A virtual tomato plant for optimising assimilation light in greenhouse cultivation

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ABSTRACT
The use of assimilation light for the cultivation of tomato in greenhouses has become a widespread practice. It allows for an increase in yield as well as year-round production by providing a bridge for the darker winter periods. A large selection of assimilation lights, such as high-pressure sodium (HPS) lamps or LED lighting, can be used in an even larger variety of different compositions above or within the crop. Customising of modern LED lamps specific for horticulture allows even further finetuning of light recipes specific to the crop. This large degree of flexibility, as well as the constantly changing greenhouse light environment during the growing season, begs the question of which assimilation light selection and composition is ideal when balancing yield, investment and energy costs. Such a question warrants a dedicated understanding of the plant-light interactions at a truly 3-dimensional level, as not all possible scenarios can feasibly be tested physically. For this purpose, a functional-structural plant model for tomato was developed, which accurately describes the 3D structure of a tomato crop alongside its leaf spectral characteristics, including a mechanistic photosynthesis model. The structure of the greenhouse and the physical and wavelength distributions of HPS, LED, and sunlight were also incorporated. The resulting model is truly a customizable tool for virtually evaluating the potential effectiveness of assimilation light in terms of yield and energy efficiency in limitless user-defined cases. Within this study, various scenarios of assimilation light compositions were theoretically evaluated for their cost-effective yield contributions under various intensities of natural sunlight. In a next step, the model could be used to search for potentially optimal light compositions. Such theoretically optimal compositions could greatly speed up the manual experimental search for the optimal light composition and recipe for tomato growth in specific growth settings.

Keywords: FSPM, LED, HPS, photosynthesis, virtual plant, model, 3D, raytracing

INTRODUCTION
Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops in Belgium as well as globally, with over 300,000 tons produced in Belgium in 2020 (FAOSTAT 2020). The use of assimilation light for growing tomatoes has greatly benefitted yields and year-round production in recent decades. A standard assimilation light setup often combines high-pressure sodium (HPS) toplights with light emitting diode (LED) interlights. The addition of such LED bars, typically suspended between tomato plants, has been found to be very beneficial for production with additional yields up to 20% (Moerkens et al. 2016). As these lamps are a major investment cost, an optimal placement to get the maximum benefit is warranted. The most straightforward way for evaluating the yield benefits of different assimilation setups is by doing physical experiments. This can be very time consuming for growers or research institutes as there are many possible setups (Vermeiren et al. 2020). Variation in, e.g., row spacing, plant distance within the rows, number of LED bars, height of these LED bars, number of HPS lights and their distribution can all

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lead to different results. All these variations lead to a practically infeasible number of combinations, especially when considering that the optimal configuration can also change depending on the available amount of sunlight. This makes it very difficult to determine the configuration for optimal production via traditional trial and error experiments.

Development of functional-structural plant models (FSPM) may offer opportunities to circumvent this problem (Sievänen et al., 2014). FSPMs are models that take the complex 3D structure of the plant to map accurate interactions between plant and environment. Such a model has the capability to translate changes in light conditions on net photosynthesis, and indirectly on fruit production, of the plants. This allows a virtual evaluation of the potential of different assimilation light setups, unconstrained by physical limitations of time, infrastructure or labour that hinders practical evaluation (Buck-Sorlin et al., 2011). As a result, only a smaller number of combinations, put forward by the virtual screening method, need to be validated.

In this study, an existing FSPM (Vermeiren et al., 2020) was used to illustrate the potential of FSPMs as a tool in finding the theoretically ideal configuration for various lamp positions, as a tailor-made decision-support tool for existing or new commercial tomato greenhouse architecture. As such, one specific greenhouse configuration was chosen as a case-study whereby several combinations of different intensities of sunlight, HPS toplighting and different heights of one or two LED bars as intermediate lighting were simulated on a purely theoretical level to evaluate which set-up is likely to be optimal for the tomato production. Net photosynthesis was used a direct proxy for yield improvements, based on the observation of an approximate 1:1 relationship between light interception and yield for tomato (Buitelaar, 1984; Van Rijssel & De Visser, 1985; De Koning, 1989; Cockshull et al., 1992; Heuvelink, 1995). By considering a current benchmark of investment and energy costs of assimilation lighting scenario-specific efficiency estimations can be made, with the caveat that technological improvements have led to these costs trending down over time over the past years and will likely continue to do so (Zissis et al., 2021).

