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Research Paper

An improved light efficiency LED array design via increasing uniformity for pea sprouts

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ABSTRACT

Light distribution is an important factor affecting plant growth under facility lighting. However, traditional lighting provides uneven illumination, which increases the difficulty of cultivation management and creates challenges in standardised plant production. Achieving the best light environment is highly significant for high-efficiency production. To effectively address uneven light distribution in the planting layer, this study proposed a high light efficiency LED array design that increases light distribution uniformity based on the improved genetic algorithm. This design has been verified by optical simulation, spectrometer measurement and pea sprout cultivation. The simulation results showed that the illumination uniformity of the optimised LED array and traditional square LED array were 91.7 % and 85.7 %, respectively. The uniformity of the illuminance measured by the spectrometer for two LED arrays was 92.5 % and 80.2 %, respectively. Furthermore, the effects of the two LED arrays on the growth of pea sprouts were compared. The total light intensity of the optimised LED array was reduced by 20.1 % lower; however, the yield of the pea sprouts increased by 8.6 % higher. The light intensity required to produce pea sprouts per unit mass was 26.5 % lower, while the energy and economic efficiency improved. Therefore, the LED array designed based on the improved genetic algorithm has high illumination uniformity and light use efficiency and presents a novel method for improving pea sprout production and lighting optimisation strategy.

Nomenclature

Abbreviations/symbols	
2D	Two dimensional
3D	Three dimensional
GA	Genetic algorithm
IGA	Improved genetic algorithm
LED	Light-emitting diode
PWM	Pulse width modulation
E	Light intensity at a point on the target receiving surface (μmol·m^{-2}·s^{-1})
EE	Energy efficiency (g·kW^{-1})
$\overline{E}$	Average light intensity on target receiving surface (μmol·m^{-2}·s^{-1})
E_{max}	Maximum light intensity on target receiving surface (μmol·m^{-2}·s^{-1})
EF	Evaluation function
fit	Reciprocal of the evaluation function
h	Distance between the receiving surface and the LED plane (mm)
I	Luminous intensity of an individual LED (μmol·m^{-2}·s^{-1})
I_0	Luminous intensity perpendicular to the surface of the light source (μmol·m^{-2}·s^{-1})
m	Lambertian coefficient
N	Number of LEDs
$P(X, Y, 0)$	Individual LED coordinates on the LED plane (mm)
$Q(x_p, y_q, h)$	Coordinates of a point on the light source receiving surface (mm)

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(*continued*)

r	Light illuminance required to produce a unit mass of pea sprouts (μmol·m^{-2}·s^{-1} g^{-1})
T	Cumulative time of pea sprouts growth light period (s)
TIL	Total illuminance of light consumed (μmol·m^{-2}·s^{-1})
TLI	Total light intensity measured on the receiving surface (μmol·m^{-2}·s^{-1})
TY	Total yield (g)
U, V	*U* rows × *V* columns
θ	View angle of the LED (°)
$\theta_{1/2}$	Luminous half angle width (°)
η	Uniformity of light intensity
σ	Standard deviation of the light intensity in the target plane light field (μmol·m^{-2}·s^{-1})

1. Introduction

Light is the energy source for photosynthesis. It triggers a wide range of physiological responses and plays an important role in plant growth, development and physiological metabolism (Jones, 2018; Wang et al., 2021; Zhang et al., 2020). Artificial lighting is a fundamental environmental factor for plant growth in facility horticulture, which enables stable and effective production of horticultural crops (Arabzadeh et al., 2023; Weidner et al., 2021; Zhang, Yang, et al., 2022).

Plant factories use artificial light sources to provide lighting for plants. Specifically, light-emitting diodes (LEDs) are widely used because of their long lifespan, low power consumption and adjustable spectra (Jensen et al., 2018; Katzin et al., 2023; Zou et al., 2020). Artificial light sources can meet the growth needs of many crops, such as tomatoes (*Solanum lycopersicum* L.), lettuce (*Lactuca sativa* L.) and sprouts. Sprouts, such as radishes (*Raphanus sativus* L.) and peas (*Pisum sativum* L.), are widely cultivated in plant factories because of their short growth cycle, low production cost, delicious taste and certain medical and health benefits (Thwe et al., 2014; Zhang, Guo, et al., 2022). The optimal artificial lighting enables the high quality production of plant produce (Balasus et al., 2021).

Light conditions in plant factories include light quality (wavelength), light quantity (intensity), light photoperiod (duration) and light uniformity direction (Zhang et al., 2020). Previous studies have shown that blue LEDs can increase the content of phenolic compounds of pea sprouts (Liu et al., 2016). Under a long photoperiod (22 h/2 h), LED lighting with a red-to-blue ratio of 2:1 (R2B1) was more conducive to improving the antioxidant capacity and nutritional quality of pea sprouts when compared with white light (W), red-to-blue ratio 4:1 (R4B1), and red-to-blue ratio 7:1 (R7B1) (Zhang, Guo, et al., 2022). For some photosensitive crops, even a slight change in light intensity can result in plant growth changes (Chen et al., 2023). Exposure to a light intensity of approximately 30 μmol m^{-2}·s^{-1} increases the soluble sugar and protein levels in pea sprouts (Liu et al., 2016). However, when light is insufficient, plants cannot maximise photosynthesis, which prolongs their respiration, resulting in a net decrease in plant biomass (Ooms et al., 2016). Due to the effect of photoinhibition, the photosynthesis and even the growth of plants will be impaired under excessive light intensity (Zhang et al., 2020). Low light grown plants have frequently been shown to be more susceptible to photoinhibition than those plants grown under high light intensity (Fan et al., 2013; Tian et al., 2017). For an artificial light source with weak light intensity, the linear centralised distribution of traditional lamp panels and the secondary optical design of the LEDs have led to a more uneven light distribution in the cultivation layer (Wu et al., 2020). The highest light intensity occurs at the centre of the planting layer (the centre point of the light intensity receiving surface) and progressively diminishes towards the periphery. When the central light intensity of the planting layer is optimal for the crop, the light intensity at the edge of the planting layer will fall below the optimal value, thereby failing to meet the crop's growth requirements. Conversely, if illumination at the periphery of the planting layer is adjusted to the optimal light intensity for the crop, the light intensity at the centre of the planting layer will become excessive, potentially causing crop damage. Uneven light distribution on the target receptive surface will cause developmental differences in individual plants, resulting in uneven or insufficient growth across plant populations. The uniform growth of plants is a requirement for standardised production and harvesting management processes in plant factories. Uneven light exposure will not only affect standardised cultivation but also affect automatic harvesting standards. Thus, standardised lighting and irradiance uniformity must be achieved in plant factory production (Barceló-Muñoz et al., 2021). From an experimental perspective, the random manual or systematic relocation of plants can ensure the consistency of the experimental materials and reduce the detrimental effects of uneven light intensity (Balázs et al., 2022; Choi et al., 2022). However, this increases the complexity of the experimental management process (Balázs et al., 2022). Moreover, plant relocation can damage the plants and affect the experimental results. Clearly, this is not a viable option for commercial plant factories. Meanwhile, ensuring that all indoor plants receive a uniform light intensity and spectrum is crucial and a necessary condition for indoor experiments investigating the expression of specific genes (Hitz et al., 2019). In general, the uniform distribution of light in the planting layer will significantly impact experimental research, production management, standardised cultivation, and yield. Therefore, the design of uniform artificial light source is a key issue needing to be addressed for current production and experimental systems.

