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Light use efficiency of lettuce cultivation in vertical farms compared with greenhouse and field

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Abstract

Vertical farming is a relatively new fresh fruit and vegetable production system, where lamps (mostly light emitting diodes [LED]) are the sole light source. A high light use efficiency (LUE_{inc}), defined as shoot dry weight per incident photosynthetic photon flux density (PPFD; $g\,mol^{-1}$) integral, is crucial for the economic viability of vertical farming. Very different values for LUE_{inc} have been reported in the literature and it is not clear whether LUE_{inc} is higher in vertical farming than in greenhouse or open field cultivation. Values of LUE_{inc} of lettuce grown in a vertical farm (53 studies), greenhouse (13 studies) and open field (8 studies) were collected from literature, as well as relevant cultivation aspects such as lettuce weight at harvest, cultivation period (plant age at harvest), daily light integral, cumulative daily light integral for the whole cultivation period, planting density and CO_2 concentration. The average LUE_{inc} for lettuce grown in a vertical farm was 0.55 $g\,mol^{-1}$ which was higher than 0.39 $g\,mol^{-1}$ for greenhouse-grown lettuce. Both were substantially higher than for field-grown lettuce (0.23 $g\,mol^{-1}$). The maximum measured LUE_{inc} for lettuce grown in a vertical farm (1.63 $g\,mol^{-1}$) is close to the published maximum theoretical value, which ranges from 1.26 to 1.81 $g\,mol^{-1}$. Since all environmental factors can be fully controlled, vertical farming has the capability to achieve the theoretical maximum LUE_{inc}. Using the highest reported LUE_{inc} based on shoot fresh weight (44 $g\,mol^{-1}$ at 200 $\mu mol\,m^{-2}\,s^{-1}$ PPFD and 16 h photoperiod), it is estimated that each layer of a vertical farm can potentially produce annually up to 700 kg of lettuce per m^2 at 500 $\mu mol\,m^{-2}\,s^{-1}$ of continuous light.

KEYWORDS

indoor farming, light use efficiency, plant factory, potential production, vertical farming

1 | INTRODUCTION

Vertical farming, where plants are grown in stacked layers and lamps are the sole light source, is a production system considered as a solution for water and land scarcity, as well as a system to reduce transport distance, especially for fresh fruit and vegetables (SharathKumar et al., 2020; van Delden et al., 2021). However, compared with conventional production of fresh fruit and vegetables in open field and greenhouses, vertical farming's energy consumption is substantially higher, mainly because of electricity use for lighting (Kozai, 2013). Hence, increasing the light use efficiency (LUE) is urgently needed to improve the economic feasibility of vertical farming.

Light use efficiency can be defined in different ways. For analyzing the economics or sustainability of commercial production, the marketable crop fresh weight per unit of electricity used is important. Therefore, several studies define LUE as gram of marketable fresh weight per joule electricity consumed by the lighting system (Kozai, 2013). There are many aspects affecting this efficiency, including the efficacy of the lamps (photons emitted by the lamp per Joule electricity), which is not relevant for understanding the effect of environmental factors on LUE. For that purpose LUE is often based on photosynthetically active radiation (PAR, 400–700 nm), commonly indicated as photosynthetic photon flux density (PPFD), or it can be based on a wider range of photons (300–800 or 400–800 nm), which can be indicated as photon flux density (PFD). In physiological research, LUE is often calculated as crop dry weight per intercepted (LUE_{int}) or incident photosynthetic photons (LUE_{inc}), the latter representing the efficiency of the whole process from photon capture to biomass accumulation.

Crop growth in vertical farms results from photosynthetic photons emitted from the light source and absorbed by the leaves. The fraction of emitted photons captured by a leaf depends on the leaf area, leaf optical properties and leaf orientation. Captured photons result in photosynthetic assimilate production (carbohydrates). These assimilates are partitioned to different crop organs, such as roots, stem, leaves and fruits. The efficiency of all these processes and therefore also LUE is affected by crop management and environmental factors, such as planting density, light intensity and spectrum, photoperiod, temperature, air humidity, carbon dioxide (CO_2) concentration, air movement and water and nutrient availability.

When crops are grown in the field there are limited opportunities to increase LUE compared with crops grown in vertical farms or greenhouses as there are limited measures that can be applied to the canopy environment such as controlling light, temperature or CO_2. Nevertheless, growers can still affect the LUE by crop management practices such as planting density and harvest time. In greenhouses, the environmental factors can be controlled within a certain level and the light intensity is determined completely or partly by the natural light. In a vertical farm environmental factors can be fully controlled. Here, light is normally the only limiting factor as other resources can be supplied at relatively low cost. Therefore, LUE is expected to be closer to its potential value in a vertical farm compared with greenhouse or field cultivation. The potential LUE based on incident PPFD (gram of plant dry mass per incident mole of photosynthetic photons) has been discussed and calculated in several publications (Bugbee & Salisbury, 1988; Kozai, 2013; Loomis & Williams, 1963; Pattison et al., 2018; Zhu et al., 2010). An optimal environment for the crop, although not specifically defined, is assumed in these calculations for example an elevated CO_2 concentration. Therefore, vertical farming is expected to realize a LUE closest to the potential LUE.

The aim of this study was to quantify LUE based on incident light of lettuce grown in a vertical farm where lamps are the sole light source and compare it with LUE of lettuce grown in greenhouse, or open field, based on data in scientific literature. Furthermore, we aim to analyze the relative importance of several factors determining LUE in vertical farming. We hypothesize that vertical farming's LUE based on incident light is higher than that for greenhouse or field cultivation as the environment is well-controlled, and light is the only limiting environmental factor.