MATERIALS AND METHODS

The functional-structural plant model (FSPM) of tomato under greenhouse conditions, originally developed by Vermeiren et al. (2020), was used for this study. This model allows evaluation of the effect of virtual growing conditions of tomato on leaf photosynthesis with adjustable light conditions, planting distance and row spacing. Details on the calibration experiment setup can be found in Vermeiren et al. (2020).

Description of the model

An FSPM consists of a structural and a functional part, outlined in detail in Vermeiren et al. (2020). A short overview of the model components is given below. To construct the structural part of the FSPM the growth of tomato plants was accurately tracked for model calibration. Measured structural elements included length and thickness of all internodes, length and width of all compound leaves, leaf angle, petiole thickness and petiole angle. All these data were combined to virtually recreate an “average” tomato plant in the GroIMP modelling platform (Kniemeyer et al., 2007). The use of an “average” plant allowed direct comparison of the different virtual light treatments without interference of the heterogeneity contained within the crop itself. Each virtual plant consists of eleven sympodial units, with one sympodial unit consisting of four phytomers (leaf + bud + internode). Canopy uniformity was prevented by randomly rotating the plants around their main stem.

In the model, parameters such as planting distance, row distance, HPS top lights, LED interlights or even diffuse sunlight can be customized to run the desired configurations. The parameterisation of the assimilation light was based on the physical light distribution of the lamps as well as their emission spectra. Direct sunlight was excluded from this study as it leads to large variability in the results based on weather conditions, seasonal changes and greenhouse orientation but can be easily integrated in the tool (Evers et al., 2007; Buck-Sorlin et al., 2011). An overarching greenhouse is also simulated with the 'glasshouse module', which contains the basic physical light characteristics (i.e., reflectance and transmission) of glass and aluminum frames typically used in greenhouse construction (Vermeiren et al., 2020).

Based on the structural part of the model, light interception, intensity, and wavelength can be determined at the individual leaf level. Leaf spectral characteristics, to accurately model leaf absorbance, transmittance, and reflectance for each wavelength, were included through the PROSPECT-D radiation-transfer model integrated into the tomato FSPM (Jacquemoud & Baret, 1990; Féret et al., 2017; Coussement et al., 2018). Lastly, to convert leaf light absorption to leaf photosynthesis, the photosynthesis-stomatal conductance-transpiration (P-SC-T) model of Kim-Lieth (originally designed for Rose) was integrated in the model and recalibrated for the tomato dataset (Kim & Lieth, 2003; Vermeiren et al., 2020). No mechanistic fruit growth module was included in the model and photosynthesis was used as a direct proxy for evaluating increases in yield.

Scenarios

The chosen benchmark for scenario simulation in this study was an arrangement with five rows of plants and five plants per row, as a trade-off between calculation time and model accuracy. As the plant light conditions at the edge of the canopy can be drastically different from those in the center, and less representative for the production unit, only the middle plants were selected for analysis. In this study, a step-by-step search was made for the optimal arrangement for growing tomatoes in a greenhouse. First, the ideal planting distance in the row and the optimal distance between plants were determined. The best spatial arrangement of the plants obtained in these simulations was then used to determine optimal positions for several combinations of assimilation light with natural light conditions.