LED lighting uniformity can be achieved via two aspects. The first aspect is improving the structure of the LEDs to achieve a more uniform light intensity. For example, improved uniformity of illumination is achieved using a paraboloid reflector and a free-form lens designed by quadratic optics (Ma and Luo, 2019). Furthermore, diffuse transmission free-form surfaces, based on the LED collimation effect, can also achieve uniform illumination (Zhu et al., 2019). However, the hardware production cost of the secondary optical design is high. The second aspect is the use of intelligent algorithms to optimise the design of the LED arrays to achieve uniform illumination. Alternative machine-learning approaches have been tried and the design of uniformly illuminated LED arrays using simulated annealing and particle swarm optimisation algorithms have been previously reported (Ni et al., 2022; Su et al., 2012). Intelligent optimisation algorithms have some problems, such as high randomness of LED positions, differences between the results and optimisation and time cost that increases with the number of LEDs. The genetic algorithm (GA) approach is widely recognised for its strong robustness, parallelism and extensive application range, making it a popular choice in machine learning, layout optimisation and other fields (Bai et al., 2024; Ren et al., 2022; Sun and Zhou, 2022). A GA simulates the evolutionary behaviour of biological populations and reflects natural selection process (Adade et al., 2024). The algorithm mainly depends on selection, crossover and mutation operators to iteratively develop solutions to complex optimisation problems (Zou et al., 2019). Highly fit individuals are more likely to be selected for reproduction in the next generation than those with lower fitness. However, in few studies have investigated a uniform LED light array design as the artificial light source for plant growth (Wu et al., 2020), especially for sprouts under low light conditions in plant factories.

To improve the production efficiency and standardization of sprout cultivation in plant factories, this study hypothesises that the design of LED arrays within plant factories can be better optimised using an improved genetic algorithm approach. This optimisation aims to address uneven light intensity and low light energy utilisation efficiency in square LED array, while improving the yield and quality of pea sprouts. More specifically, the research objectives of this study are threefold: (1) designing an LED array that can provide uniform light intensity in the planting layer and enhance the growth of pea sprouts; (2) measuring the indicators of pea sprout growth under the optimised LED array; (3) comparing the energy efficiency and economic benefits between the optimised and the traditional square LED array. The results of the study will provide a novel way of thinking about optimisation strategies for the production and lighting of pea sprouts.

2. Materials and methods

2.1. Overall experimental design process

Light distribution in the plant canopy can affect the growth of plants. In this study, the improved genetic algorithm (IGA) is adopted to optimise the artificial light sources for pea sprouts cultivation. Through the evolutionary selection of the IGA, an LED array scheme is designed for uniform light on the plant canopy. The optimised and traditional LED arrays are compared and verified through simulation and actual light field measurement. Building on the LED array optimised by IGA, a cultivation light regulation system is designed, and the cultivation contrast experiment of pea sprouts is prepared in the artificial climate box. A comparative analysis is performed between the IGA-optimised LED array and traditional light sources through cultivation and application (Fig. 1).

2.2. LED uniform light array light source

2.2.1. LED array lighting model

An individual LED is equivalent to a point light source. Light intensity differs significantly at different dispersion angles. The highest light intensity is at the centre of the point light source, gradually decreasing towards the edges (Fig. 2a). In actual cultivation environments, the light intensity at the centre of the planting layer is higher while the surrounding light intensity is lower due to the overlapping of multiple light beams in traditional matrix light sources. Therefore, the LED array must be optimised based on the principles of LED lighting model. According to Lambert's theorem, the luminous intensity of an individual LED can be expressed using Eq. (1) (Moreno et al., 2006; Qin et al., 2010):

$$I = I_0 \cos^m \theta \tag{1}$$

where θ is the view angle of the LED, and I_0 is the luminous intensity perpendicular to the surface of the light source. The number of m depends on the luminous half angle width $\theta_{1/2}$, which is usually provided by the manufacturer.

The light intensity of the target plane is determined by the distance of the light source (h), the luminous parameters of the LED (I, θ) and the number of LEDs (Fig. 2b). The light intensity generated by an individual

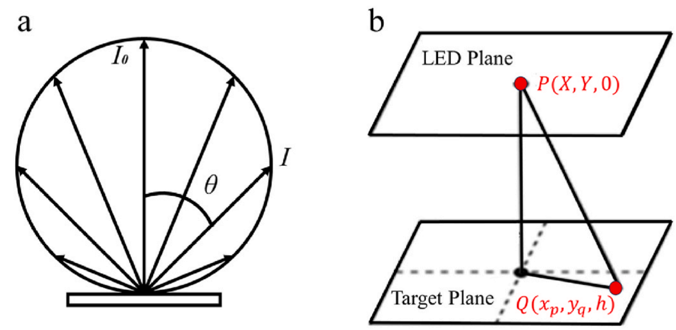

Fig. 2. (a) LED Lambert distribution, θ is the view angle of the LED, I_0 is luminous intensity at the vertical direction to the source surface, I is the luminous intensity. (b) LED array lighting model, P is the coordinates of the LEDs on the LED array, and Q represents the coordinates of a point on the target plane.

