EFFECT OF LED LIGHT INCIDENCE ANGLE ON MORPHOMETRIC TRAITS AND PRODUCTIVITY OF HOT PEPPER ‘HUNGARIAN YELLOW’ IN AN EBB-AND-FLOW SYSTEM

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Abstract. The subject of the study is the quantitative relationship between the geometry of the light field created by light-emitting diode sources and the morphometric structure, biomass accumulation and early generative performance of hot pepper (*Capsicum annuum* L.) of the Hungarian Wax type, cultivar Uhorskyi Zhovtyi, grown in an ebb-and-flow hydroponic module under fully artificial lighting. Whereas photon flux density, spectral composition and photoperiod have been extensively characterised for most greenhouse vegetables, the angle at which the photon flux crosses the canopy surface remains a largely unexploited control variable, even though it determines how the emitted photons are distributed among the productive layers of foliage.

The methodology was based on a single-factor design with three lighting treatments that differed exclusively in the geometry of the light field: treatment A (control), in which the entire flux was delivered vertically from above at an incidence angle of 90 degrees; treatment B, in which the entire flux was delivered from above and to the side at 45 degrees; and treatment C, a combined scheme in which 70 per cent of the flux was delivered vertically and 30 per cent laterally at 45 degrees. Five plants per treatment were recorded, giving fifteen experimental units in total. The critical methodological requirement was the equalisation of photosynthetic photon flux density at the level of the upper leaf layer across all treatments, achieved by adjusting the distance between the luminaires and the plants and verified weekly with a quantum sensor; without this correction the cosine law would have introduced an intensity difference of

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approximately 29 per cent and the effects of geometry and intensity could not have been separated. Nutrient solution composition, electrical conductivity, pH, air and solution temperature, relative humidity, photoperiod duration and flooding regime were held identical in all treatments. Plant height, stem diameter, stem deviation angle, crown projection radii on the illuminated and shaded sides, average internode length and the number of buds and flowers were recorded on days 0, 7, 14, 21 and 28. Fresh and dry mass of shoots and roots and the number of set fruits were determined on day 28. A crown asymmetry index and a compactness index were calculated, together with absolute and relative growth rates, shoot-to-root ratio, dry matter content, node number, specific productivity and the realisation coefficient of generative structures. Data were processed by one-way analysis of variance with the least significant difference at the five per cent level, Pearson correlation and linear regression.

The aim of the study was to establish the quantitative effect of light incidence angle on the morphometric traits, biomass accumulation and early productivity of hot pepper and to substantiate a lighting configuration that offers the best balance between biomass gain and preservation of a technologically acceptable plant architecture.

The results demonstrate that the geometry of the light field is an independent and quantitatively significant agronomic factor. Under equalised photon flux density the combined scheme increased total dry mass by 31.6 per cent, stem diameter by 28.9 per cent, the number of buds and flowers by 58.1 per cent and the number of set fruits by 65.2 per cent relative to the vertical control, while the stem deviation angle reached only 5.0 degrees and the crown asymmetry index only 1.060. Fully inclined lighting also raised dry mass, by 18.9 per cent, and fruit number, by 43.5 per cent, but at the cost of a stem deviation of 20.1 degrees and an asymmetry index of 1.824, values that exceed the limits of technological acceptability for unsupported cultivation. Height and stem diameter responded in opposite directions, so that the compactness index proved to be the most sensitive integral indicator of the plant response, with more than 99 per cent of its variation attributable to the treatment. Root dry mass increased more strongly than shoot dry mass in both experimental treatments, indicating an improvement of the overall carbon balance rather than a redistribution of a limited resource. Stem diameter was very closely correlated with

total dry mass, whereas plant height showed no significant correlation with it at all.

The conclusion of the study is that a combined lighting scheme delivering seventy per cent of the flux vertically and thirty per cent laterally at forty-five degrees is the preferable configuration for modular hydroponic systems growing hot pepper. It requires no additional installed power and no capital expenditure, being achieved by rearranging existing equipment, and it converts the same electricity input into substantially more biomass and more fruit. The phototropic response to the lateral component is markedly non-linear, so that reducing the lateral share threefold reduces the deformation fourfold, which makes the compromise configuration disproportionately advantageous. Because deformation and biomass gain are not correlated, further optimisation of the ratio between the vertical and lateral components is a promising and practically accessible direction of research.

INTRODUCTION

In plant production technologies operating in a fully controlled environment, light is the only production resource that performs two fundamentally different functions at once. On the one hand, it supplies the energy for photosynthetic carbon assimilation and is, in this sense, a direct analogue of fertiliser or irrigation water. On the other, light acts as a carrier of information about the spatial organisation of the surroundings; the plant reads this information through its photoreceptor systems and rebuilds its own architecture long before the balance of assimilated carbon changes [7, p. 405; 5, p. 2532]. It is precisely this duality that makes light the most subtle and, at the same time, the least exploited lever for controlling productivity in closed production systems.

The practice of supplementary artificial lighting that has taken shape over the past half-century has concentrated mainly on three parameters of the light field: intensity (the photosynthetic photon flux density, PPFD), spectral composition and photoperiod duration. These three parameters are well described, their optima have been established for most vegetable crops, and the transition to light-emitting diode sources has made their control technically trivial [16, p. 1952; 19, p. 78]. Considerably less attention has been paid to a fourth parameter – the geometry of the light field, that is, the direction in which the photon flux crosses the surface of the leaf canopy.

