 nm), green (523 nm), red (664 nm), and far red (743 nm) regions.

Energy efficiency

LED lamps are more energy efficient than MD or HPS lamps. LEDs convert a higher percentage of the energy they consume into usable light for plants, whereas HID lamps produce a significant amount of heat, which is wasted energy. It has been calculated that LED can provide photons of photosynthetically active radiation (PAR) per joule of input by 2.5–3 µmol J^{-1} (Katzin et al., 2020), while HPS reaches values of 1.7–1.8 (Nelson and Bugbee, 2014). This efficiency advantage of LED lamps translates to lower electricity costs and reduced heat output in the growing environment.

Heat release

HID lamps generate a substantial amount of heat compared with LED (Katzin et al., 2020). HPS lamps during operation can reach 200°C with high infrared release that generates heat (Sena et al., 2024). This heat release can lead to an increase in temperature in the growing area. At crop level this higher temperature can affect photosynthesis and respiration in crops, with direct effect on growth. This can be a problem, particularly in VF, for uniform crop growth and delay of the harvesting time. The excess of heat can negatively impact plant growth, and a cooling system is required. In contrast, LED lamps produce significantly less heat, reducing the risk of high-temperature damage to crops and enabling growers to more easily maintain optimal temperature conditions.

Lifespan, maintenance, size, and design

LED lamps generally have longer lifespans than HPS lamps do. While HID lamps typically last approximately 10,000 h, LED lamps can last up to 50,000 h or even more (Singh et al., 2015). This extended lifespan reduces the frequency of lamp replacement and lowers the maintenance costs for growers (George Allwyn et al., 2021). LED lamps are typically lighter and more compact than HID lamps, allowing for greater flexibility in their placement and installation. This compact design also makes LED lamps more suitable for indoor or vertical farming systems where space is often limited. Moreover, the LEDs can be placed close to plants because of the lower heat release from the lamp. Therefore, LED lamps can be used in VF on the shelf and close to crop's canopy. (Tennessen et al., 1994).

Light intensity and coverage

HID lamps have traditionally been favoured because of their high light intensity and wide coverage area, making them suitable for large-scale commercial operations. However, advancements in LED technology have significantly increased the light intensity of LED lamps, allowing them to compete with HID lamps in terms of coverage and intensity, while maintaining their energy efficiency advantages.

Controllability

LED lamps offer greater control over the light spectrum, allowing growers to adjust lighting conditions to match the specific needs of different plant species and growth stages. This level of control is particularly beneficial for optimising plant growth, increasing yield, and influencing specific plant characteristics. The increase of light quality can be achieved by adding additional diodes with emission in the specific wavelength.

The selection of LED or HPS lamps depends on various factors, including the specific requirements of the plant species being cultivated, available budget, size of the cultivation area, and grower's goals and preferences. Many growers now opt for LED lamps because of their energy efficiency, customisable spectrum, and longer lifespan; however, HID lamps still have their place in certain cultivation scenarios. LED lamps compared with HID lamps can be used also for controlling the growth of crops by increasing the blue light intensity compared to the red (Islam et al., 2012).

In VF, LED lamps are the most used because they are more energy efficient. The use of LED lamps coupled with intelligent lighting management can help reduce the overall VF energy consumption. In the future, artificial intelligence applied to energy management can significantly limit consumption through a digital dialogue between crop needs and energy costs. The implementation of advanced energy control systems and adequate thermal insulation are current research topics that can contribute to lowering the energy costs in VF, and to these are added renewable energy sources which also contribute to reducing the environmental impact.

The cost of lighting in vertical farms can vary depending on several factors, including the type of lighting technology used, size of the farm, and specific requirements of the crops being grown.

The most used lamps in vertical farms are LED because of their energy efficiency and ability to provide specific light spectra tailored to plant growth. The initial investment in LED lighting systems can be higher than that of traditional lighting technologies, but they offer long-term benefits, such as reduced energy consumption and a longer lifespan.

The cost of installing LED lighting, on a vertical farm, ranges from 161 to 270 \$ m^{-2} in the growing area (Zhen et al., 2020a). Another study estimated the cost of LED lighting for vertical farms to be around 27–54 \$ m^{-2} per year, including both capital and operating expenses. This means that the annual energy cost of LED lighting in a vertical farm is approximately 5.4–10.8 \$ m^{-2} (Hoque Klemeš, 2017).