Plant and row distance

First, the planting distance between the plants in the row was optimized. For this purpose, simulations were performed with a fixed row spacing of 1.576 m, a common spacing in contemporary tomato cultivation in Belgium. The HPS toplight was placed at 4.50 m and one 1.5 m LED bar at 2.00 m above the ground. No sunlight was added for this simulation as in the absence of sunlight, the optimalisation of the setup will be most crucial. Minimal distance between the plants was set at 0.10 m in the row and incremented at 0.05 m steps up to a maximum of 1.55 m distance. The plants are grown on rockwool slabs with two stems for each plant as done in Vermeiren et al. (2020). For each setup, net photosynthesis per plant was calculated as well as converted to total photosynthesis per hectare, considering the lower planting density of plants at higher spacings, which has important economic implications. Row spacing was optimized in an identical manner, ranging from a minimum of 0.5 m up to 2 m.

After determining the ideal plant and row spacing, these plant spacings were used as the standard for remaining simulations, whereby the optimal position of assimilation lights was determined.

Light configurations

To determine the optimal assimilation light configurations, several combinations of the use of HPS toplights and one or two LED interlight bars were simulated at various intensities of solar irradiance. The plants were 2.96 m tall and placed 1 m above the ground, which is the lowest height used for placement of the LED interlights in the simulation. Each combination was simulated first without sunlight, then again with 150 µmol PAR m^{-2} s^{-1} diffuse light and finally with 300 µmol PAR m^{-2} s^{-1} diffuse light. This was used to represent the different intensities of sunlight on an average winter day in Belgium, which is when assimilation light serves their primary purpose. For the double LED bars a first, broader search was conducted per 0.50 m, after which a more focused search was conducted in the determined optimal range in 0.10 m increments.

To evaluate the cost-effectiveness of assimilation light in year-round production, higher intensities of solar irradiance were also evaluated. To do so, the ideal LED heights and planting distances obtained at 0 μmol PAR m^{-2} s^{-1} diffuse solar radiation were used to compare with other illuminances, this up to 500 μmol PAR m^{-2} s^{-1} diffuse solar radiation in increments of 50 μmol PAR m^{-2} s^{-1}. 500 μmol PAR m^{-2} s^{-1} is the point at which lamps are generally discarded in practice. All combinations of lamps were simulated, i.e., HPS only, a single LED, double LEDs, single LED with HPS, and double LEDs with HPS.

Cost-efficiency calculation

From the results of the study, a cost calculation is done taking energy and tomato prices into account to see which setup is theoretically most efficient. The average energy price of January 2021 (€30.45 MWh^{-1}) (Elexys, 2022) was used to calculate the cost of each combination of lamps when lit year-round for 16 hours a day. This is a commonly used day length in tomato cultivation. When longer photoperiods are applied, this does not contribute to a higher production and in the long run it is even unfavorable for the plants (Velez-Ramirez et al., 2011). The price of the lamps and their life span were also investigated. For this purpose, a distributor of lighting installations for the horticultural sector was contacted (personal communication with Dumon F., 2021). The price of the lamps was divided by their lifetime so that the investment cost of the lamps could also be considered. This brings the total cost of the lamps to €189,595.68 ha^{-1} $year^{-1}$ (personal communication with Dumon F., 2021).

A theoretical benchmark scenario was used to compare yield gains or losses of different setups, where it was assumed that in the optimal combination with all lights on, there is a tomato yield of 500,000 kg ha^{-1} $year^{-1}$. Based on the differences in simulated photosynthesis, it was then calculated how much less photosynthesis was achieved in combinations with less assimilation light. By multiplying this relative amount by the fictive 500,000 kg ha^{-1}, a theoretical production per hectare was obtained for each lamp combination, assuming that the reduced production was directly and linearly caused by photosynthesis (Buitelaar, 1984; Van Rijssel & De Visser, 1985; De Koning, 1989; Cockshull et al., 1992; Heuvelink, 1995). This production quantity was multiplied by the average price of tomatoes over the winter months of 2020-2021 to obtain a hypothetical turnover. The price per kg tomatoes was €2.0022 in the observed period (March 2020) (Boerenbond, 2021). For each combination, the energy cost of the lamps and the price of the lamps divided by their lifetime were then factored in to get an idea of the profit per combination (Elexys, 2022). Other costs such as labor, infrastructure and planting materials were not considered, because these were assumed to differ only slightly among light combinations, especially if planting and row spacing were kept constant.
Scenarios were evaluated for different light intensities of diffuse sunlight from darkness up to 500 μmol PAR m^{-2} s^{-1} in steps of 50 μmol PAR m^{-2} s^{-1} to evaluate the cost efficiency of the lamp arrangements at various stages of the day and season.