Yet it is geometry that determines what proportion of the emitted photons will be intercepted by the productive leaf layers and what proportion will be scattered into the inter-row spaces or absorbed by the lower, already non-photosynthesising leaves.

Classical overhead lighting, in which the light flux falls perpendicular to the horizontal plane of the crop, is a direct transfer of the natural geometry of the solar noon into artificial conditions. It is convenient in structural terms, provides a uniform distribution of illuminance across the area and causes no distortion of the plants. At the same time it has a fundamental drawback: in a dense canopy the upper leaves intercept the overwhelming part of the flux, creating deep shade for the middle and lower layers. In crops with pronounced layering and a long fruiting period – tomato, cucumber and pepper – this leads to premature ageing and death of the lower leaves, to a narrowing of the effective photosynthetic surface and to an upward displacement along the stem of the point from which the fruits are supplied [23, p. 292; 22, p. 1068].

The idea of using inclined and intracanopy (inter-lighting) illumination arose precisely as a response to this problem. Experiments with cucumber and tomato have shown that supplementary illumination of the middle canopy layer can substantially extend the period of active photosynthesis of the lower leaves, increase dry matter accumulation and raise yield without increasing the total electrical power of the system [23, p. 295; 18, p. 8; 11, p. 202]. A change in the direction of the light flux, however, inevitably entails a phototropic response: the plant perceives the asymmetry of illuminance as a signal and rebuilds its own geometry, tilting the stem towards the source [15, p. 41; 10, p. R385]. This response may be either beneficial (better access of light to the axillary buds, activation of the lower layers) or undesirable (curvature of the stems, crown asymmetry, complication of mechanised husbandry and harvesting).

A practical question therefore arises which still has no unambiguous answer for most vegetable crops: is it possible to find a configuration of the light field that simultaneously delivers the advantages of inclined lighting in terms of light penetration into the crown and does not cause an unacceptable deformation of plant architecture? The most obvious candidate for such a compromise is a combined scheme in which the greater share of the flux is delivered from above and a smaller share laterally at an angle. Quantitative

assessments of the efficiency of such a scheme for pepper, and especially for hot cultivar types grown in low-volume hydroponic systems, are extremely scarce in the available literature.

For Ukraine, the relevance of this question has a further dimension. The development of closed production systems – from urban vertical farms to modular units at educational institutions and farm enterprises – is constrained by the high unit cost of electricity for lighting. In the operating-cost structure of a modern unit with artificial lighting, lighting alone accounts for 40 to 60 % of energy consumption [14, p. 452]. Under such conditions, any solution that yields additional biomass without increasing the installed power of the luminaires has immediate economic meaning. Changing the incidence angle of the light flux belongs precisely to this class of solutions: it requires neither additional diodes nor additional electricity, merely a rearrangement of equipment that is already in place.

The object of the study is the process by which the morphometric structure and productivity of hot pepper (*Capsicum annuum* L.) plants of the cultivar Uhorskyi Zhovtyi are formed in an ebb-and-flow hydroponic system. The subject of the study is the quantitative patterns of change in linear growth, stem thickness, plant compactness, crown symmetry, biomass accumulation and allocation, and the initiation of generative organs under the influence of the incidence angle of the light flux emitted by light-emitting diode sources.

The aim of the study was to establish the quantitative effect of the LED light incidence angle on the morphometric traits, biomass accumulation and early productivity of hot pepper plants of the cultivar Uhorskyi Zhovtyi grown in an ebb-and-flow module, and to substantiate a lighting configuration that offers the best balance between biomass gain and the preservation of a sound plant architecture.

The following tasks were addressed in order to achieve this aim: to establish a single-factor experiment on lighting scheme with equalised photon flux density at the level of the upper leaf layer; to follow the dynamics of linear growth, stem thickening and change in the compactness index over 28 days of vegetation; to quantify the phototropic response of the plants through the stem deviation angle and the crown asymmetry index; to determine the fresh and dry mass of the shoot and the root system and to analyse its allocation between organs; to record the number of buds, flowers and set fruits and to calculate indicators of the efficiency of generative

development; to establish the correlations between morphometric traits and productivity; and to formulate practical recommendations on luminaire configuration in modular hydroponic units.

The methodological basis of the work is the classical scheme of a field and pot experiment in which all factors except the one under study are equalised, followed by analysis of variance of a single-factor complex and calculation of the least significant difference [4, p. 112; 2, p. 6]. The material is presented according to the principle of moving from vegetative to generative traits: the response of linear growth is considered first, then stem thickening and the integral shape indices, then the phototropic indicators, then biomass accumulation and allocation, and finally the initiation of generative organs and the correlations linking morphometry with productivity. This order makes it possible to trace how the primary signalling response to a change in light geometry is successively transformed into a change in economically valuable traits.

The scientific novelty of the results obtained lies in the fact that, for the first time for hot pepper of the *Hungarian Wax* type grown in an ebb-and-flow module, a quantitative assessment has been obtained of the separate effects of inclined and combined lighting on a complex of morphometric traits under equalised photon flux density. It is shown that the biomass gain traditionally attributed to inclined lighting is realised not through an increase in plant height but through stem thickening and root system development, and that the compactness index is a more sensitive indicator of the plant response to light geometry than any single linear dimension taken on its own.