Traditional High-Intensity Discharge (HID) lighting is less used than LEDs, which are becoming more popular, some vertical farms still use traditional lighting technologies such as high-pressure sodium (HPS) or metal halide (MH) lamps. These lamps have a lower upfront cost but are less energy efficient than LEDs.

According to a report published by Agritecture Consulting, the cost of traditional HID lighting for vertical farms can range from 65 to 270 \$ m^{-2} of growing area for initial installation and around 16.1 to 38 \$ m^{-2} per year for electricity consumption (https://www.agritecture.com/).

Operating costs are also important for artificial lighting. In fact, besides the initial installation cost, the operating costs for lighting in VF include electricity consumption, maintenance, and replacement of bulbs or LED modules. Energy costs vary depending on the local electricity rates and the duration and intensity of the light required by crops.

Shifting the electricity demand in indoor vertical farms with artificial lighting can potentially lead to energy cost reductions. By optimising the timing of electricity usage, farms can take advantage of variations in electricity pricing throughout the day and reduce peak demand charges. Time-of-use (TOU) pricing: many electricity providers offer TOU pricing plans, where the cost of electricity varies based on the time of the day. By shifting the electricity demand to off-peak hours, when electricity rates are lower, vertical farms can reduce energy costs. This can be achieved by running the lighting system during off-peak periods and accordingly adjusting the crop lighting schedule. A study performed on basil grown on vertical farms demonstrated potential cost savings from demand shifting. Research showed that by aligning lighting demand with off-peak periods, energy cost reductions of up to 34% were achievable (Zhen et al., 2020b). One study focused on the modelling of a vertical farm's energy system with the aim of managing and reducing electricity costs. This study was conducted using lettuce, wheat, and soybean crops with different electricity price profiles. The results showed a reduction of 5–30% in electricity consumption costs (Arabzadeh et al., 2023).

Crop species and light requirements

Vegetables

The species grown in vertical hydroponic systems in the VF are generally leafy vegetables, such as salads (lettuce, spinach, lamb's lettuce, rocket), aromatic herbs (basil, parsley, thyme, and rosemary), and microgreens (newly germinated seedlings with the appearance of the first leaves true). All these species were characterised by reduced development in terms of aerial and root biomass. Fruit species, such as tomatoes and peppers, must have reduced development to improve the efficiency of use of the volume and surface area. The technological evolution of VF and plant genetic improvement work to find a meeting point to maximise crop productivity. Plant genetic improvements aim to produce ideotypes with reduced development and high productivity. Examples of tomatoes that can be grown under VF are cherry tomatoes and Micro-Tom which have reduced development (Richardson and Arlotta, 2022). Experimentally, several crosses have been made between Micro-Toms and cherry tomatoes to produce compact tomatoes that are promising for use in VF (Rajendran et al., 2022).

The total energy required for lettuce is estimated to vary from 185 to 770 kWh kg^{-1} dry weight. It depends on the number of moles of photons per joule of electrical power (photosynthetic active radiation efficiency) and the geographical area. The artificial lighting for growing lettuce in vertical farms usually ranges from 100 to 150 µmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD), with a photoperiod of 18 h, resulting in a daily light integral (DLI) of 6.48–9.72 mol m^{-2} d^{-1} (Arabzadeh et al., 2023). In Romaine lettuce, cultivation in vertical farms has been carried out with a light intensity ranging from 166/63 (h by h alternation) to 196 µmol m^{-2} s^{-1} with a photoperiod of 16–18 h. The energy demand was lower in the 166/63 µmol m^{-2} s^{-1} treatment without a significant yield reduction and an energy consumption of 36 kWh kg^{-1} fresh weight corresponding to 400 kWh kg^{-1} dry weight (Loconsole et al., 2019).

A similar amount of light is required for fruit vegetables, such as sweet pepper that requires 12–15 mol m^{-2} d^{-1} for the growing cycle. The suggested photoperiod for lettuce is over 16 h and can even be 24 h. Lettuce does not show negative symptoms of continuous light, but an economic evaluation is needed considering the costs. Different blue:red ratios were tested for lettuce cultivation, and an RB ratio of 1:3 with 215 µmol m^{-2} s^{-1} PPFD and a photoperiod of 16 h provided the highest yield (Pennisi et al., 2019). Tomatoes instead require a higher light amount with a DLI higher than 30 mol m^{-2} d^{-1}.