RESULTS AND DISCUSSION

Plant and row distance

When looking at the results for individual plant photosynthesis under assimilation light (with no additional sunlight) in terms of row distance, a rather intuitive pattern emerges (Figure 1A). As the simulations were conducted with a LED interlight bar set between each row regardless of distance, a shorter row distance corresponded to the plants being closer to the light sources. The resulting photosynthesis/row distance pattern is distinctive of a trade-off between higher light intensity at closer distances and better light distribution at further distances. A better distribution of light in the underilluminated lower parts of the canopy can compensate, in part, for the lower light intensity due to the non-linear shape of the light response curve of photosynthesis. Under these conditions, a small amount of light on a shaded leaf can lead to a larger net effect on overall photosynthesis than higher light intensities concentrated on a small subset of the canopy which can lead to local saturation. This effect is similar to the evaluation of 100% HPS versus the same light intensity distributed between 50% HPS and 50% LED interlight, which is observed to lead to consistently higher yields (Deram et al., 2014) due to a better light distribution in the canopy.

By multiplying the number of plants per ha with the accompanying photosynthesis rate for that configuration, a maximal net photosynthesis per greenhouse ground surface area was obtained (Figure 1C, D), which is the relevant metric for the economic implications of these results. The emerging pattern for the row spacing corresponded to highest planting density (Figure 1C), likely because the additional costs of added interlights (which is set to 1 per row regardless of row distance) and plant material was not yet considered in this setup, nor the reduced yield and quality resulting from the low individual production per plant. Additionally, these theoretically very dense row spacings are practically constrained due to making plants inaccessible for harvest, as well as significantly reducing light penetration of natural radiation.

In terms of planting distance (Figure 1B), net photosynthesis per plant was unsurprisingly greater when the plants are further apart with no real limitation, an effect which was observed to be even more pronounced when canopy sunlight penetration is also considered (Amundson et al., 2012). The optimal plant spacing when considering production per area has a similar constraint to the row spacing, with individual plant photosynthesis rapidly decreases due to neighboring plant shading (Figure 1D).