2 | MATERIALS AND METHODS

2.1 | Data acquisition, extraction, and processing

Light use efficiency (LUE_{inc}) in this paper is defined as the shoot dry weight (SDW; $g\,m^{-2}$) divided by cumulative incident PPFD (Cumulative Daily Light Integral, DLI_{cum}; mol m^{-2}). Shoot dry weight is the weight at harvest, and cumulative incident PPFD is calculated from transplanting to harvesting. Publications reporting LUE or with sufficient data available to calculate LUE for lettuce grown in vertical farming, greenhouse, or open field were collected. Peer-reviewed publications were searched in SCOPUS (https://scopus.com/). The keywords applied included lettuce, LUE, radiation, light intensity, PPFD, vertical farming, greenhouse, field, and open field (Supplementary S1 in Appendix S1). Furthermore, data from one PhD thesis were used (Both, 1995).

In addition to SDW, shoot fresh weight (SFW) and total dry weight (TDW) were also collected or calculated from the studies. When only dry weight was given, fresh weight was calculated assuming a dry matter content and vice versa (Table 1). When only total plant dry weight was reported SDW was calculated based on fixed fraction of shoot and vice versa (Table 1). In studies where plant dry and fresh weight, including SDW, SFW, and/or TDW, were reported per plant, it was multiplied by the planting density to obtain values per square meter of cultivation surface.

There are a few other variables related to the calculation of DLI_{cum}. DLI_{cum} is the product of daily light integral (DLI) and the duration in days of the experiment

TABLE 1 Assumptions made for the calculations when data on shoot dry weight, shoot fresh weight, or solar light inside greenhouse were not reported in the study. When only data on dry weight were given, fresh weight was calculated assuming a dry matter content of 0.04 and vice versa. When only total plant dry weight was reported shoot dry weight was calculated based on fraction shoot of 0.8 and vice versa. When only radiation outside but not inside the greenhouse was reported, a greenhouse transmissivity of 0.62 was assumed. For solar light, a conversion factor of 4.6 Mol per MJ was applied when solar light data were provided in MJ

Parameter	Value	References
Dry matter content (ratio dry to fresh weight)	0.04	Gent (2014), Carotti et al. (2021)
Fraction of biomass partitioned to shoot	0.85	De Pinheiro Henriques (2000)
Greenhouse transmissivity (glass)	0.62	Heuvelink et al. (1995)
Conversion factor for solar light ($mol\,MJ^{-1}$)	4.6	Sager and McFarlane (1997)

TABLE 2 Theoretical LUE (g DW per incident mole of photosynthetic photons) reported in publications. Fa (dimensionless) is the fraction of incident photons absorbed by the crop, QY is the quantum yield (mole of carbon fixed per mole of photon absorbed), CUE is the carbon use efficiency (moles of carbon incorporated into plant biomass per mole of carbon fixed), HI is the harvest index (moles of carbon in edible product per mole of carbon in plant biomass), k is the mass of CH_2O (g carbohydrate) per mole of carbon in the edible product, E_{PAR} (dimensionless) is the conversion efficiency from the energy within incident PAR to the energy fixed into the dry weight and E_{total} (dimensionless) is the conversion efficiency from the energy of incident total radiation to the energy fixed into the dry weight

		Parameters values used in the calculations						
Publication	**LUE_{inc}**	**Fa**	**QY**	**CUE**	**HI**	**k**	**E_{PAR}**	**E_{total}**
Loomis and Williams (1963)	1.81[a]	0.90	0.10	0.67	1	30		
Bugbee and Salisbury (1988)	1.64[a]	0.95	0.077	0.75	1	30	13%	6.0%
Zhu et al. (2010)	1.26[b]							4.6%
Kozai (2013)	1.26[c]						10%	
Pattison et al. (2018)	1.33[a]	0.95	0.08	0.65	0.90	30		

[a]LUE_{inc} calculated as $Fa \times QY \times CUE \times HI \times k$.

[b]Calculated from E_{total}, assuming proportional relation between E_{total} and LUE_{inc} based on Bugbee and Salisbury (1988), hence 4.6%/6.0% × 1.64.

[c]Calculated from E_{PAR}, assuming proportional relation between E_{PAR} and LUEinc based on Bugbee and Salisbury (1988), hence 10%/13% × 1.64.

from transplanting to harvest (plant age). When there is no transplanting between sowing and harvesting, 7 days were taken out of the calculation of plant age. When the incident PPFD ($\mu mol\,m^{-2}\,s^{-1}$) was reported, DLI was calculated by multiplying this PPFD with the photoperiod. For greenhouse, field, and a few vertical farming studies, averaged DLI over the cultivation period was reported. For greenhouse cultivations, since the cover material (mostly glass) transmits only part of the outside radiation, a fixed transmissivity was assumed (Table 1), when PPFD at canopy level was not reported. For greenhouse studies with supplemental light, incident light intensity from the lamps was always reported (DLI or PPFD).

When data were not reported in the text but in a figure, chart, and/or plot, they were extracted using WebPlotDigitizer (Ankit Rohatgi, WebPlotDigitizer, Version 4.3., Pacifica).

Box plots were used to present median and variation in the analyzed variables for vertical farming, greenhouse, and open field. These box plots cover the whole range of data, with the end of the lower whisker being the minimum value and the end of the top whisker the maximum value, and the lower and upper section of the box represent the second and third quartile, respectively. The bar in the middle of box stands for the median.

For LUE analysis, we took the data from the treatment that resulted in the highest LUE_{inc}, when a paper contained more than one treatment. Presented data were extracted from 53 publications for vertical farming, 13 publications for greenhouse production, and 8 publications for production in open field (Supplementary S2 in Appendix S1). A typical vertical farm contains several features including a multi-layer production system. However, when plants were grown in a single layer in a climate room, the data were also considered as being representative for vertical farming and, therefore, used in this study. Without further explanation, such conditions were considered as representing vertical farming.