LED P $(X, Y, 0)$ on the LED light source plane at coordinate Q (x_p, y_q, h) on the target plane are expressed using Eq. (2) (Abeysekera et al., 2020; Su et al., 2012; Wang et al., 2011):

$$E\left(x_p, y_q, h\right) = \frac{I_0 h^{m+1}}{\left[\left(x_p - X\right)^2 + \left(y_q - Y\right)^2 + h^2\right]^{\frac{m+3}{2}}} \tag{2}$$

The light intensity in the light source receiving surface is produced by the superposition of discrete LEDs. Each LED is assumed to be an ideal Lambertian source. When N LEDs are present on the LED array, the light intensity generated by the LED array at the Q (x, y, h) point on the target plane is given by Eq. (3):

$$E\left(x_p, y_q, h\right) = \sum_{n=1}^{N} \frac{I_0 h^{m+1}}{\left[\left(x_p - X_n\right)^2 + \left(y_q - Y_n\right)^2 + h^2\right]^{\frac{m+3}{2}}} \tag{3}$$

where (X_n, Y_n, h) are the coordinates of the $n-th$ LED in the LED array.

2.2.2. LED uniform light optimisation algorithm

In traditional genetic algorithms (GAs), the initialisation of the population significantly impacts both the quality of the results and the convergence speed of the algorithm. The initial population is randomly generated in most cases. Consequently, the initial population usually consists of solutions with relatively poor quality (Vlašić et al., 2019).

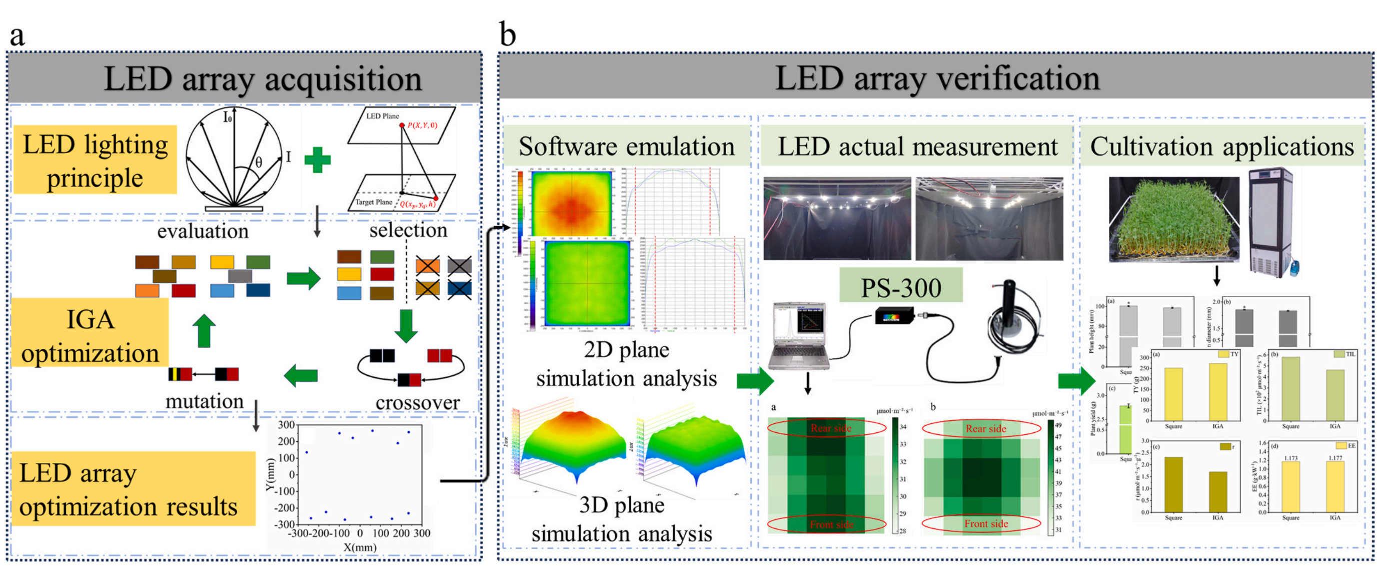

Fig. 1. Overall experimental design (a) LED array acquisition: integrate LED lighting principle into the improved genetic algorithm to obtain the optimised array; (b) LED array verification: verify through software simulation, spectrometer measurement and pea sprout cultivation.

Furthermore, the mutation process is also random, which requires a prolonged duration for obtaining satisfactory results.

To address this, an improved genetic algorithm (IGA) obtained through population initialisation and a variation range constraint is proposed. Specifically, in this study, prior to the initialisation, the input quantities of the coordinates of the 12 LEDs are constrained. First, the entire LED array is designed to exhibit a certain symmetry. It was divided into two parts in the horizontal axis direction and six parts in the vertical axis direction (Fig. 3a). After obtaining 12 partitions, each LED is initialised within the defined boundary conditions. Second, the variation range constraint is also derived from the above-mentioned partitioning design. The LED coordinate in each partition undergoes customised mutation operations, rather than the traditional random mutation. The LED coordinates within each region are initialised and mutated within their own region to accelerate the convergence speed of the algorithm and improve the quality of the final solution. In this study, the population size is set to 100, the maximum number of iterations is 500, the crossover rate is 0.8, and the mutation rate is 0.1. The basic flowchart is shown in Fig. 3b, in which the selection operation utilises the roulette principle. This study is programmed in Python 3.7.

In this optimisation, the ratio of the standard error of irradiance to the mean irradiance value is used as an evaluation function for assessing the uniformity of the target plane light field. A smaller value refers to the more uniform light field, which can be expressed as Eq. (4) (Su et al., 2012):

$$EF(x_1, y_1; \ldots; x_i, y_i; \ldots x_n, y_n) = \sigma / \overline{E} \tag{4}$$

where σ is the standard deviation of the light intensity in the target plane light field, which can be calculated using Eq. (5):

$$\sigma = \sqrt{\frac{1}{U \times V} \sum_{p=1}^{U} \sum_{q=1}^{V} \left[E\left(x_p, y_q, z\right) - \overline{E} \right]^2} \tag{5}$$

The average light intensity is obtained by dividing the target plane into $U \times V$ grids, which can be calculated using Eq. (6):

$$\overline{E} = \frac{1}{U \times V} \sum_{p=1}^{U} \sum_{q=1}^{V} E\left(x_p, y_q, h\right) \tag{6}$$

The optimal coordinates of the LEDs are determined by iteratively calculating the value of the evaluation function. To optimise the layout of the LED array and achieve a high level of light uniformity in the planting layer, the evaluation function EF needs to be minimised. A smaller EF value indicates a smaller difference in the light intensity around the target illumination surface and thus a higher level of uniformity. The IGA is required to maximise its fitness function value. Therefore, in this study, the fitness value is defined as Eq. (7):

$$fit = 1/EF \tag{7}$$

The independent variable in the evaluation function (fit) consists of the coordinates of all the LEDs. At this point, the higher the fit, the higher the light uniformity. Furthermore, changing the fitness function of the GA is difficult after it reaches a certain number of iterations. In this study, a rule of direct outputs is also designed if the fitness is consistent for 100 consecutive generations, thereby ensuring the reduction of time costs (Fig. 3b). The method combined with the constraints of population initialisation and mutation can determine the optimised LED coordinates more effectively and construct an LED array capable of realising a high uniformity of light intensity in the planting layer.