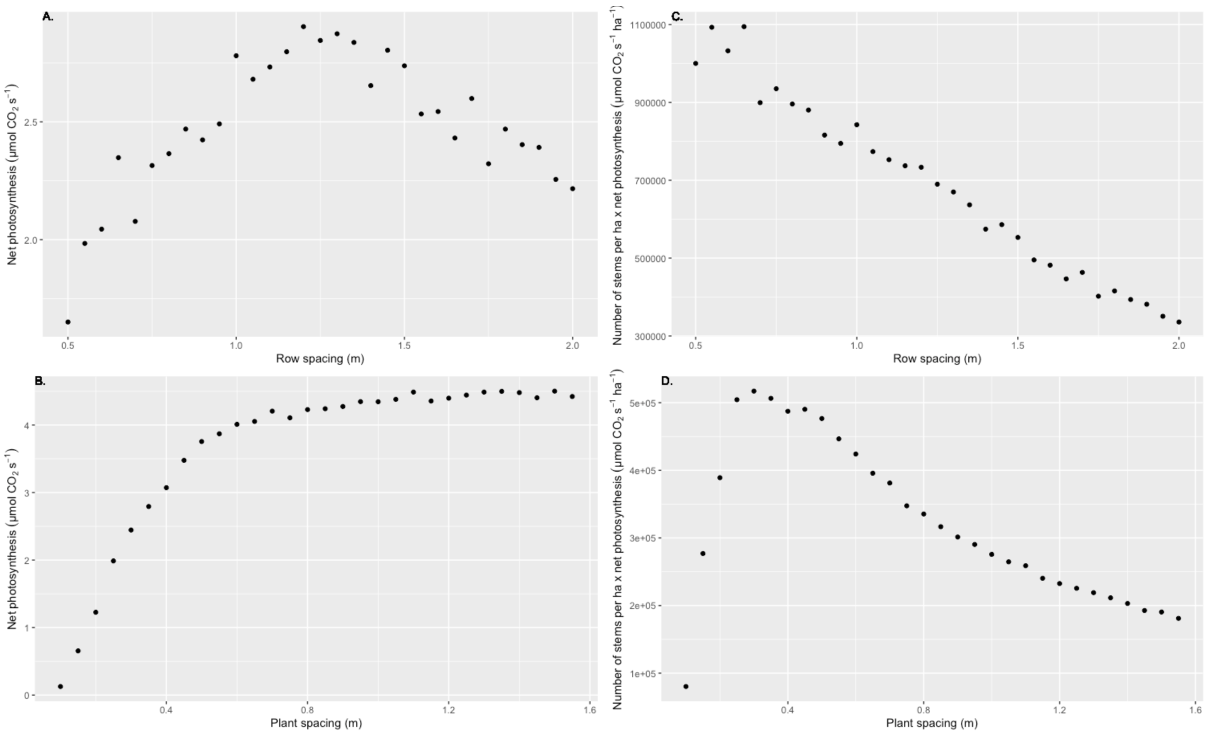

Figure 1. Various light simulations with the goal of identifying (A) optimal row spacing, (B) optimal plant distance, (C) optimal row spacing for maximum production, (D) optimal planting distance for maximum production. The cases for individual plants (A, B) consider solely the photosynthesis on individual plants with no regard for optimizing available space, which is considered in C and D, respectively, by recalculating the results with the number of plants per area with the given plant and row spacing.

Optimal LED height of one LED bar combined with HPS toplighting

Practical research towards light placement optimization has shown promising results for the use of both single and double interlight LED lighting but also illustrates the difficulty of doing manual optimisation (e.g., Moerkens et al., 2016). Hence, the use of 3D models allows more rapid and thorough screening of a large number of potential setups.

When evaluating the optimal position of a single LED bar in combination with HPS toplights at several intensities of solar irradiance, a near identical pattern emerged (Figure 2) illustrating that the optimal height appears to be independent of the incoming solar radiation intensity. The optimal height in each case was found to be around 2 m above the ground which, considering that the plants were placed at a height of 1 m and were 2.96 m tall, constitutes an optimal height of approximately 33% along the main stem. This illustrates that the HPS toplight is highly efficient in providing near saturated light quantities of photosynthesis for the top level of the canopy to which additional LED interlighting provides little benefit. The lower leaf levels, however, remain underutilized without additional lighting. The optimum around 2 m can be explained by the lower light penetration of both HPS and sunlight, but also due to the gradually increasing leaf age within the lower levels of the canopy. The photosynthesis model of Kim-Lieth (2003) used in this model includes an age-dependent function whereby the potential maximum photosynthesis of a leaf depends on its age, with a maximum appearing while the leaf is still relatively young. While this model with model was initially designed for Rose, the photosynthetic data for tomato used to calibrate the FSPM showed a similar pattern (Vermeiren et al., 2020). The older leaves at the bottom of the canopy can thus have lower photosynthesis capacity at similar light intensities than younger ones. The relatively stable pattern displayed regardless of sunlight intensity illustrates the low amount of light penetration at these planting densities.