In leafy vegetables, higher light intensity and photosynthesis increase nitrate assimilation, avoiding leaf nitrate accumulation, which is an important quality parameter (Loconsole et al., 2019). In VF the combination of optimised light intensity and closed loop soilless cultivation can allow the management of nutrient solutions avoiding the leaf nitrate accumulation (Guffanti et al., 2022).

Unfortunately, the plant growth and biomass of fruit vegetables limit cultivation in VF, and appropriate breeding programs should be planned to develop crop ideotypes for indoor cultivation.

The yield of vegetables in VF is directly proportional to

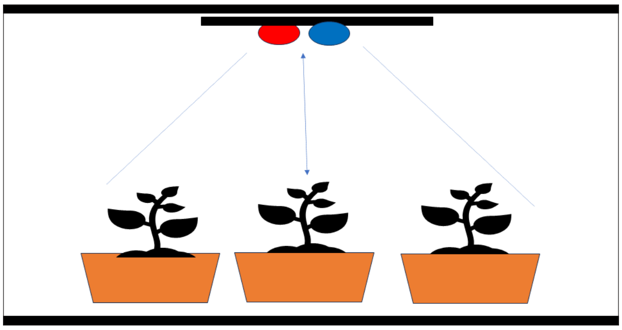

Figure 3. Lamps must be positioned at an adequate distance from the canopy to allow for the best uniformity and light distribution. Moreover, lamp distance affects the amount of light received from the canopy.

Table 1. Crop light requirements for cultivation on vertical farms.

Species	Light intensity ($\mu mol\ m^{-2}\ s^{-1}$)	Daily light integral ($mol\ m^{-2}\ d^{-1}$)	References
Lettuce	150	9.7	Arabzadeh et al., 2023
Basil (*Ocimum basilicum* L.)	200–228	11.5	Avgoustaki et al., 2021
Rape (*Brassica napus* L.) seedlings	200–400	12 h of light	Yao et al., 2017
Lettuce (*Lactuca sativa* L. 'Tiberius')	200	16 h of light	Zou et al., 2019
Basil (*Ocimum basilicum* L.) Lettuce (*Lactuca sativa* L.)	100, 150, 200, 250 and 300	5.8, 8.6, 11.5, 14.4 and 17.3	Pennisi et al., 2020
Basil (*Ocimum basilicum* L.)	–	7.5 and 15.0	Ciriello et al., 2023
Sage (*Salvia miltiorrhiza* Bunge)	300	16 h of light	Zhang et al., 2020
Cannabis (*Cannabis sativa* L.)	135–1,430	7.8–82.4	Moher et al 2022
Chinese spinach or red amaranth (*Amaranthus tricolor* L.)	From 250 to 2,500	From 2 to 35	Song et al., 2018
Chinese flowering cabbage (*Brassica rapa* L. subsp. *chinensis* (L.) Hanelt var. *parachinensis* (L.H. Bailey) Hanelt) Chinese cabbage (*Brassica rapa* L. subsp. *pekinensis* (Lour.) Hanelt) Chinese kale (*Brassica oleracea* L. var. *alboglabra* (L. H. Bailey) Musil Water spinach/convolvulus (*Ipomoea aquatica* Forssk.) Lettuce (*Lactuca sativa* L.) Chinese chard (*Brassica rapa* L. subsp. *chinensis* (L.) Hanelt)		Optimal values 33.95 ± 8.43 24.51 ± 3.33 17.35 ± 2.57 47.22 ± 3.48 19.90 ± 4.37 14.51 ± 4.16 39.96 ± 13.15	
Lettuce (*Lactuca sativa* L. 'Rebelina') Chicory, (*Cichorium intybus* L. 'Bionda a foglie larghe') Basil (*Ocimum basilicum* 'Superbo') Rocket (*Eruca sativa* 'Coltivata')	14	16 h of light	Pennisi et al., 2020
Strawberry (*Fragaria* × *ananassa* Duch. 'Benihoppe') rooting stage	90	16 h d^{-1}	Zheng et al., 2019
Potato (*Solanum tuberosum* L. 'Innovator')	220–300	14 h d^{-1}	Kamenchuk et al., 2023
Spinacia oleracea L., *Ocimum basilicum* L., *Beta vulgaris* L., *Lactuca sativa* L. 'Garrison' and 'Blade', *Brassica rapa* 'Japonica' and 'Chinensis', *Brassica juncea* 'Scarlet Frills' and 'Wasabina', *Eruca sativa* *Perilla frutescens* L.	261 256 (5 h) + 20 (1 h)	20 h d^{-1} 24 h d^{-1} (better results)	Boucher et al., 2023
Barley (*Hordeum vulgare* L. 'Lord')	40, 100, 160 and 220	20 h d^{-1}	Yeşil et al., 2020
Lettuce (*Lactuca sativa* L. 'Little Gem')	Between 134 and 491 Between 340 and 570	16 h d^{-1}	Touliatos et al., 2016
Lettuce (*Lactuca sativa* L. 'Klee')	237 (differenti lunghezze d'onda)	16 h d^{-1}	Chen et al., 2019
Lettuce (*Lactuca sativa* L.) 'Blackhawk'	130–389	16 h d^{-1}	Modarelli et al., 2022
Beet (*Beta vulgaris* L. ssp. *vulgaris*)	120–160–220	12 and 16 h d^{-1}	Hernández-Adasme et al., 2023
Spinach (*Spinacia oleracea* L.) 'Zhirnolistny'	120–180	12 h d^{-1}	Semenova et al., 2023
Mizuna (*Brassica rapa* var. *japonica*) and lettuce (*Lactuca sativa* 'Green Salad Bowl').	50–425	16 h d^{-1}	Jayalath and Van Iersel, 2021
Lemna minor and *Wolffiella hyalina*	50, 100 and 150	12 h d^{-1}	Petersen et al., 2022
Lettuce (*Lactuca sativa* L., 'Crunchy' and 'Deangelia') Spinach (*Spinacia oleracea* L., 'Shawen')	120, 180, 240, and 300	16 h d^{-1}	Miao et al., 2023
Kale microgreens (*Brassica oleracea* var. *acephala* L., 'Kapral' and 'Scarlet')	230	13.2	Frąszczak et al., 2023
Cherry radish (*Raphanus sativus* L., 'Changfeng')	180, 240, 300	12 and 16 h d^{-1}	Zha and Liu, 2018
Ginseng (*Panax ginseng* C.A. Meyer)	30, 130, 230, 220, 370	14 h d^{-1}	Kawakatsu and Fukuda, 2023
Lettuce (*Lactuca sativa* L., 'Rebelina')	215±5	16 h d^{-1}	Pennisi et al., 2019
Iceberg lettuce (*Lactuca sativa* L., 'Glendana'	200	12 h, 16 h, and 20 h d^{-1} (DLI) 8.64, 11.5, and 14.4	Gavhane et al., 2023
Lettuce (*Lactuca sativa* L. var. *longifolia*)	from 63.2 to 194.54	14, 16 h d^{-1}	Loconsole et al., 2019