2.2.3. Simulation and measurement method of uniform light LED array

Both the IGA-optimised and traditional square LED arrays (3×4) are verified and compared using optical simulation and actual light field measurements. The optical simulation is carried out through TracePro® software (Lambda Research Corporation, USA), using a circular lattice point light source to simulate an individual LED. The total luminous flux of an individual LED model is set to 210 lm, the luminous half-angle is 60°, the number of light rays is 21,421 (number of rings is 85) and the simulation acceptance surface is located 500 mm from and directly underneath the light source. Furthermore, to replicate the actual cultivation environment, while reducing the impact of inaccurate calculation results caused by the omission of part of the edge light resulting from edge truncation, the size of the simulation receiving surface is set to 500 mm × 500 mm, subdivided into 128 × 128 areas for calculation, and then downscaled to the target area of 400 mm × 400 mm to calculate the irradiance uniformity.

The actual experimental light field is measured using a PS-300 spectrometer (StellarNet, Inc., Florida, USA) in an artificial climate box. A black light-absorbing cloth is used to cover the side walls of the artificial climate chamber to block the influence of light reflection. The target receiving surface is positioned at a distance of 500 mm from the LED array and measured 400 mm × 400 mm. During the experiment, the target receiving surface was divided into a grid of 6 × 6 measurement

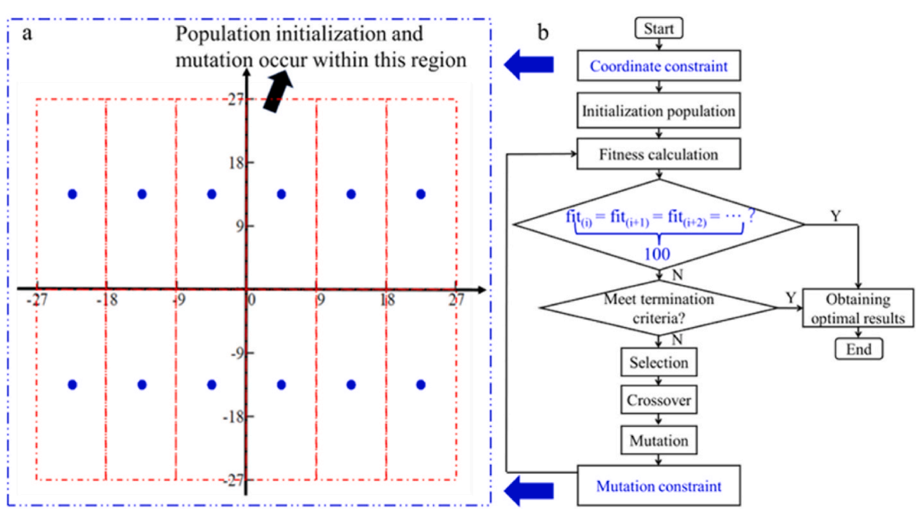

Fig. 3. (a) Spatial constraints for population initialisation and mutation in the improved genetic algorithm (IGA). The 12 blue dots represent 12 LEDs, the red dashed lines denote the optimisation regions for the LEDs, and the blue dashed lines indicate the overall constraint method; (b) Flowchart of the IGA. The blue arrows indicate that the coordinate constraint and mutation constraint in the flowchart adopt the overall constraint method defined by the blue dashed lines in (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

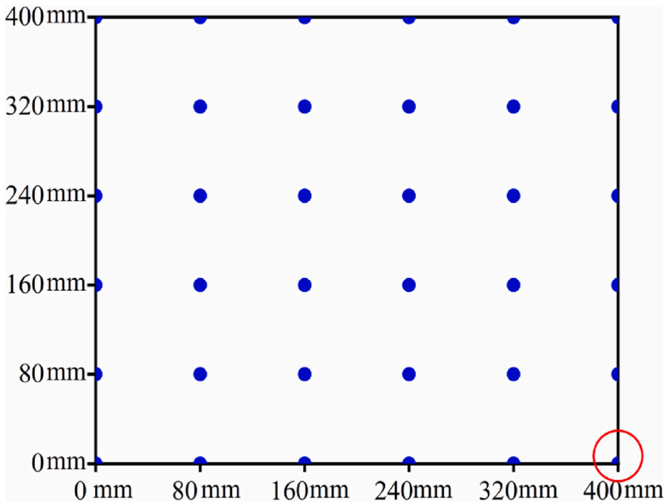

Fig. 4. Thirty-six grid points of the measured plane. The light intensity in the red area was set to 30 μmol $m^{-2}·s^{-1}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

points (Fig. 4). The marker points (Fig. 4) are determined by a light intensity of 30 μmol $m^{-2}·s^{-1}$, which is the requirement for pea sprouts cultivation. Finally, 36 grid points of the two light sources are measured and recorded respectively. To evaluate the lighting uniformity on the target plane, the parameter describing the uniformity of lighting η was calculated using the formula in Eq. (8) (Bai et al., 2021):

$$\eta = \overline{E}/E_{max} \tag{8}$$

where $\overline{E}$ represents the average irradiance of all grids on the target plane.

2.3. Cultivation and application

2.3.1. Experimental materials and cultivation environment

The experiment was conducted at Anhui Agricultural University from July to October 2023. The spotted pea (*Pisum sativum* L.) was provided by Nanjing Lufengyuan Seed Company. Seeds are sown in a 400 mm × 400 mm seedling tray with one seed in each hole (planting density: ~1.36 kg m^{-2}), and the tray is soaked in water. The tray is then placed in the artificial climate box (RGL-P500D-CO_2, Hefei Youke Scientific Equipment Co. Ltd, Hefei City, China). The cultivation plane is placed 500 mm directly below the LED array. Seeds are first germinated in an artificial climate chamber in the dark (25 °C and 85 % humidity). Furthermore, spare seeds are soaked during the same time period as described above to replace germination failures to ensure 100 % germination. When the seeds have germinated and grown to ~20 mm (about 48 h), LED arrays (3 W white light LEDs at 6500 K) are used to irradiate the pea sprouts. The photoperiod is set to 14 h/10 h (light/dark), and the light intensity set to 30 μmol $m^{-2}·s^{-1}$. The position where the light intensity is set is the same as that in Fig. 4. The temperature in the artificial climatic chamber is maintained at 25 °C with 80 % humidity, and air circulation is maintained inside the chamber. The