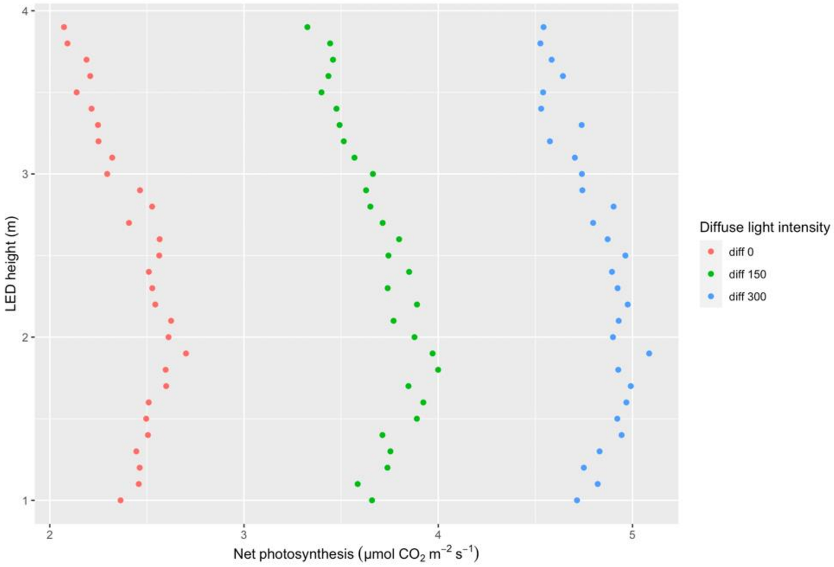

Figure 1. Net full plant photosynthesis simulated for different intensities of diffuse (diff) solar radiation. In each simulation (represented by the individual points), the crop is supplied with HPS toplighting and one LED light bar at varying heights (y-axis).

Optimal LED height for two LED bars combined with HPS toplighting

When repeating the same optimization with not one, but two LED bars, the number of potential combinations substantially increases. Intuitively, it could be expected that the optimal combination will still be found in the lower leaf regions of the canopy similar to the single LED bar. An initial broad search, exploring each 0.5 m combination between 1 and 4 m height confirmed this hypothesis and a more narrow search was conducted. Optimal results were found as 1.60 and 2.10 m, 1.60 and 2.10 m, and 1.80 and 2.00 m for intensities of diffuse light of 0, 150 and 300 μmol PAR m^{-2} s^{-1}, respectively (Figure 3). The lack of variation in optimal placement at different intensities of diffuse sunlight shows also here the low amount of light penetration in the lower levels of the canopy. This is reinforced by the result that optimal placement of the second LED bar is even lower within the canopy, towards the oldest leaves, which otherwise receive very low light intensities.