3 | RESULTS

Several publications provide information to obtain a theoretical LUE_{inc} (g DW per incident mole of photosynthetic

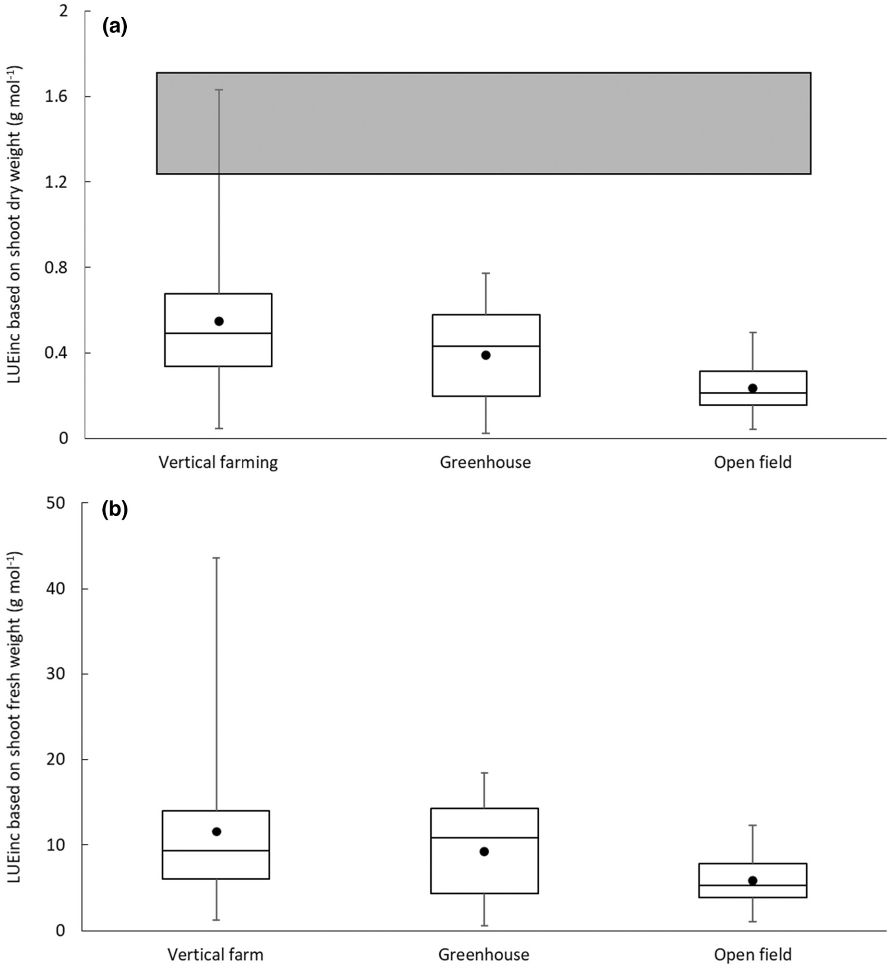

FIGURE 1 Box plots of LUE_{inc} (g [shoot weight] mol^{-1} [cumulative incident DLI]) for vertical farming, greenhouse, and open field lettuce cultivation based on shoot dry weight (a) or shoot fresh weight (b). Data used are the highest LUE_{inc} values reported in each publication, so excluding suboptimal treatments. The black dots represent the average values. The grey area (a) represents reported theoretical maximum LUE_{inc} values (Table 2)

photons; Table 2). Pattison et al. (2018) calculated LUE_{inc} as the product of Fa (fraction of incident photons absorbed by the crop), QY (quantum yield; mole of carbon fixed per mole of photon absorbed), CUE (carbon use efficiency; moles of carbon incorporated into plant biomass per mole of carbon fixed), HI (harvest index; moles of carbon in edible product per mole of carbon in plant biomass) and k (mass of CH_2O [g carbohydrate] per mole of carbon in the edible product). In several papers, different values were assumed for these five parameters (Table 2) resulting in different values for LUE_{inc}: 1.81 g mol^{-1} for Loomis and Williams (1963), 1.64 g mol^{-1} for Bugbee and Salisbury (1988) and 1.33 g mol^{-1} for Pattison et al. (2018). Bugbee and Salisbury (1988) conservatively assumed their calculated LUE_{inc} of 1.64 g mol^{-1} incident photosynthetic photons is only possible for low-lipid plants even though it is lower than Loomis and William's 1.78. Zhu et al. (2010) calculated the minimum energy losses from solar radiation to the energy fixed within crop biomass to obtain a theoretical maximum energy fixation in the crop. They estimated for C3 species that 4.6% of solar radiation energy is fixed into the crop (E_{total}). The LUE_{inc} for Zhu et al. (2010), which was 1.26 g per incident mole of photosynthetic photons, was calculated based on the proportionality between E_{total} and LUE_{inc} from Bugbee and Salisbury (1988). Kozai (2013) calculated a theoretical maximum LUE_{inc} for vertical farming. He assumed a maximum efficiency of 10% from PAR to chemical energy in the crop (E_{PAR}) and based on the proportionality between E_{PAR} and LUE_{inc} from Bugbee and Salisbury (1988) this means a LUE_{inc} of 1.26 g mol^{-1}.