1. The Light Vector as an Agronomic Factor

The response of a plant to the direction of the light flux is mediated by a specialised photoreceptor system – the phototropins, the blue-light receptors phot1 and phot2, which are localised mainly in the plasma membrane of the cells of the shoot apex and of young tissues [6, p. 205]. Activation of a phototropin on the illuminated side of an organ triggers a cascade that ends in the lateral redistribution of auxin: the hormone migrates to the shaded side, where it stimulates cell elongation. The consequence is a bending of the axial organ towards the light source. The rate of this response is extremely high – the first measurable changes in auxin distribution are

recorded within tens of minutes of a change in the light vector, whereas a visible bend forms over several hours [15, p. 43; 10, p. R386].

It is of fundamental importance that the phototropic response is not a single event but a continuous tracking process. As long as the asymmetry of illuminance persists, the plant continues to adjust the deviation angle of its axis, and the accumulated bend increases with the age of the organ. This has a direct methodological implication: the stem deviation angle is not a constant characteristic of a treatment but a function of time, and it should be analysed precisely in dynamics. Moreover, as the lower part of the stem lignifies, the bend formed earlier becomes fixed, and further tracking is carried out by the subsequent, younger internodes. The overall shape of the plant axis under inclined light therefore takes the form of a smooth arc rather than of a single break.

In parallel with phototropism, a second signalling system responds to changes in light geometry – the phytochrome system, which controls the complex of shade-avoidance reactions. Its classical stimulus is a decrease in the ratio of red to far-red light (R:FR), which under natural conditions indicates the approach of a competitor [7, p. 410; 5, p. 2534]. Under artificial conditions with narrow-band light-emitting diode sources, the R:FR ratio is determined by the design of the luminaire and does not change when its mounting angle is altered. What does change is another component of the signal – the total illuminance of the individual layers and the degree of its heterogeneity. Shaded parts of the crown receive fewer photons and respond by elongating their internodes, whereas illuminated parts form shorter and sturdier internodes [8, p. 9]. It is this mechanism that explains the appearance of crown asymmetry, which under experimental conditions is recorded as the difference between the projection radii on the illuminated and the shaded sides.

Besides its purely phototropic signalling function, blue light also has a distinct morphogenetic effect. An increase in the blue share of the spectrum shortens the internodes, thickens the stem and raises leaf density and dry matter content [12, p. 3112; 17, p. 6]. These effects are mediated by cryptochromes and phototropins and are largely dose-dependent. In the context of the light incidence angle this circumstance acquires practical significance: under inclined lighting, blue light penetrates more deeply into the crown because a smaller share of it is intercepted by the horizontally

oriented upper leaves. A change in geometry therefore also changes, indirectly, the effective spectral regime of the inner layers, even though the spectrum of the source itself remains unchanged.

The geometry of light interception by the leaf canopy is described by the cosine law: the flux density per unit surface area is proportional to the cosine of the angle between the normal to the surface and the direction of propagation of the radiation. For a horizontally oriented leaf under vertical incidence this cosine equals unity; at an incidence angle of 45° it is approximately 0.71. This means that, at a constant source power, inclined lighting delivers approximately 29 % fewer photons per unit leaf area to the upper layer. This is precisely why, in a correctly designed experiment, photon flux density should be equalised not by luminaire power but by the actual reading of a quantum sensor at the level of the upper leaf layer. Without such equalisation, any differences between treatments cannot be attributed unambiguously to geometry rather than to intensity.

At the same time, the same cosine law works in favour of inclined lighting, but now with respect to the deeper layers. A beam travelling at an angle passes through the canopy along a longer path and has a higher probability of entering the gaps between leaves, whereas a vertical beam is blocked by the first horizontal leaf it encounters. Simulations with functional–structural tomato models have shown that an architecture with more vertically oriented leaves combined with more diffuse light provides a substantially higher total canopy assimilation for the same incident radiation [22, p. 1070]. Inclined lighting acts in the same direction – it changes not the number of photons but their spatial distribution within the crown.

Experimental confirmation of this logic has accumulated first of all for crops with a tall, long stem. In an experiment with cucumber, supplementary intracanopy lighting increased light interception by the lower layers, extended the period of their photosynthetic activity and raised fruit yield [23, p. 294]. For tomato it has been established that intracanopy supplementary lighting increases the growth rate of the fruits through higher light use efficiency and altered root system activity [18, p. 9]. A comparison of overhead and intracanopy sources for high-wire tomato showed that, for the same total number of photons delivered, distributed lighting provides higher productivity [11, p. 204]. For lettuce, an effect of lighting from below

has been demonstrated which retards the senescence of the outer leaves and increases the marketable mass of the rosette [26, p. 1113].

For pepper such data are considerably scarcer, and there are reasons for this. Pepper forms a more compact plant than tomato or cucumber, of moderate height, and suffers less conspicuously from shading of its lower layers. At the same time, pepper has a feature that makes it sensitive to light geometry: its fruits are initiated at the branching points, and the number of productive branches depends directly on how many axillary buds are released from dormancy. The release of axillary buds is largely controlled by the illuminance of the corresponding node: a shaded node will in all likelihood remain inactive. For pepper, therefore, the effect of inclined lighting should be sought not so much in a prolonged life of the lower leaves as in the activation of lateral branching and an increase in the number of fruit initiation sites.

The *Hungarian Wax* type, to which the cultivar Uhorskyi Zhovtyi belongs, is a convenient model object for such studies. It is a semi-determinate type with clearly expressed layering, a comparatively short period to the first crown bud and a pronounced Y-shaped first fork. At early stages the fruits are oriented upwards and bend downwards only as they fill. Such a structure makes it possible to record clearly both the phototropic response of the axis and the changes in generative organ initiation at each layer, which is far more difficult in crops with a continuous drooping habit.