the amount of light supplied (Table 1; Figure 3). Therefore, higher intensity corresponds to faster crop growth and the yield of production is determined by the number of growing cycles that can be achieved in a year.

Light quality on plant growth

The quality of light is distributed in the spectrum of different wavelengths, which have varying effects on various plant processes, including photosynthesis, photomorphogenesis, and flowering. The energy carried out by wavelengths and short wavelengths is high, whereas high wavelengths are low. This means that a wavelength of 400 nm carries almost double the energy compared with a wavelength of 700 nm. The light absorbed for photosynthesis must be distributed between 400–700 nm. Other regions of PAR can induce specific responses and improve the quality of crops.

Plants can perceive light changes in the growing environment using photoreceptors such as phototropins and cryptochromes, which absorb UV-A or blue light, phytochromes, which sense red/far-red light, UV-B, and UV RESISTANCE LOCUS 8 (UVR8).

The absence of bands in the light spectrum can modify plant growth, quality, and yield. Blue Light (440–490 nm) alone induced compact, hardened, and dark-coloured plants. It can also induce biosynthesis of phytonutrients. Red light (620–760 nm) causes soft plants with elongated internodes to develop in height. This shading avoidance response is mediated by phytochrome B. Short infrared (short IR, 760–1,000 nm) causes deep green, well-branched dwarf plants. Blue and short-infrared light can be used as alternative nonchemical agents for plant height control. Long Infrared (long IR, 2,000–26,000 nm) increases the length of internodes and leaf sizes, reduces branching, and reduces the colour of flowers and leaves.