The observed LUE_{inc} of crops grown in vertical farming covers a wider range than greenhouse and open field (Figure 1a,b). LUE_{inc} for lettuce grown in vertical farming showed a high variability in the fourth quartile, whereas for greenhouse-grown lettuce more variation was found in the second quartile. The highest and the second-highest observed LUE_{inc} for lettuce in a vertical farm based on SDW (1.63 and 1.23 g mol^{-1}) is in the reported range of the theoretical maximum LUE_{inc} (Table 2) and significantly larger than the highest LUE_{inc} for greenhouse (0.77 g mol^{-1}) or open field (0.49 g mol^{-1}) lettuce production. The median LUE_{inc} of vertical farming is lower than for greenhouse cultivation, whereas for field production this is clearly lower. However, the average LUE_{inc} for lettuce production in vertical farming (0.55 g mol^{-1}) is 41% higher than for greenhouse production (0.39 g mol^{-1}) and 139% higher than for production in the open field (0.23 g mol^{-1}).

A similar pattern is observed for LUE_{inc} based on SFW (Figure 1b). The highest fresh weight LUE_{inc} was 43.6 g mol^{-1} and the highest values for greenhouse and open field were 18.5 and 12.4 g mol^{-1}, respectively. Median fresh weight LUE_{inc} for vertical farming was 9.3 g mol^{-1}, which was lower than 10.8 g mol^{-1} for greenhouse cultivation. Both were higher than the median fresh weight LUE_{inc} for open field cultivation (5.3 g mol^{-1}). However, average fresh weight LUE_{inc} for vertical farming was 11.6 g mol^{-1}, which is higher than for greenhouse or open field (9.2 g mol^{-1} and 5.9 g mol^{-1}, respectively).

Based on Carotti et al. (2021) who observed an incident LUE_{inc} in fresh weight of 44 g mol^{-1} (as observed in plants grown at 200 µmol m^{-2} s^{-1} PPFD and 16 h photoperiod), potential annual lettuce production was estimated for several combinations of photoperiod and incident PPFD (Figure 2). Since the lettuce cultivated in a vertical farm is clean, total shoot weight is taken as harvestable weight. Potential annual yield was only 35 kg m^{-2} year^{-1} when grown at 50 µmol m^{-2} s^{-1} and a photoperiod of 12 h but reached up to 700 kg m^{-2} year^{-1} when grown at 500 µmol m^{-2} s^{-1} and a photoperiod of 24 h.

For the reported maximum LUE_{inc} values from each publication, several potentially explaining factors were compared (Figure 3a–f), including SDW at harvest (plant size), plant age (the number of days from transplanting to harvesting), DLI (the daily incident PPFD sum), cumulative DLI (the total incident PPFD from transplanting to harvesting), planting density (the density applied at transplanting), and CO_2 concentration. The size of harvested lettuce plants differed substantially when comparing studies of vertical farming, greenhouse, and open field. In vertical farming studies the SDW of the harvested lettuce was lower than for greenhouse-grown lettuce, which was again lower than for open field-grown lettuce (Figure 3a). Lettuce in vertical farming takes a shorter growing period. Surprisingly, the growing duration in greenhouses was rather similar to open field (Figure 3b). Lettuce grown on the field received the highest and vertical farming the lowest DLI (Figure 3c) and cumulative light during the growing period (Figure 3d). The median planting density in vertical farming was higher than for greenhouse (Figure 3e) and open field Greenhouse and open field cultivation's CO_2 concentration was not different from the atmospheric concentration (Figure 3f). However, elevated CO_2 concentration was often applied in vertical farming cultivation to promote plant growth.

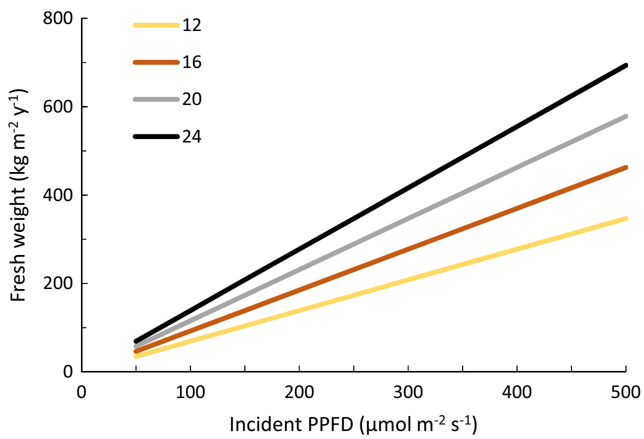

FIGURE 2 Potential annual yield of fresh lettuce production for different combinations of incident PPFD and photoperiods of 12, 16, 20, and 24 h day^{-1}. The calculations of potential yield were based on the highest observed incident LUE of 44 g (shoot fresh weight) mol^{-1} (Carotti et al., 2021)

As plants in the vertical farming studies are usually harvested as smaller plants (Figure 3a) and at a younger age (Figure 3b) than in greenhouse or open field, we analyzed the dependence of LUE_{inc} on plant age and size. During cultivation the LUE_{inc} based on cumulative plant dry mass and cumulative PPFD integral increased strongly (Figure 4). Hence the older or the bigger the plant at harvest the higher the LUE_{inc}. At the end of a recent experiment (Jin et al., 2021), LUE_{inc} averaged over the whole growing period was 0.5 g mol^{-1}. However, when calculated only for the last week before harvest LUE_{inc} was 1.2 g mol^{-1}.