The cost of the phototropic response is no less important a question. Stem bending is in itself neither harmful nor beneficial – it becomes a problem only when it exceeds the technologically acceptable limit. A distorted plant requires tying, fits less well into the planting density, complicates mechanised husbandry, and at large deviation angles there is a risk of lodging as the fruits fill. Assessing the efficiency of a lighting scheme by biomass gain alone is therefore insufficient: an integrated approach is required in which the gain in productivity is set against the deformation of architecture. The analysis in this work is built on precisely such a comparison.

The allocation of assimilates between the shoot and the root deserves separate attention. A meta-analysis of biomass allocation in plants has shown that the root share increases under a deficit of root-zone resources and decreases under a light deficit [20, p. 38]. In fully controlled systems mineral nutrition is not limiting, so changes in the shoot-to-root ratio reflect

mainly changes in the light regime and in the overall supply of assimilates to the plant. An increase in the absolute mass of the root at an unchanged or even reduced shoot-to-root ratio indicates an improvement in the energy balance of the plant as a whole rather than a redistribution of resources in favour of one organ. This criterion is applied below in interpreting the results.

Summarising the review presented above, the working hypothesis of the study can be formulated. Inclined lighting at 45° should increase the penetration of light into the crown, activate the axillary buds and increase dry matter accumulation, while at the same time causing pronounced phototropic deformation of the axis and crown asymmetry. Combined lighting with a predominant overhead component should retain most of the advantages of the inclined treatment while substantially reducing the deformation. The experimental part of the work is devoted to testing this hypothesis.

2. Conditions and Methods of the Experiment

The experiment was carried out in an ebb-and-flow (flood and drain) hydroponic module housed in a room with fully artificial lighting and a controlled microclimate. The crop was hot pepper (*Capsicum annuum* L.) of the *Hungarian Wax* type, cultivar Uhorskyi Zhovtyi. The recording period lasted 28 days, with assessments on days 0, 7, 14, 21 and 28 after the transplants were set into the module.

The experimental design comprised three treatments differing exclusively in the geometry of the light field:

– treatment A (control) – the light flux directed strictly vertically from above, at an incidence angle of 90° to the horizontal plane of the crop;

– treatment B – the light flux directed from above and to the side at an angle of 45° to the horizontal plane;

– treatment C – combined lighting, in which 70 % of the light flux was delivered vertically from above and 30 % laterally at an angle of 45°.

The experiment was carried out in fivefold replication; the recording unit was the individual plant, five plants were recorded in each treatment, and the total number of recorded plants was fifteen. The plants were selected so as to be uniform in height, number of true leaves and stem diameter: at the start of recording, mean height was 8.46–8.60 cm and mean stem diameter

2.64–2.72 mm, and the differences between treatments in these traits were statistically non-significant, which confirms the correctness of the initial equalisation.

Table 1

Design of the experiment and controlled environmental parameters

Parameter	Specification
Crop	hot pepper (*Capsicum annuum* L.), cultivar Uhorskyi Zhovtyi, *Hungarian Wax* type
Growing system	ebb-and-flow hydroponics (flood and drain)
Treatment A (control)	100 % of the light flux from above, incidence angle 90°
Treatment B	100 % of the light flux from above and to the side, incidence angle 45°
Treatment C	70 % of the flux from above (90°) + 30 % of the flux from the side (45°)
Replication	5 recorded plants per treatment, 15 plants in total
Duration of recording	28 days; assessments on days 0, 7, 14, 21 and 28
PPFD at the level of the upper leaf layer	equalised in all treatments; 200 μmol·m^{-2}·s^{-1}
Photoperiod duration	14 h per day
Spectral composition of the source	LED (red 660 nm / blue 450 nm)
Electrical conductivity of the solution (EC)	1.8–2.2 mS/cm
Solution reaction (pH)	5.8
Air temperature (day / night)	28 / 18 °C
Relative air humidity	60 %
Flooding regime	cycles per day of 4/15 min duration

The key methodological requirement was the equalisation of photosynthetic photon flux density (PPFD) at the level of the upper leaf layer in all treatments. Since the illuminance of a horizontal surface under inclined incidence decreases in proportion to the cosine of the angle, simply moving the luminaire into an inclined position without correction would automatically have created a difference in intensity of about 29 %, after which the effects of geometry and of intensity could no longer be separated. The distance from the LED panels to the plants in treatments B and C was

therefore adjusted until the readings of the quantum sensor at the level of the upper leaf layer coincided with the readings in the control within the measurement error. PPFD checks were repeated weekly as the plants grew, with corresponding adjustment of the suspension height.

All other factors were maintained identical across the treatments: the composition and concentration of the nutrient solution, electrical conductivity, solution reaction, air and solution temperature, relative air humidity, photoperiod duration, and the frequency and duration of the flooding cycles. The modules of all treatments were placed in a single room with screening that prevented mutual illumination of adjacent treatments.

The recorded indicators and the methods used to determine them were as follows.

Plant height H (cm) was measured with a ruler from the root collar to the growing point along the stem axis, to the nearest 0.1 cm.

Stem diameter d (mm) was determined with a vernier caliper at the height of the first true leaf, to the nearest 0.1 mm; measurements were taken in two mutually perpendicular planes and then averaged.

The stem deviation angle α (degrees) was measured as the angle between the tangent to the stem axis in the upper third of the plant and the vertical, using a protractor with a plumb line.