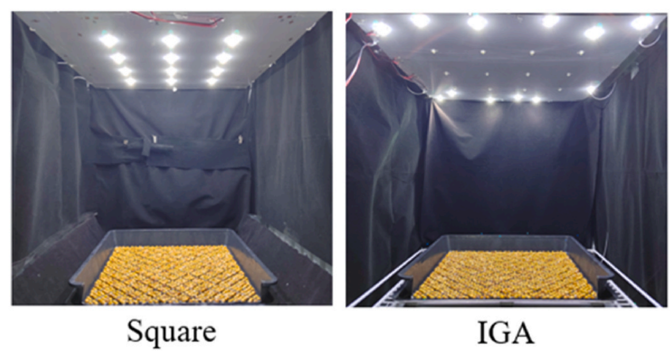

Fig. 6. The cultivated light environment was provided by IGA and square LED array.

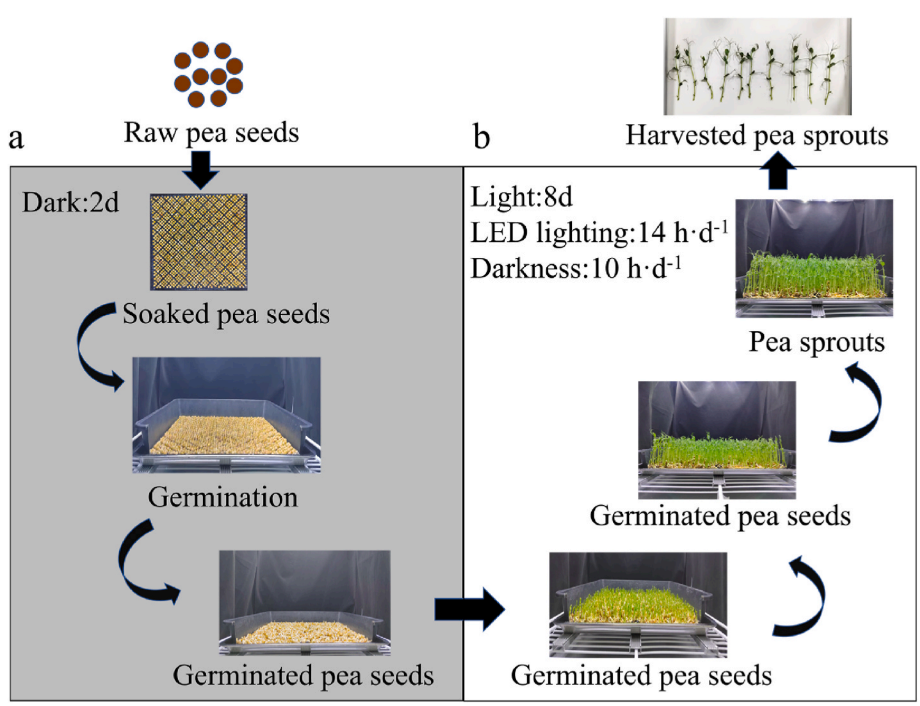

Fig. 5. The growth and cultivation process of pea sprout (a) Dark: sprouting in the dark; (b) Light: daily light processing is 14h/10h (day/night) for a total of 8 days.

cultivation method for pea sprouts is shown in Fig. 5.

2.3.2. Cultivation experiment design

To explore the effect of light intensity uniformity on plant growth, a controlled-environment light uniformity experiment is performed in an incubator (Fig. 6). The driving modes of the IGA-optimised and traditional square LED arrays in the artificial climate box are identical. The LEDs for each array are divided into two groups, with each group containing 6 LEDs. Both groups are controlled by the same pulse width modulation (PWM) signal. The duty cycle of the PWM signal is adjusted by changing the resistance value of the sliding rheostat, to control the light intensity of the entire LED array. The light intensity is set to 30 μmol $m^{-2}\cdot s^{-1}$. Photos are taken from the vertical and horizontal directions once a day. Irrigation water is replenished in a timely manner, and meticulous daily management is performed, including temperature, humidity and light conditions monitoring and ensuring proper ventilation.

2.4. Index measurement method

2.4.1. Biomass index

After 8 days of LED array irradiation, the pea sprouts grew to approximately 100 mm, and the true leaves at the top are ready for harvest as soon as they unfolded. Measurements of relevant data are made by cutting the sprouts 20–30 mm from the root (first young shoot from below). The measurements included plant height, stem diameter, and pea sprout yield.

The whole plate of pea sprouts is divided equally into 16 areas, and 10 plant samples are collected from each area (Fig. 7). The plant height is measured with a ruler from the first tender leaf at the bottom of the plant to the top leaf. The stem diameter is measured using an electronic vernier calliper, and the average value of two measurements taken from two different directions (0° and 90°) is obtained. During the measurement, care is taken to ensure the plants remain intact to reduce errors in subsequent weight measurements. Plant yield was determined through an electronic balance. The plant samples are dried in an oven at 75 °C until a constant weight was obtained. An electronic balance is then used to measure the dry weight. The entire experiment on the germination, growth, and index measurement of pea sprouts is repeated twice. The health index is determined using Eq. (9) (Fan et al., 2013):

$$Health\ index = \frac{stem\ diameter}{stem\ height} \times dry\ weight \tag{9}$$

An independent sample *t*-test was performed using SPSS25 statistical software (SPSS, Inc., Chicago, IL, USA) to assess the significant differences in the measurements of the two LED arrays. $P < 0.05$ indicates a significant difference. Furthermore, the total output of the sample, including the remaining pea sprouts, are analysed to calculate economic benefits.

2.4.2. Energy efficiency index

Energy efficiency (EE) was determined using Eq. (10) (Fan et al., 2013):

$$EE = \frac{Dry\ weight}{Power\ consumed\ by\ LEDs} \tag{10}$$

The total illuminance of light consumed (*TIL*) and light illuminance required to produce a unit mass of pea sprouts (*r*) during pea sprout growth are calculated as follows (Chen et al., 2023):

$$TIL = \frac{TLI \times T}{1000000} \tag{11}$$

where *TLI* is the total light intensity measured on the receiving surface ($\mu mol\cdot m^{-2}\cdot s^{-1}$); and *T* is the cumulative time of pea sprouts growth light period (s);

$$r = \frac{TIL}{TY} \tag{12}$$

where *r* is light illuminance required to produce a unit mass of pea sprouts in $\mu mol\cdot m^{-2}\cdot s^{-1}\ g^{-1}$, and *TY* is the total yield of pea sprouts (g).