Using the six variates on the *y*-axes of the panels in Figure 3, a correlation analysis was performed for all production systems combined (Supplementaries S4 and S5 in Appendix S1) and vertical farming only (Supplementaries S6 and S7 in Appendix S1). For all production systems combined, from the six regressors three showed a significant correlation with LUE_{inc} (DLI with $r = -0.29$; cumulative DLI with $r = -0.35$; planting density with $r = 0.46$), while plant age and SDW at harvest and CO_2 concentration showed no significant correlation with LUE. Multiple linear regression starting with a model with all six regressors followed by backward elimination resulted in a model with three significant ($p < 0.05$) regressors. Shoot dry weight at harvest, planting density and cumulative DLI together explaining 45% of the variance in LUE_{inc}. The first two regressors (SDW at harvest, planting density) positively influenced LUE_{inc} and the last regressor (cumulative DLI) negatively influenced LUE_{inc}. For vertical farming only SDW at harvest ($r = 0.45$) and planting density ($r = 0.48$) showed a significant correlation with LUE_{inc} (Supplementaries S6 and S7 in Appendix S1). Multiple linear regression starting with a model with all six regressors followed by backward elimination resulted in a model with four significant ($p < 0.05$) regressors. Shoot dry weight at harvest, planting density, DLI, and plant age

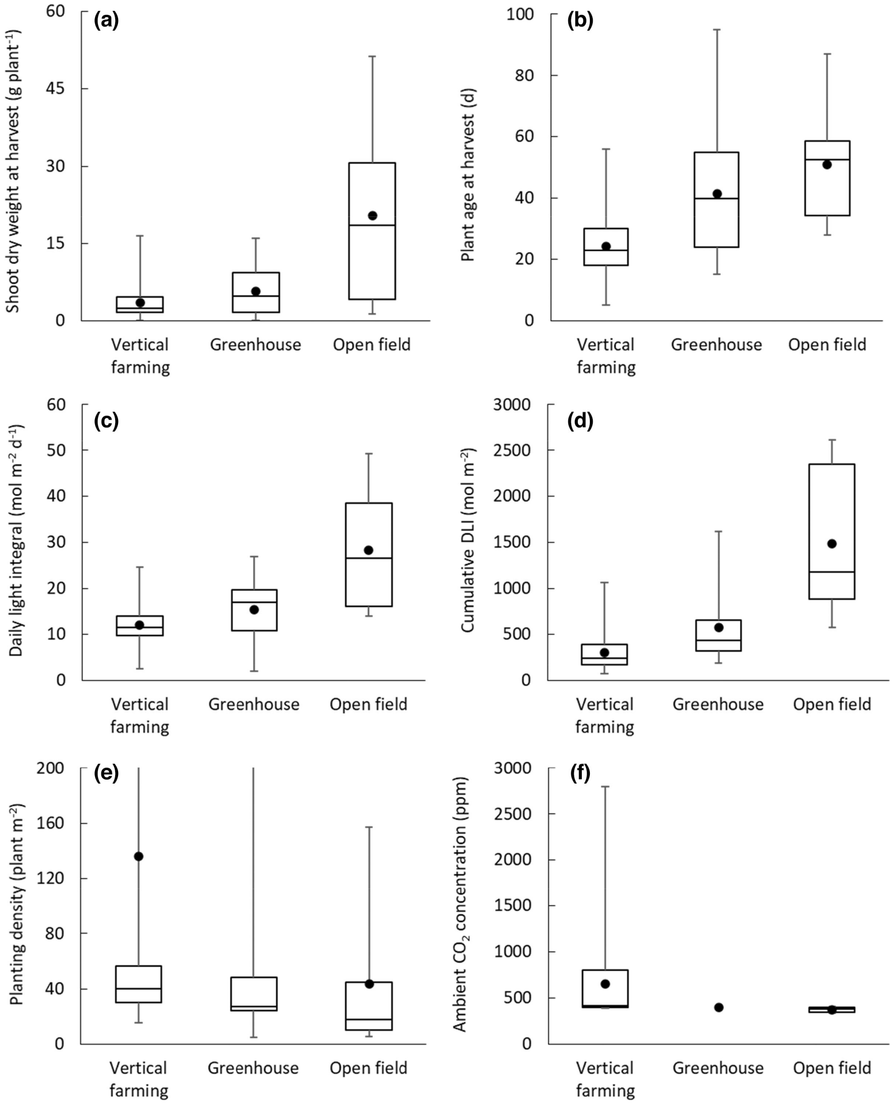

FIGURE 3 Boxplots of shoot dry weight at harvest (a), plant age (from transplanting to harvest, (b)), daily light integral (c), DLI_{cum} (d), planting density (e; three extremes of 700, 1000 and 1300 plants m^{-2} for vertical farming not shown, and ambient CO_2 concentration (f) for lettuce cultivation in vertical farming, greenhouse, and open field. Black dots represent the average values

together explaining 83.0% of the variance in LUE_{inc}, the former two regressors positively influencing LUE_{inc} and the latter two negatively influencing LUE_{inc}.

4 | DISCUSSION

4.1 | Highest observed LUE in vertical farming close to its theoretical maximum

LUE_{inc} in vertical farming can be high, and there is only a 10% gap between the highest LUE_{inc} observed in a vertical farming experiment, which is 1.63 g mol^{-1} (Pennisi et al., 2019), and the maximum theoretical value of 1.81 g mol^{-1} (Table 2). The majority of the theoretical LUE_{inc} values (Table 2) were estimated by simplifying the actual process of biomass production from photosynthetic photon absorption to the biomass accumulated in the harvestable organs with different efficiencies for these processes (Bugbee & Salisbury, 1988; Loomis & Williams, 1963; Pattison et al., 2018; Zhu et al., 2010). One exception is Kozai (2013) who calculated LUE_{inc} by applying a constant conversion factor from dry mass to chemical energy fixed in dry mass. These calculations were conducted based on a closed canopy absorbing at least 90% of the incident PPFD. A theoretical maximum LUE_{inc} is based on the assumption that the ambient environment for growing is always optimal, with ample supply of CO_2, water, and nutrients. In the actual experimentation and production, the incident PPFD between transplanting and canopy closure is not fully absorbed. The highest LUE_{inc} reported in experiments is 1.63 g mol^{-1} (Pennisi et al., 2019) and was achieved at a high planting density of 100 plants m^{-2} and by transplanting rather large plants 14 days after sowing. Therefore, the fraction light intercepted was very high from the start of the cultivation. The second highest measured LUE_{inc} is 1.23 g mol^{-1} (Carotti et al., 2021) obtained at a much lower planting density of 25 plants m^{-2}. These cases demonstrate the great potential of vertical farming to get close to the theoretical