The crown projection radii on the illuminated (R_{ill}) and shaded (R_{sh}) sides were measured as the distance from the stem axis to the most distant point of the crown projection on the horizontal plane, in the plane passing through the plant axis and the light source.

The crown asymmetry index I_a was calculated as the ratio of the crown projection radius on the illuminated side to the radius on the shaded side:

$$I_a = R_{ill} / R_{sh}.$$

A value of $I_a = 1.00$ corresponds to a perfectly symmetrical crown; an increase in the index indicates a stronger one-sidedness of development.

The compactness index I_c was defined as the ratio of plant height in centimetres to stem diameter in millimetres:

$$Ic = H / d.$$

In practical use this indicator is a dimensionless measure of the balance between elongation and thickening of the axis. A decrease in I_c means the formation of a squatter, sturdier plant; an increase means elongation and a weakening of the stem.

Average internode length (cm) was determined by dividing the length of the leafy part of the stem by the number of internodes formed.

The number of buds and flowers (units) was recorded by counting all visible generative structures on the plant on the assessment date.

At the final stage of the experiment (day 28) the plants were cut at the root collar, the root system was washed free of substrate residues and blotted with filter paper. The fresh mass of the shoot and of the root system (g) was determined by weighing on a technical balance to the nearest 0.1 g. The material was then dried to constant mass and the dry mass of the shoot and of the roots (g) was determined to the nearest 0.01 g. The number of set fruits (units) was recorded by counting.

A number of derived indicators were calculated from the primary data: total fresh and dry mass as the sum of the corresponding masses of the shoot and the roots; the shoot-to-root ratio as the ratio of shoot dry mass to root dry mass; dry matter content as the percentage ratio of total dry mass to total fresh mass; the share of the root system in total dry mass; the number of nodes as the quotient of height divided by average internode length; specific productivity as the number of fruits per unit dry mass; the realisation coefficient of generative structures as the percentage ratio of the number of fruits to the number of buds and flowers; absolute growth rate as the increment of a trait per day; and relative growth rate as the increment of the natural logarithm of a trait per day.

Statistical processing was carried out by one-way analysis of variance, followed by calculation of the least significant difference at the five per cent significance level (LSD_{05}) using the formula:

$$LSD_{05} = t_{05} \times \sqrt{(2 \times MS_e / n)},$$

where t_{05} is the critical value of Student's criterion for the error degrees of freedom; MS_e is the error mean square; and n is the number of replicates per treatment. For each trait the arithmetic mean, standard deviation, standard error of the mean, coefficient of variation and the share of factorial variance in the total variance (η^2) were determined. Correlations between traits were assessed by the Pearson linear correlation coefficient with a test of its significance; pairwise dependences were described by linear regression equations with determination of the coefficient of determination. The calculations were performed using standard statistical procedures in

accordance with generally accepted methods for processing the results of agronomic experiments [4, p. 118; 2, p. 191].

A methodological limitation concerning two of the indicators should be noted separately. The crown projection radii R_{ill} and R_{sh}, and hence the asymmetry index I_a derived from them, as well as average internode length, were recorded as averaged characteristics of the treatment on each assessment date rather than as individual values for each recorded plant. The within-treatment variance for these traits is therefore zero, and the formal application of analysis of variance to them is not valid. In the account that follows, these indicators are presented and analysed descriptively, without calculation of LSD_{05}, and the conclusions drawn about them are formulated with the corresponding reservation. For all other indicators the analysis of variance was performed in full.

3. Dynamics of Linear Plant Growth

Plant height is the simplest morphometric indicator and the easiest to record, yet it is precisely because of its simplicity that it is often misinterpreted. In production practice, vigorous growth in height is frequently taken as a sign of well-being, whereas in most cases elongation is rather a symptom of insufficient or poorly distributed light. The results of the experiment provide a good illustration of how cautiously this indicator should be treated.

Table 2

Dynamics of plant height of hot pepper cultivar Uhorskyi Zhovtyi depending on the light incidence angle, cm

Treatment	Day 0	Day 7	Day 14	Day 21	Day 28
A (90°, control)	8.60	11.50	14.50	17.40	20.40
B (45°, inclined)	8.46	10.90	13.32	15.80	18.22
C (combined 70+30 %)	8.54	11.70	14.84	18.00	21.14
LSD_{05}	0.38	0.40	0.38	0.40	0.38

Note. Means of 5 plants per treatment are given.

At the start of the experiment the difference between treatments in height did not exceed 0.14 cm and was statistically non-significant ($F = 0.32$; $p = 0.732$), which confirms the correctness of the selection of the

initial material. Within a week of the change in light regime the picture had already altered: plants of treatment B lagged behind the control by 0.60 cm, while those of treatment C exceeded it by 0.20 cm. The first difference exceeded LSD_{05} = 0.40 cm and was significant; the second remained within the error.