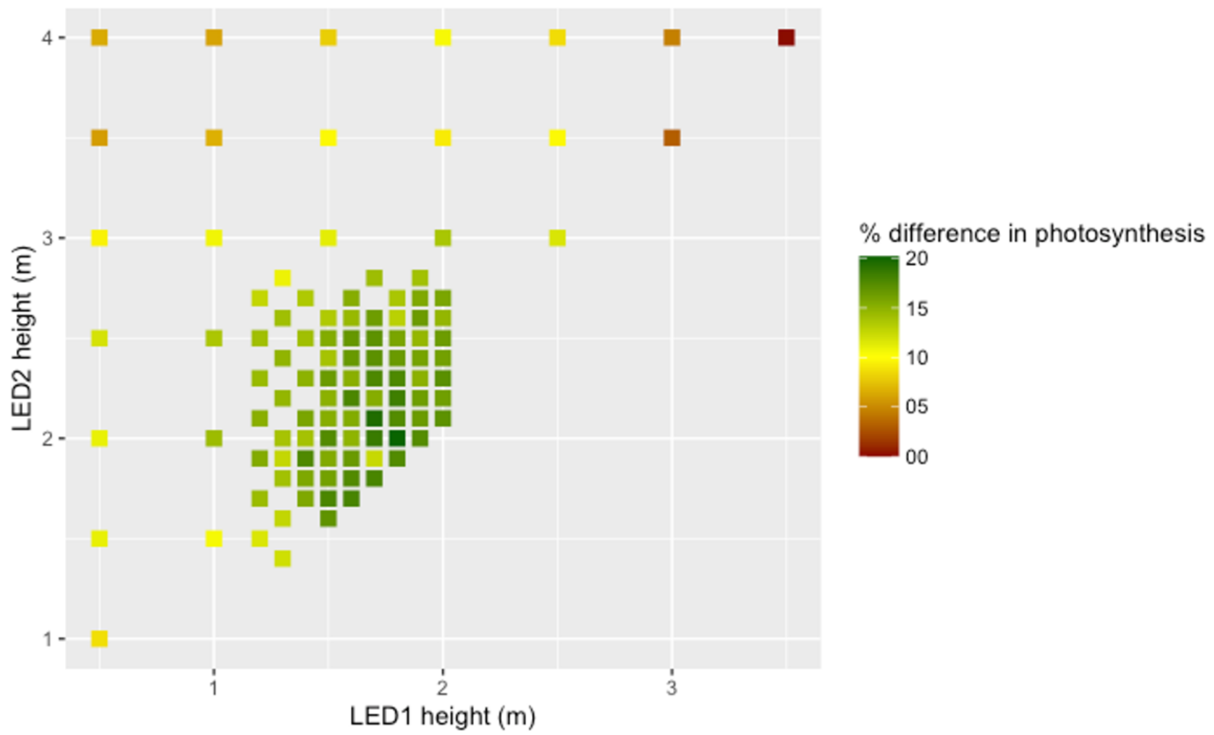

Figure 2. Search for the optimal light emitting diode (LED) height for double LED at 300 µmol PAR m^{-2} s^{-1}. Green: maximum percentage additional photosynthesis relative to lowest value (red).

Efficiency calculation

The theoretical profitability assessment made in this study, which includes only investment and operating costs of assimilation light, with no labor or maintenance costs, demonstrate a clear trend (Figure 4). Even with these rough estimates, economic feasibility of HPS toplights is abundantly clear, with each scenario, regardless of solar irradiance, benefitting from their application. The use of LED interlights, however, is impeded by their high investment costs, and profitability diminishes as the amount of available solar irradiance increases. On a standalone basis (i.e., without toplights), LED interlights are not profitable at very low sunlight intensities. As shown in Figure 4, simulated plants without assimilation light only reach positive net photosynthesis from 200 µmol PAR m^{-2} s^{-1}. This is the result of plant respiration included in the model, which must be overcome to get a net positive result. The base level of profitability is much higher with interlights, as these additional costs also need to be overcome.

At low light intensities the setup with maximal assimilation light was the most profitable. This condition occurs daily at the start and end of the lighting period and therefore maximal use of these lights by a grower is warranted. During low sun irradiance winter days, this condition remains largely unchanged. Only at higher doses of diffuse sunlight, the added benefit of the LED interlights diminishes. Our study suggests that from 200 µmol PAR m^{-2} s^{-1}, a single LED bar becomes more efficient than two, and the scenario with only toplights takes the upper hand from 500 µmol PAR m^{-2} s^{-1} onwards. This means that during sunny days, an active decision could be taken to turn off the interlights to preserve their longevity, as their economic feasibility decreases.

The main purpose of this study was to illustrate the potential of FSPMs as tailor-made decision-support tools for optimizing assimilation light in tomato product. Therefore, the results obtained serve only as an illustrative case-study for a specific situation and thus should not be taken as generalizable conclusions. While the tool was demonstrated to allow for specific and quantifiable decision support, several adjustments could be considered to give more accurate and statistically sound advice. Namely, the tool should be customized to consider specific growing infrastructure and the conditions of direct radiation across the growing season, which can differ with seasonality, orientation, and atmospheric conditions. Additionally changes in plant architecture could affect the results (Chen et al., 2014) and interplant variation could be considered as well. Including these effects is relatively straightforward but will likely require larger-scale simulations whereby variations in natural lighting conditions and plant architecture are simultaneously considered, which was outside of the scope of this research.