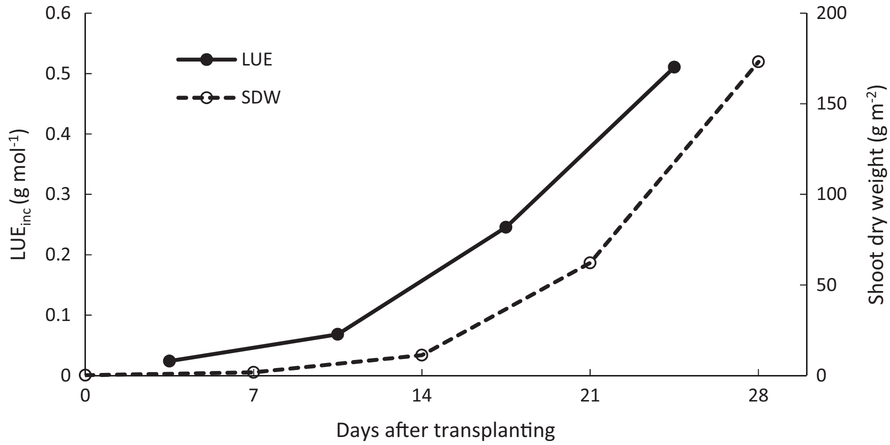

FIGURE 4 LUE_{inc} (solid line) based on cumulative incident PPFD and lettuce shoot dry weight (dashed line; $g\,m^{-2}$) as a function of days after transplanting. Data were taken from the experiment described in Jin et al. (2021) for lettuce (*Lactuca sativa* cv. Expertise RZ) grown at 220 $\mu mol\,m^{-2}\,s^{-1}$ red (88%) and blue (12%) LED with 45 $\mu mol\,m^{-2}\,s^{-1}$ far-red and at 51 plants m^{-2}. LUE_{inc} is calculated for each 7-day interval between two destructive harvests and plotted against the middle of each interval

LUE_{inc}, as incident photons will have inevitably been falling on the floor instead of being utilized by crops in the early crop stage especially in the Carotti et al. (2021) case. Quicker full light interception may be obtained by adding far-red light (Jin et al., 2021; Meng & Runkle, 2019; Zou et al., 2019) or dynamically changing planting densities, that is, gradually decreasing as the plant develops (van Delden et al., 2021). Considering that not all researchers are very good growers, that many experiments were not conducted with the aim to maximize growth and that vertical farming is relatively new, it can be expected that still quite some improvements in LUE_{inc} are possible for the LUE_{inc} data presented in the literature. A higher fraction of assimilate partitioned to leaf will benefit further light interception and thus increase the biomass production, especially in the relatively short growing period. With a cultivation practice such that a high fraction of incident light is absorbed by canopy already from the start of the cultivation lettuce cultivation in vertical farming may well be able to realize the theoretical LUE_{inc} as environmental factors such as temperature and CO_2 (Becker & Kläring, 2016), nutrients and water availability can be kept at optimal levels.

4.2 | LUE_{inc} is largest in vertical farming followed by greenhouses and smallest in open field

The average LUE_{inc} for vertical farming (0.55 $g\,mol^{-1}$) was higher than for greenhouse-grown lettuce (0.39 $g\,mol^{-1}$). In vertical farming, when other factors become non-limiting, such as nutrient and water availability, and CO_2 concentration, light may become the only limiting factor, by which the LUE_{inc} can be maximized. Moreover, new cultivation practices can be easily applied in vertical farming and further improve LUE_{inc}. Elevating CO_2 concentration is another practice to promote plant growth which can be rather simply realized in the closed environment of a vertical farm (Figure 3f). In greenhouses, a non-limiting root environment and a shoot environment closer to optimal than in open field cultivation can be obtained, but less optimal than in a fully controlled vertical farm. In addition, as solar light is the only or main light source in a greenhouse, PPFD could be close to crop photosynthetic saturation level which will result in a lower LUE. Therefore, LUE_{inc} in greenhouse varies over the seasons. In summer, when the PPFD is high, the LUE_{inc} will be reduced and LUE_{inc} is expected to be higher when PPFD is lower, typically in winter. Such a seasonal variation in LUE_{inc} has been observed for greenhouse cut chrysanthemum cultivation (Lee et al., 2002). Moreover, in the field or greenhouse PPFD may fluctuate rapidly during a day. As photosynthetic induction may take some time, this may lead to less photosynthesis (e.g., Kaiser et al., 2017) compared with a vertical farm where PPFD can be kept constant. Even though there are many modern techniques applied, the temperature, relative humidity, and CO_2 concentration in a greenhouse cannot always be maintained at the desired level, which will negatively affect LUE_{inc} in greenhouses. Climate control is most advanced for vertical farming, less so for a greenhouse and absent for open field cultivation. Therefore, the LUE_{inc} is expected to be lowest for open field cultivation and lower for greenhouse-grown lettuce than for vertical farming.

In addition, the lettuce types and cultivars grown in vertical farming, greenhouse, or open field differ because of different markets. Remarkably in the vertical farming studies the lettuces were harvested at a smaller size (Figure 3a) and after a shorter growing period (Figure 3b) than in greenhouse or open field, which negatively affects LUE_{inc} (Figure 4). If a longer cultivation period would be adopted, the period of closed canopy would most likely represent a larger fraction of the total cultivation period leading to a higher LUE_{inc} as a closed canopy intercepts most of the incident light. Therefore, if similar lettuce types would be grown in vertical farming, greenhouse, and open field, the differences in LUE_{inc} are expected to be much larger than observed now (Figure 1).