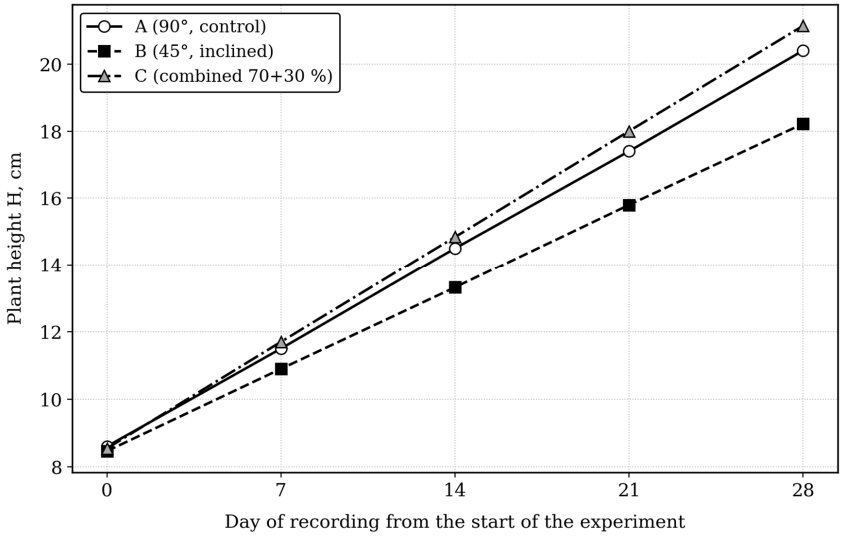


Figure 1. Dynamics of plant height of hot pepper cultivar Uhorskyi Zhovtyi under different geometries of the light field

Thereafter the divergence between treatments increased steadily. On day 14 the lag of treatment B behind the control was 1.18 cm, on day 21 it was 1.60 cm and on day 28 it was 2.18 cm, or 10.7 % in relative terms. All these differences significantly exceeded LSD_{05}. Treatment C, by contrast, gradually increased its advantage: 0.34 cm on day 14 (within the error), 0.60 cm on day 21 and 0.74 cm on day 28. The latter two differences were significant. At the end of the experiment the ranking of treatments by height was C (21.14 cm) > A (20.40 cm) > B (18.22 cm) at LSD_{05} = 0.38 cm, with all three treatments differing significantly from one another.

The coefficient of variation of height within treatments decreased steadily from 2.85–3.68 % at the start of the experiment to 1.28–1.55 %

at its end, which is a typical picture for a well-equalised pot experiment and indicates the absence of random sources of heterogeneity. The share of factorial variance in the total variance for height on day 28 exceeded 0.96, that is, more than 96 % of the variation in the trait is explained by the lighting scheme.

Calculating growth rates makes it possible to characterise the nature of the differences more precisely. The absolute growth rate in height over the whole experimental period was 0.421 cm/day in the control, 0.349 cm/day in treatment B and 0.450 cm/day in treatment C. In other words, inclined lighting slowed the elongation of the axis by about 17 %, whereas combined lighting accelerated it by 7 % relative to the control. It is notable that within each treatment the absolute growth rate remained practically constant throughout all four weekly intervals (fluctuations did not exceed 0.01 cm/day), that is, none of the treatments reached a plateau and the plants remained in a phase of steady linear growth.

The relative growth rate, calculated as the increment of the natural logarithm of height per day, declined in all treatments as the plants increased in size, as would be expected – from 0.036–0.045 day^{-1} in the first week to 0.020–0.023 day^{-1} in the fourth. Mean values over the period were 0.0309 day^{-1} in the control, 0.0274 in treatment B and 0.0324 in treatment C. The ranking of treatments by this indicator entirely repeats their ranking by absolute rate, which indicates that the differences in the pattern of growth are stable rather than temporary.

The restraint of growth in height in treatment B deserves a separate comment, since at first sight it contradicts expectations. The shade-avoidance response that might have been expected from partial shading of the lower layers ought to have manifested itself precisely as elongation. Under inclined lighting, however, the shading of the lower layers is not intensified but, on the contrary, reduced, because an angled beam penetrates the crown more effectively. At the same time the shoot apex receives a strong directional signal that triggers the phototropic response, and this is realised not so much in elongation of the axis as in its bending. In addition, a substantial part of the growth resources in this treatment is directed to stem thickening and root system development, as will be shown below. The lower height in treatment B is therefore not a consequence of suppression but a consequence of a different allocation of growth resources.

A further circumstance is that height was measured along the stem axis rather than as a vertical projection. Since the axis in treatment B deviates from the vertical by 20.1°, the actual vertical height of these plants was lower still: at an angle of 20.1° the vertical projection amounts to about 94 % of the axis length, that is, approximately 17.1 cm as against the 18.22 cm measured. In treatment C, where the deviation angle was only 5.0°, the difference between axis length and vertical projection did not exceed 0.4 %. This reinforces the trend already identified: in terms of the actual height of the plant, the gap between treatment B and the others is greater still.

The practical conclusion to be drawn from the dynamics of linear growth is that height as an independent criterion for evaluating a lighting scheme carries little information. The shortest plants (treatment B) proved not to be the poorest, and the tallest (treatment C) were not simply elongated, as the data on stem thickness considered in the next subsection demonstrate. Height should be analysed exclusively in conjunction with stem diameter, and it is for this reason that the integral compactness index is given the main attention in what follows.

4. Stem Thickness and Plant Compactness

Stem diameter is an indicator that reflects the supply of assimilates to the plant far more accurately than height does. Thickening of the axial organ requires direct expenditure of carbon on the construction of conducting and mechanical tissues and, unlike elongation, which is largely achieved by stretching cells that already exist, it cannot be “cheapened” by water filling. This is why stem diameter usually shows the closest relationships with dry matter mass, as the data of this experiment also confirm.