2.4.3. Electrical parameter index

The voltage and current of the LED arrays circuit are measured using a digital multimeter (UT890C). The electric power consumption and electricity cost of the two LED arrays are calculated. The energy consumption of the two LED arrays and the economic benefits in pea sprouts cultivation are comparatively analysed.

3. Results and discussion

3.1. Effect analysis of the improved genetic algorithm

The maximum iteration of the program was set as 500. The program terminated if it has not changed for 100 consecutive generations, or the program has run the maximum iteration. The termination condition of GA was reaching the maximum iteration number of 500 (Fig. S1a), but

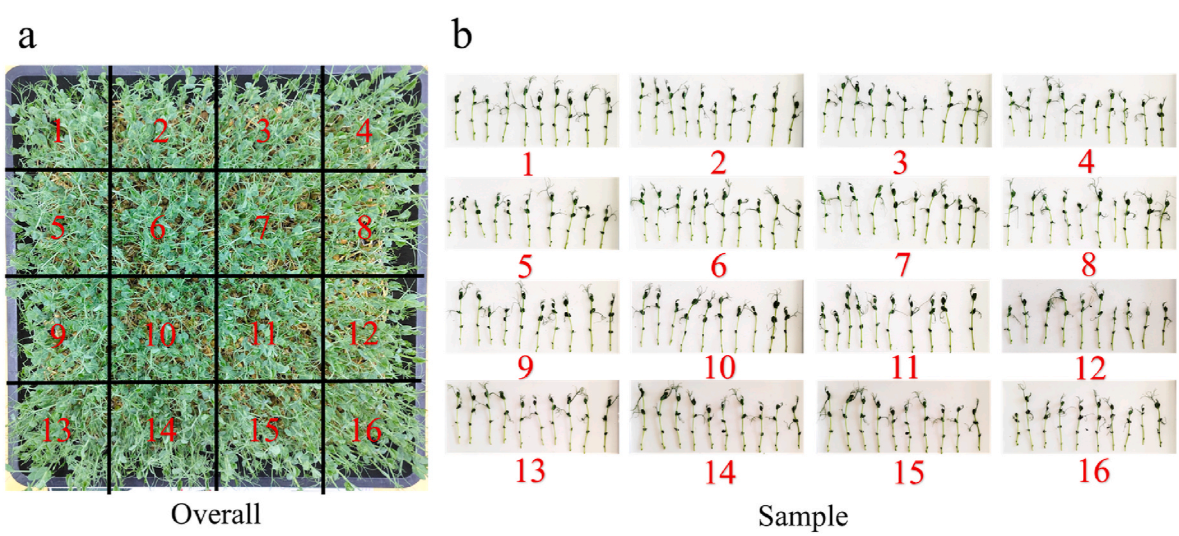

Fig. 7. Data collection methods for pea sprouts (a) the regional division of the overall population into sampling areas, and (b) images of the random selection of 10 plants in each corresponding region as the samples to be measured.

IGA satisfied the termination condition of no change for 100 consecutive generations at the 125th generation (Fig. S1b). At the same time, the fitness of IGA was higher and the optimisation effect was better.

The fitness function of GA reached 15.8 at the 25th generation. When the GA reached the maximum number of iterations of 500 generations, the obtained fitness function fit value was 17.0 (Fig. S1a). In contrast, the fitness function fit value of the IGA has already reached 16.6 in the first iteration, increased to 22.1 in the 25th iteration, and the algorithm has stopped in the 125th iteration, demonstrating excellent optimisation performance and efficient convergence characteristics (Fig. S1b).

3.2. Analysis of simulation results of uniform light LED array

To verify the feasibility of optimising the LED array, the coordinates of the IGA-optimised LED array and the traditional square LED array were imported into the optical simulation software. The light source parameters that met the requirements were set in the software for comparative analysis. The traditional square array was designed as a 3 × 4 equally spaced distribution. The arrangements of the coordinates of the two arrays are shown in Fig. 8a and b.

The irradiance maps and profiles of the two LED arrays are shown in Fig. 8c–f. The range of light intensity fluctuation of each point in the horizontal and vertical directions of the IGA target receiving surface was smaller than that of the square. Fig. 8e & f presents the square spot of the