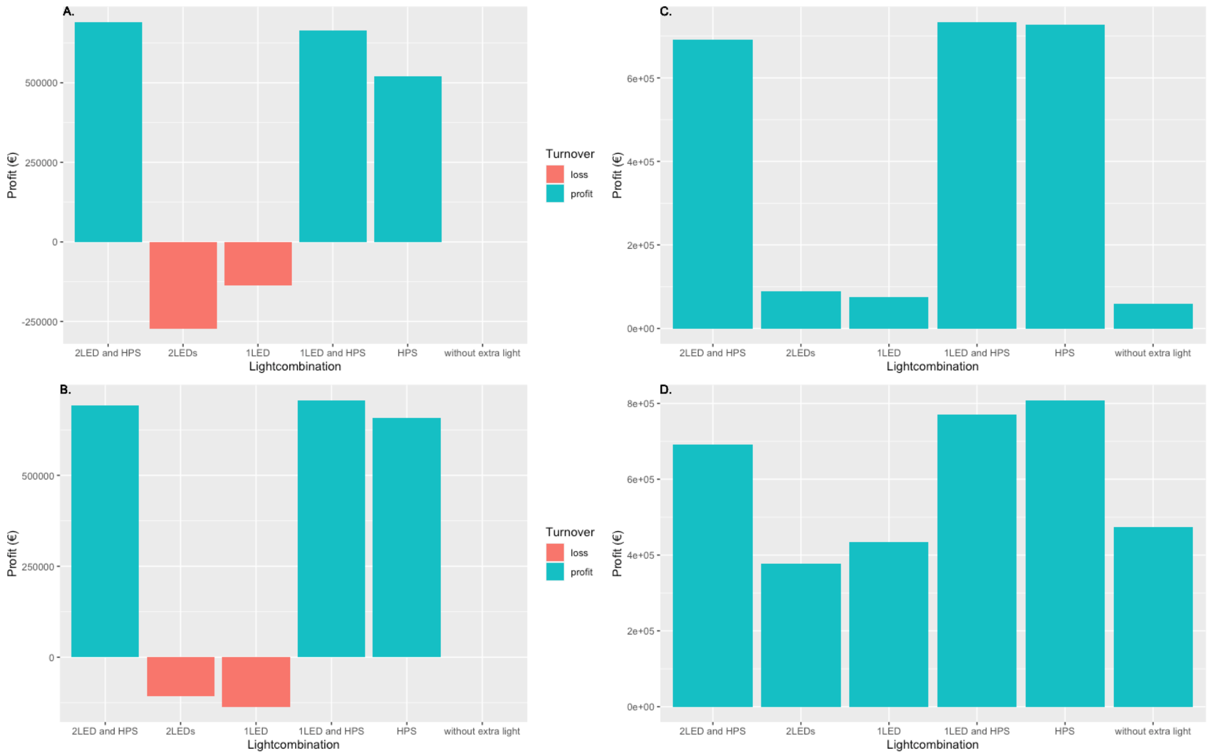

Figure 3. Profit per combination assimilation lighting at 0 (A.), 100 (B.), 200(C.) and 500 (D.) µmol PAR m^{-2} s^{-1}. For the possible combinations of two light emitting diodes (LED) and high-pressure sodium (HPS) lights.

CONCLUSIONS

This study illustrates the use of an FSPM as a tool to easily and quickly perform various virtual optimisation experiments. Such simulations can aid in determining the optimal setups for placing assimilation lights in a tomato greenhouse at different environmental conditions. The economic feasibility of assimilation light heavily depends on investment costs and non-linear response of leaf photosynthesis to additional light, which makes it non-trivial to evaluate. Additionally, this approach has the added benefit of being *in silico*, which makes it unconstrained in terms of time and especially labour and space. Rather than conducting a similar broad search in reality, such a model can prevent the waste of resources by first proposing a set of very likely optimal candidates, which can then be tested in reality.

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