A high planting density can strongly increase the light interception in a young crop. However, in practice planting density is first of all determined by lettuce type. Therefore, vertical farming, which often focuses on relatively small lettuce plants, is the system that allows for a higher planting density than others (Figure 3e). As mentioned in the previous section, variable planting density, starting with a very high density when the plants are small and gradually decreasing during the crop cultivation as the plants get larger would result in consistently intercepting most of the incident light, which would increase LUE_{inc} and is most feasible to apply in a vertical farm.

Using data of lettuce experiments with a relatively long growing duration and a reasonable harvest size the potential yield per unit growing surface was calculated. At a continuous (day and night) PPFD of 500 $\mu mol\, m^{-2}\, s^{-1}$ annual yield could be as high as 700 $kg\, m^{-2}$ yield. This might be a too optimistic estimation ("best case scenario"), as it assumes that the LUE is maintained at high PPFD with continuous light. At higher light levels LUE of lettuce may decline or growth rate might even reduce, but these responses seem to depend on cultivar and growth conditions (Lee et al., 2019; Pennisi, Pistillo, et al., 2020b; Pérez-López et al., 2013; Viršilė et al., 2019). A number of crops cannot stand continuous 24 h lighting (Velez-Ramirez et al., 2011), but lettuce seems to be capable of growing under continuous light, although optimal photoperiod might be lower than 24 h (Pennisi, Orsini, et al., 2020a). Furthermore, tipburn is often a severe problem at high growth rates (Sago, 2016). Here, we ignored potential occurrence of tipburn, but it might be an important limiting factor for realizing these high growth rates. This would need further experimental testing in order to verify the estimations. On the other hand, this estimate is not even based on the highest observed LUE_{inc} (1.23 instead of 1.63 $g\, mol^{-1}$ was used). Compared with a commercial Dutch greenhouse productivity (33 $kg\, m^{-2}$ [Raaphorst et al., 2019]), one layer of vertical farming could be 20 times more productive. For wheat Asseng et al. (2020) estimated yield per layer in a vertical farm to be 22–60 times higher than in the field. Considering multiple layers are applied in vertical farming, production per unit of floor area can become manyfold higher than in greenhouse or open field. However, the economical optimum yield might be different from the maximum yield.

5 | CONCLUSION

The average LUE_{inc} (light use efficiency; ratio of SDW and incident PPFD integral) of lettuce was higher in vertical farming (0.55 g dry weight mol^{-1}) than for greenhouse cultivation (0.39 $g\, mol^{-1}$), which was higher than in the open field (0.23 $g\, mol^{-1}$). Since all environmental factors can be fully controlled, vertical farming has the capability to achieve the theoretical maximum LUE_{inc}. Indeed, the maximum measured LUE_{inc} for lettuce grown in vertical farming (1.63 $g\, mol^{-1}$) is close to the maximum theoretical values, ranging from 1.26 to 1.81 $g\, mol^{-1}$, which can make LUE_{inc} in vertical farming about 5 times higher compared with average production in the open field.

ACKNOWLEDGEMENT

None.

CONFLICT OF INTEREST

The authors have stated explicitly that there no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

Most of the data are already in the supplementary information. Additional data are available upon request.

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REFERENCES

Asseng, S., Guarin, J. R., Raman, M., Monje, O., Kiss, G., Despommier, D. D., Meggers, F. M., & Gauthier, P. P. G. (2020). Wheat yield potential in controlled-environment vertical farms. *Proceedings of the National Academy of Sciences of the United States of America*, *117*, 19131–19135. https://doi.org/10.1073/pnas.2002655117

Becker, C., & Kläring, H. P. (2016). CO2 enrichment can produce high red leaf lettuce yield while increasing most flavonoid glycoside and some caffeic acid derivative concentrations. *Food Chemistry*, *199*, 736–745. https://doi.org/10.1016/j.foodchem.2015.12.059

Both, A. J. (1995). *Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production*. PhD. Dissertation. PhD Thesis (p. 172). Cornell Univ. Libr. Ithaca. https://doi.org/10.13140/RG.2.2.11209.29282

Bugbee, B. G., & Salisbury, F. B. (1988). Exploring the limits of crop productivity. I. Photosynthetic efficiency of wheat in high irradiance environments. *Plant Physiology*, *88*, 869–878. https://doi.org/10.1104/pp.88.3.869

Carotti, L., Graamans, L., Puksic, F., Butturini, M., Meinen, E., Heuvelink, E., & Stanghellini, C. (2021). Plant factories are heating up: Hunting for the best combination of light intensity, air temperature and root-zone temperature in lettuce production. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.592171

De Pinheiro Henriques, A. (2000). Regulation of growth at steady-state nitrogen nutrition in lettuce (*Lactuca sativa* L.): Interactive effects of nitrogen and irradiance. *Annals of Botany*, *86*, 1073–1080. https://doi.org/10.1006/anbo.2000.1268

Gent, M. P. N. (2014). Effect of daily light integral on composition of hydroponic lettuce. *HortScience*, *49*, 173–179. https://doi.org/10.21273/hortsci.49.2.173

Heuvelink, E., Batta, L. G. G., & Damen, T. H. J. (1995). Transmission of solar radiation by a multispan Venlo-type glasshouse: Validation of a model. *Agricultural and Forest Meteorology*, *74*, 41–59. https://doi.org/10.1016/0168-1923(94)02184-L

Jin, W., Urbina, J. L., Heuvelink, E., & Marcelis, L. F. M. (2021). Adding far-red to red-blue light-emitting diode light promotes yield of lettuce at different planting densities. *Frontiers in Plant Science*, *11*, 1–9. https://doi.org/10.3389/fpls.2020.609977