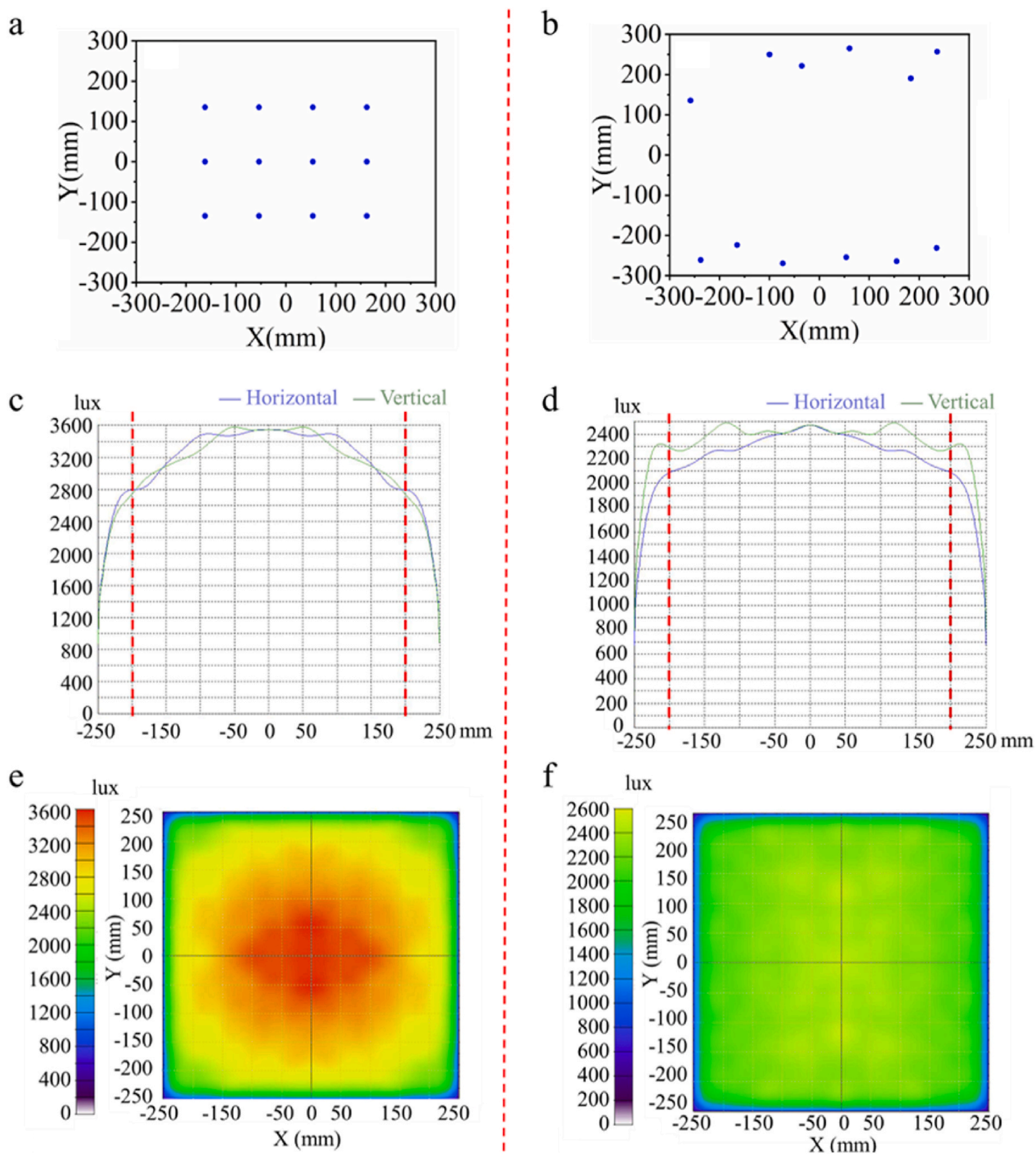

Fig. 8. Comparison of the simulation results between the traditional square LED array and the IGA-optimised LED array. Array arrangements for (a) the traditional square approach and (b) IGA-optimised solutions; Horizontal (blue line) and vertical (green line) light intensity distribution for (c) the traditional square LED array and (d) IGA-optimised LED array (the red vertical lines denote the size of the light source receiving surface); Irradiance maps of (e) the traditional square LED array and (f) the IGA-optimised LED array. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

500 × 500 mm plane. These two figures plainly show that the light intensity uniformity of the IGA was better than that of the traditional square array. Furthermore, after downsizing the plane area to that of the target plane of 400 × 400 mm (approximately 102 × 102 areas), the uniformity of the IGA-optimised array and traditional square array were 91.7 % and 85.7 %, respectively. The IGA-optimised array irradiance decreased at a much flatter slope from the centre to the target edge (red dashed line in Fig. 8d). Furthermore, the IGA-optimised array had fewer LEDs on both sides of the horizontal axis and generated relatively low irradiance in the horizontal direction (Fig. 8d). In the 3D space, the irradiance distribution of the IGA-optimised LED arrays fluctuated less and was flatter and more uniform in the vertical direction of space (Fig. S2a and S2b). In general, the simulation result of the LED array designed by the IGA was better than that of the traditional square array and aligned with actual conditions.

3.3. Analysis of the measured results of uniform light LED array

Based on the software simulation, practical spectrometer measurements were performed on the IGA-optimised and traditional square LED arrays before the formal cultivation of the experiment. A portable PS-300 spectrometer was used to measure the light intensity at the target plane. The light intensity at each point, with wavelengths between 400 and 700 nm, was summed and analysed. The thermograms of the measured spectrometer results for both LED arrays are shown in Fig. 9.

The two types of LED arrays were compared by analysis and calculation (Table 1). The range of the traditional square LED array was approximately three times that of the IGA-optimised LED array, and the standard deviation for the traditional array was also approximately three times greater, which further demonstrated that the light intensity fluctuation of the IGA-optimised LED array was small. Furthermore, the illuminance uniformity of the IGA-optimised LED array measured on the spectrometer was 92.5 %, which is better than that of the traditional square array (80.2 %).

The LED array designed in this study was further characterised. The LEDs were distributed on both the front and rear sides. No LEDs were distributed towards the left and right directions. As confirmed by the measurement results of the LED array, the light intensity in the left and right directions was slightly lower, which is in line with reality. The light intensity on the target receiving surface (at the planting level or canopy) reached 30 μmol $m^{-2} \cdot s^{-1}$, thereby satisfying the light intensity requirement of pea sprouts.

3.4. Cultivation verification results

The two LED arrays produced light intensities with different levels of uniformity. These differences can be used to evaluate the effects of different light uniformities on crop growth and development. A comparison of the pea sprout growth indicators under the two types of LED array irradiation is shown in Table 2.

Significant differences were observed in plant height, stem diameter and yield of pea sprouts under different LED arrays. Compared with the square LED array, the height of pea sprouts under irradiation by the IGA-optimised LED array decreased by 1.9 %, the stem diameter decreased by 1.6 % and the yield increased by 5.8 % (Table 2). The decrease in light intensity uniformity in the planting layer increased the average height of the pea sprouts. Under irradiation by the IGA-optimised array, the yield of pea sprouts was higher than that under the square array. Thus, poor uniformity of light intensity in the crop canopy (cultivation layer) decreases the pea sprout yield. The results confirmed further that light uniformity influenced the pea sprout yield, which had not been reported thus far in other studies. However, the yield under irradiation by the traditional square LED array was lower, which may be caused by the significant difference in light intensity, low light uniformity on the planting surface and high average light intensity. Strong light may damage the photosynthetic cells and inhibit the accumulation of organic matter (Chen et al., 2022; Fan et al., 2013). Notably, the health index of pea sprouts under the IGA-optimised LED array was higher than that under the square LED array (Table 2). This indicated that significant differences in light intensity on the planting surface inhibited the pea sprout growth.

3.5. Analysis of light energy utilisation efficiency

Plant factories or vertical agriculture have introduced the concept of sustainable development, aiming to significantly reduce electricity consumption in controlled environment agriculture (Balasus et al., 2021). Compared with traditional field crop production, plant factories or vertical farming are expensive to run because they require large amounts of electricity (Arabzadeh et al., 2023). Therefore, optimising LED array lighting, reducing power costs and improving light energy utilisation efficiency are valuable achievements in plant factories.