Table 3

Dynamics of stem diameter of hot pepper plants depending on the light incidence angle, mm

Treatment	Day 0	Day 7	Day 14	Day 21	Day 28
A (90°, control)	2.64	3.48	4.32	5.18	6.02
B (45°, inclined)	2.68	3.72	4.78	5.84	6.88
C (combined 70+30 %)	2.72	3.96	5.24	6.48	7.76
LSD_{05}	0.15	0.13	0.13	0.15	0.13

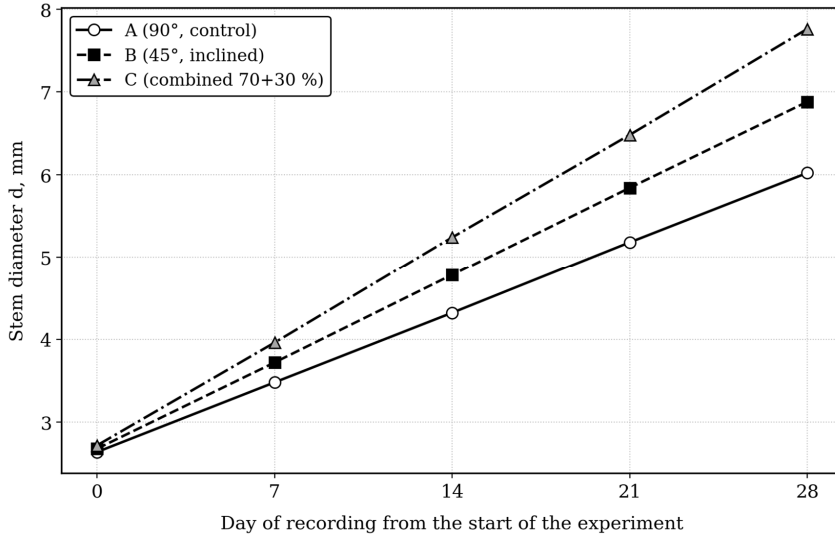


Figure 2. Dynamics of stem diameter of hot pepper under different geometries of the light field

The initial differences between treatments in stem diameter were non-significant ($F = 0.65$; $p = 0.540$), with means ranging from 2.64 to 2.72 mm. Within a week, however, a clear ranking had formed which was maintained without a single exception to the end of the experiment: C > B > A. On day 7 the stem diameter in treatment B exceeded the control by 0.24 mm and in treatment C by 0.48 mm at $LSD_{05} = 0.13$ mm; both differences were significant, as was the difference between the two experimental treatments.

By day 28 the advantage of the experimental treatments had increased to 0.86 mm (14.3 %) in treatment B and 1.74 mm (28.9 %) in treatment C at $LSD_{05} = 0.13$ mm. The value of Fisher's criterion for this trait at the final assessment reached 420.5 at a significance level below 0.001, which indicates an exceptionally high reproducibility of the effect. The coefficient of variation within treatments did not exceed 1.5 %.

The absolute rate of stem thickening was 0.121 mm/day in the control, 0.150 mm/day in treatment B and 0.180 mm/day in treatment C, that is, an increase of 24 and 49 % respectively relative to the control. Unlike

the growth rate in height, which was highest in treatment C and lowest in treatment B, the rate of thickening ranked the treatments differently, with both experimental treatments exceeding the control. This is the key observation of the entire work: a change in light geometry shifts the balance of growth processes from elongation towards thickening, and this shift occurs in both experimental treatments, albeit to different degrees.

Taking height and stem diameter into account simultaneously yields the compactness index I_c, the dynamics of which are given below. Since this indicator is calculated as the quotient of height in centimetres divided by diameter in millimetres, a decrease means the formation of a squatter and sturdier plant, and an increase means elongation.

Table 4

Dynamics of the compactness index Ic of hot pepper plants, cm/mm

Treatment	Day 0	Day 7	Day 14	Day 21	Day 28
A (90°, control)	3.258	3.304	3.356	3.359	3.389
B (45°, inclined)	3.157	2.930	2.787	2.706	2.648
C (combined 70+30 %)	3.142	2.955	2.832	2.778	2.724
LSD_{05}	0.062	0.035	0.028	0.024	0.021

Note. A decrease in the compactness index corresponds to the formation of a squatter plant with a relatively thicker stem.

The divergence between treatments in the compactness index proved to be the most pronounced of all the traits studied. In the control the index not only failed to decrease but actually rose – from 3.258 at the start of the experiment to 3.389 on day 28 – that is, the plants gradually became elongated, with the increment in height outpacing the increment in diameter. In treatments B and C the opposite dynamics were observed: the index fell from 3.157 to 2.648 and from 3.142 to 2.724 respectively. At the final assessment the excess of the control over the experimental treatments was 0.740 and 0.664 units at $LSD_{05} = 0.021$, that is, more than thirty times the least significant difference. The difference between treatments B and C (0.076) was also significant.

The value of Fisher's criterion for the compactness index on day 28 was 3692.7, and the share of factorial variance exceeded 0.99. This means that the compactness index is the most sensitive of the indicators studied for

the plant's response to the geometry of the light field – more sensitive than any single linear dimension. The explanation is that height and diameter respond to a change in the light vector in opposite directions, so that their ratio sums the two effects instead of allowing them to cancel each other out.