An increase in specific bands can increase the accumulation of some metabolites that can have positive effects on human health (Trivellini et al., 2023).

Light quality influences flower induction and hormonal balance in photoperiodic plants. Red and blue wavelengths promote photosynthesis, increasing stomatal opening, electron transport, and Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo, EC 4.1.1.39) activity. Blue light stimulates the antioxidant response more than red light, increasing the synthesis of polyphenols, ascorbic acid, carotenoids, and anthocyanins, which also influences the colour of leaves and flowers. In lettuce, red light induced antioxidant accumulation after four days of application, while yellow light increased the antioxidant response after six days (Arriaga et al., 2020).

The blue:red ratio can affect different aspects of plant growth and development, starting with seed germination (Kim et al., 2022). Blue and red wavelengths are the most used in difference percentage because the emissions are closer to chlorophyll *a* and *b* absorption peaks, which significantly contribute to photosynthesis (Appolloni et al., 2021; Carotti et al., 2023).

In VF, it is important to control the light distribution and uniformity of a crop that has the same height and can be harvested at the same developmental stage (Figure 3). The highest VF yield can be achieved by increasing the number of growing cycles. Light positioning must be evaluated, and mobile systems should be preferred to modify the distance from the canopy during crop growth (Cocetta et al., 2017). Light direction can affect normal growth and distortion of stems in response to gravitropism.

Conclusion

Artificial lighting supply and management in VF are extremely important and must be carefully evaluated in terms of lamp type, light quality, intensity, and photoperiod. VF can be strategically used in urban areas to provide fresh, harvested, and high-quality vegetables. Modification of light quality can be a tool for producing leafy vegetables with a high accumulation of functional metabolites, especially antioxidants, which can have beneficial effects on human health.

Conflict of interest

The authors have no conflicts of interest to declare.

Ethics statement

Not applicable.

Author's contributions

A.F.: conceptualization, writing; S.T.: writing; D.R.: writing and revision of final draft.

Funding statement

No funding to report.

Data availability

Not applicable.

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Received: Jan. 16, 2024
Accepted: Oct. 17, 2024

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Editorial

Vertical farms (VFs, also called Plant Factories with Artificial Lighting, PFALs) are an advanced crop production technology that allows to maximize resource-use efficiency and address food security challenges in a climate changing world, while also enabling cultivation within dense urban settings or extreme and remote environments. VF systems operate in controlled conditions, allowing for the precise regulation of all environmental factors (e.g., light, temperature, humidity, and CO_2). This results in higher yields, reduced water and mineral nutrient requirements, constant year-round production, and minimal transport-related food losses and impacts. Key technologies include LED lighting, which enhances energy efficiency while allowing to target crop-specific light needs, and recirculating irrigation and dehumidification systems that optimize nutrient and water use. Innovations such as dynamic lighting and aeroponics further improve sustainability by reducing energy consumption and environmental impact. Vertical farms also offer resilience against extreme weather and pandemics, ensuring a reliable food supply. Conversely, and despite these benefits, VFs face challenges that include high energy demands, significant initial investment, and reliance on both skilled workforce and logistical infrastructures. Solutions include integrating vertical farms with urban energy systems to reuse heat, explore renewable energy options, optimizing operational parameters with AI, and developing crop varieties tailored to controlled environments. While consumers increasingly require for fresh and sustainable products, innovative business models are also explored, as for the case of localized modular systems. Besides, as social and educational initiatives are essential for advancing uptake of VFs, training programs and participatory projects highlight the potential for improving stakeholder engagement and skills development. Moving forward, enhancing VF sustainability requires for strategies that consider the local economic, social, and environmental implications. Vertical farming holds promise for transforming agriculture, but its widespread implementation relies on technological advancements, innovative business models, and addressing geographical disparities in resource availability. This article belongs to a collection that builds on selected themes explored along the Third International Workshop on Vertical Farming (VertiFarm2024), held in Bologna (Italy) in January 2024 and attended by more than 200 delegates from 31 countries.

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Funding statement

The editorial work that lead to this publication received funding from has the Italian Ministry of Education and Research (MUR), within the call for Research Projects of National Interest (PRIN), within the project “VFARM – Sustainable Vertical Farming” (Project code: 2020ELWM82, CUP:J33C20002350001).

Acknowledgments
We wish to express gratitude to sponsors and partners that have supported the organization of VertiFarm2024.

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