The total light intensity on the traditional square LED array was higher (Table 3). The total light intensity of the IGA-optimised LED array is 20.1 % less than that of the traditional square LED array. However, the total pea sprout yield under IGA-optimised array increased by 8.6 % (Table 3). Furthermore, compared with the traditional square array, the light intensity required by the IGA-optimised LED array to produce pea sprouts per unit mass was lower by 26.5 % (Table 3). Therefore, these findings emphasize the important effects of uniform lighting on plant growth and yield. Notably, energy efficiency under the optimised LED array increased slightly (Table 3). The improvement in energy efficiency was also relatively small. However, if the optimised LED array was used on a larger scale, the improvement in the energy efficiency would be more significant. Because the edge relationship can be combined between multiple light receiving surfaces in the same layer, further

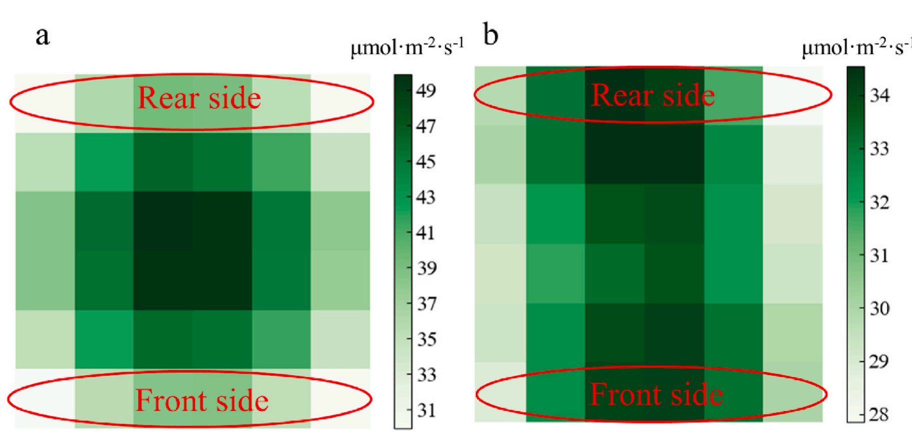

Fig. 9. Spectrometer measurements for (a) the traditional square array and (b) IGA-optimised array.

Table 1
Parameter comparison results of two LED arrays.

LED array types	Maximum value ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Minimum value ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Range ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Mean value ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Standard deviation ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Unifor-mity (%)
Square	49.9	29.9	20.0	40.0	6.0	80.2
IGA	34.5	27.9	6.6	31.9	2.1	92.5

Table 2
Comparison of growth indicators, namely plant height, stem thickness, plant yield and health index under two LED arrays. The data are represented as the Mean ± standard error of the mean. NS represents not significant at $P < 0.05$ levels ($n = 320$), * represents a significant difference at $P < 0.05$ levels ($n = 320$).

LED array types	Plant height (mm)	Stem diameter (mm)	Plant yield (g)	Health index ($\times 10^4$)
Square	100.59 ± 0.71	1.86 ± 0.01	2.78 ± 0.04	5.16 ± 0.02
IGA	98.69 ± 0.59	1.83 ± 0.01	2.94 ± 0.04	5.41 ± 0.08
Level of significance	*	*	*	NS

Table 3
Comparative results of total yield (*TY*), the total illuminance of light (*TIL*), light energy utilisation efficiency (*r*) and energy efficiency (*EE*) using IGA and square LED arrays.

LED array types	*TY* (g)	*TIL* ($\times 10^2$ $\mu mol \cdot m^{-2} \cdot s^{-1}$)	*r* ($\mu mol \cdot m^{-2} \cdot s^{-1} g^{-1}$)	*EE* ($g \cdot kW^{-1}$)
Square	251.33	5.80	2.31	1.17
IGA	272.90	4.63	1.70	1.18

increases in the constraint and overall design consciousness can be made. Therefore, as the scale of crop production increases, large-scale production can effectively utilise marginal light sources and increase the cultivation area, significantly increasing energy efficiency.

By optimising the layout and use of LED arrays, plant factories can increase the efficiency of light energy use, improve production efficiency and reduce energy consumption. Therefore, although the increase in energy efficiency may be small, these optimisation measures will significantly impact large scale cultivation, enhancing efficiency in sustainable agriculture and food production. This study used the optimised LED array to produce more and healthier pea sprouts while improving energy efficiency and light use efficiency, which are undoubtedly a wise and feasible choice.

3.6. Economic benefit analysis

In this study, the cultivation environment factors were the same under both LED arrays, differing only in electric power usage. The electricity cost required for the cultivation of pea sprouts is shown in Table 4. The electricity cost of the optimised LED array is USD 0.01 more than that of the traditional square LED array. The lowest market price for organic sprouts in China is currently USD 0.57 per 500 g. If calculated based on the lowest price, the optimised LED array needs to increase production by at least 8.77 g in order to save costs compared with the square LED array.

The total yield of pea sprouts obtained from the LED array optimised by IGA increased by an average of 21.57 g compared with the traditional square LED array (Table 3). The pea sprout yield increased under extremely low electricity consumption. Although the IGA-optimised LED array used a little more power, it yielded more and healthier pea sprouts. Through market sales, the slightly higher electricity cost can be easily recovered through market sales. As mentioned earlier, the LEDs of the

Table 4
Comparison of the electricity costs required for growing pea sprouts.

LED array types	Electrical power (W)	Electric work (KWH)	Total electricity bill (USD)
Square	23.87	2.67	0.15
IGA	24.75	2.77	0.16

IGA-optimised LED array were mainly distributed on the front and rear sides. Compared with the traditional square LED array, part of the light energy was emitted out of the target receiving surface, which is not used in plant cultivation. This also causes slightly higher electrical consumption by IGA-optimised LED arrays when the same lighting intensity was set at the same location. The IGA-optimised LED array offered certain economic benefits and practical application value.

4. Conclusion

In this study, the effect of light uniformity on pea sprouts was investigated using an IGA-optimised LED array designed in-house. The effect of light uniformity on the pea sprout growth was studied and compared with that of the traditional LED array. The IGA-optimised LED array exhibited higher light uniformity, which were consistent with the simulation and measurement results of the light source. Under the IGA-optimised LED array, a higher pea sprout yield was obtained, with better quality and more vigorous growth. Therefore, pea sprout growers should consider optimising light uniformity to increase and maximise production while strengthening seedlings. The energy efficiency and light energy use efficiency were highly improved at only a slightly higher electrical cost.

CRediT authorship contribution statement

Li Du: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yang Xu:** Validation, Data curation. **Can Wang:** Data curation. **Yiyi Chen:** Data curation. **Junhua Zhang:** Writing – review & editing, Software, Investigation, Funding acquisition, Data curation, Conceptualization. **Bin Ma:** Data curation. **Danyan Chen:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.biosystemseng.2025.104290.

Data availability

The code was released on GitHub (https://github.com/Xy14z/Improved-genetic-algorithm-IGA-.git).

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