Kaiser, E., Zhou, D., Heuvelink, E., Harbinson, J., Morales, A., & Marcelis, L. F. M. (2017). Elevated CO2 increases photosynthesis in fluctuating irradiance regardless of photosynthetic induction state. *Journal of Experimental Botany*, *68*, 5629–5640. https://doi.org/10.1093/jxb/erx357

Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. *Proceedings of the Japan Academy. Series B, Physical and Biological Sciences*, *89*, 447–461. https://doi.org/10.2183/pjab.89.447

Lee, J. H., Heuvelink, E., & Challa, H. (2002). Effects of planting date and plant density on crop growth of cut chrysanthemum. *The Journal of Horticultural Science and Biotechnology*, *77*, 238–247. https://doi.org/10.1080/14620316.2002.11511486

Lee, R. J., Bhandari, S. R., Lee, G., & Lee, J. G. (2019). Optimization of temperature and light, and cultivar selection for the production of high-quality head lettuce in a closed-type plant factory. *Horticulture, Environment and Biotechnology*, *60*, 207–216. https://doi.org/10.1007/s13580-018-0118-8

Loomis, R. S., & Williams, W. A. (1963). Maximum crop productivity: An Extimate 1. *Crop Science*, *3*, 67–72. https://doi.org/10.2135/cropsci1963.0011183x000300010021x

Meng, Q., & Runkle, E. S. (2019). Far-red radiation interacts with relative and absolute blue and red photon flux densities to regulate growth, morphology, and pigmentation of lettuce and basil seedlings. *Scientia Horticulturae*, *255*, 269–280. https://doi.org/10.1016/j.scienta.2019.05.030

Pattison, P. M., Tsao, J. Y., Brainard, G. C., & Bugbee, B. (2018). LEDs for photons, physiology and food. *Nature*, *4–11*, 493–500. https://doi.org/10.1038/s41586-018-0706-x

Pennisi, G., Orsini, F., Blasioli, S., Cellini, A., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernandez, J. A., Stanghellini, C., Gianquinto, G., & Marcelis, L. F. M. (2019). Resource use efficiency of indoor lettuce (*Lactuca sativa* L.) cultivation as affected by red:blue ratio provided by LED lighting. *Scientific Reports*, *9*, 1–11. https://doi.org/10.1038/s41598-019-50783-z

Pennisi, G., Orsini, F., Landolfo, M., Pistillo, A., Crepaldi, A., Nicola, S., et al. (2020a). Optimal photoperiod for indoor cultivation of leafy vegetables and herbs. *European Journal of Horticultural Science*, *85*, 329–338. https://doi.org/10.17660/eJHS.2020/85.5.4

Pennisi, G., Pistillo, A., Orsini, F., Cellini, A., Spinelli, F., Nicola, S., et al. (2020b). Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. *Scientia Horticulturae*, *272*. https://doi.org/10.1016/j.scienta.2020.109508

Pérez-López, U., Miranda-Apodaca, J., Muñoz-Rueda, A., & Mena-Petite, A. (2013). Lettuce production and antioxidant capacity are differentially modified by salt stress and light intensity under ambient and elevated CO2. *Journal of Plant Physiology*, *170*, 1517–1525. https://doi.org/10.1016/j.jplph.2013.06.004

Raaphorst, M. G. M., Benninga, J., & Eveleens, B. A. (2019). *Quantitative information on Dutch greenhouse horticulture* (Vol. *2019*, p. 37). Wageningen UR Greenhouse Horticulture.

Sager, J. C., & McFarlane, J. C. (1997). Radiation. In R. W. Langhans & R. W. Tibbits (Eds.), *Plant growth chamber handbook* (pp. 1–29). Iowa State University.

Sago, Y. (2016). Effects of light intensity and growth rate on tipburn development and leaf calcium concentration in butterhead lettuce. *HortScience*, *51*, 1087–1091. https://doi.org/10.21273/HORTSCI10668-16

SharathKumar, M., Heuvelink, E., & Marcelis, L. F. M. (2020). Vertical farming: Moving from genetic to environmental modification. *Trends in Plant Science*, *25*, 724–727. https://doi.org/10.1016/j.tplants.2020.05.012

van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J. A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R. S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J. C., Vialet-Chabrand, S., Woltering, E. J., van de Zedde, R., Zhang, Y. & Marcelis, L. F. M. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food*, *2*, 944-956. https://doi.org/10.1038/s43016-021-00402-w

Velez-Ramirez, A. I., Van Ieperen, W., Vreugdenhil, D., & Millenaar, F. F. (2011). Plants under continuous light. *Trends in Plant Science*, *16*, 310–318. https://doi.org/10.1016/j.tplants.2011.02.003

Viršilė, A., Brazaitytė, A., Vaštakaitė-Kairienė, V., Miliauskienė, J., Jankauskienė, J., Novičkovas, A., & Samuolienė, G. (2019). Lighting intensity and photoperiod serves tailoring nitrate assimilation indices in red and green baby leaf lettuce. *Journal of the Science of Food and Agriculture*, *99*, 6608–6619. https://doi.org/10.1002/jsfa.9948

Zhu, X. G., Long, S. P., & Ort, D. R. (2010). Improving photosynthetic efficiency for greater yield. *Annual Review of Plant Biology*, *61*, 235–261. https://doi.org/10.1146/annurev-arplant-042809-112206

Zou, J., Zhang, Y., Zhang, Y., Bian, Z., Fanourakis, D., & Yang, Q. (2019). Morphological and physiological properties of indoor cultivated lettuce in response to additional far-red light. *Scientia Horticulturae*, *257*, 108725. https://doi.org/10.1016/j.scienta.2019.108725

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