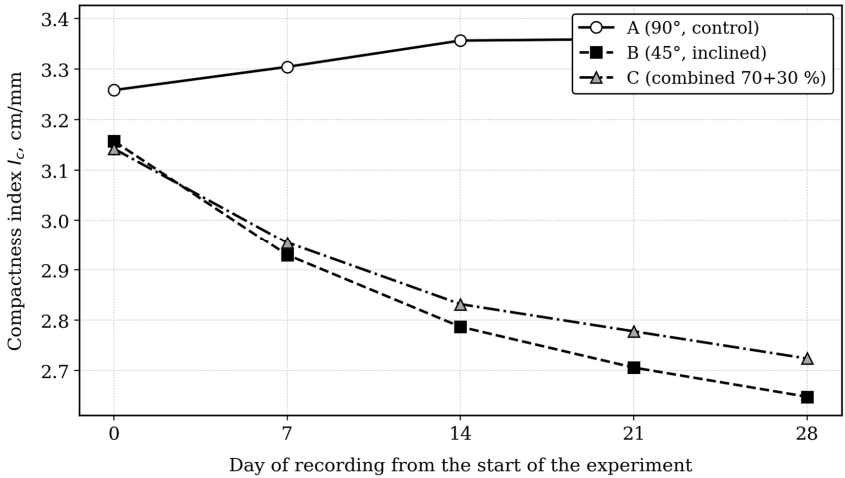


Figure 3. Dynamics of the compactness index Ic of hot pepper under different geometries of the light field

Analysis of average internode length completes this picture. In the control it increased from 1.2 to 2.6 cm, in treatment B from 1.2 to 2.3 cm and in treatment C from 1.1 to 2.4 cm. The shortening of internode length relative to the control was 11.5 % in treatment B and 7.7 % in treatment C. Since this indicator was recorded as an averaged characteristic of the treatment, no statistical assessment was applied to it; the direction of the changes, however, is consistent with the data on the compactness index and with classical understanding of the morphogenetic action of blue light [12, p. 3113; 17, p. 7].

The calculation of node number, obtained by dividing height by average internode length, is particularly revealing. In the control the plants formed an average of 7.85 nodes, in treatment B 7.92 and in treatment C 8.81, at LSD_{05} = 0.156. Treatment C therefore built almost one node more

than the control over 28 days, and did so with shorter internodes. This is a fundamentally different type of advantage from simple elongation: the plant created more potential sites for the initiation of lateral shoots and generative organs. It is this circumstance, as will be shown in the section on generative development, that largely explains the highest number of buds in treatment C.

Treatment B differed practically not at all from the control in node number (a difference of 0.08 at LSD_{05} = 0.156 is non-significant), that is, its advantage in productivity was realised by a different route – not through an increase in the number of nodes but through more efficient use of those already present. This question is returned to in the analysis of the realisation coefficient of generative structures.

From a technological point of view, the results obtained mean the following. Both experimental lighting schemes form plants with a sturdier stem, capable of carrying a heavier fruit load without tying. Treatment C achieves this effect without reducing, and indeed while slightly increasing, plant height, which is an advantage for systems with vertical plant arrangement. Treatment B forms the most compact plant but, as will be shown below, pays for this with substantial deformation of the axis.

5. Phototropic Response and Crown Asymmetry

The angle of deviation of the stem from the vertical is a direct measure of the plant's phototropic response to the asymmetry of the light field. Unlike growth indicators, which change under the influence of many factors, the deviation angle in a well-equalised experiment reflects almost exclusively the action of the factor under study, which makes it a convenient indicator of the soundness of the experimental design itself.

In the control treatment the stem deviation angle remained unchanged throughout the experiment at 1.1° – a background value determined by the individual characteristics of the plants and the natural unevenness of mass distribution rather than by a directional light signal. The stability of this indicator in the control is an important methodological confirmation that vertical lighting genuinely created no lateral vector.

In treatment B the phototropic response developed steadily and almost linearly. By day 7 the deviation angle had already reached 6.42°, almost six times the initial 1.9°. It then rose to 11.0° on day 14, 15.54°

on day 21 and 20.1° on day 28. The average rate of increase was about 0.65° per day and showed practically no slowing towards the end of the experiment. This means that over a longer growing period the deviation angle in this treatment would have continued to rise and could have reached technologically unacceptable values.

Table 5

Dynamics of the stem deviation angle α and the crown asymmetry index I_a

Treatment	Day 0	Day 7	Day 14	Day 21	Day 28
Stem deviation angle α, degrees					
A (90°, control)	1.1	1.1	1.1	1.1	1.1
B (45°, inclined)	1.9	6.4	11.0	15.5	20.1
C (combined 70+30 %)	0.8	1.9	2.9	4.0	5.0
LSD_{05}	0.45	0.47	0.45	0.43	0.45
Crown asymmetry index I_a					
A (90°, control)	1.000	1.000	1.011	1.018	1.022
B (45°, inclined)	1.000	1.382	1.592	1.733	1.824
C (combined 70+30 %)	1.000	1.030	1.042	1.049	1.060
LSD_{05}	–	–	–	–	–

Note. The crown asymmetry index was recorded as an averaged characteristic of the treatment, so analysis of variance was not applied to it; the data are presented descriptively.

Figure 4. Dynamics of the stem deviation angle of hot pepper under different geometries of the light field

In treatment C the response was qualitatively the same but quantitatively far weaker: 1.9° on day 7, 2.9° on day 14, 4.0° on day 21 and 5.0° on day 28, giving an average rate of increase of about 0.15° per day. The difference from the control (3.9°) significantly exceeded LSD_{05} = 0.45°, so partial lateral illumination does nevertheless cause a measurable curvature of the axis, although on a scale four times smaller than under fully inclined lighting.

The relationship between the share of lateral light and the magnitude of the phototropic response deserves attention. In treatment C the lateral component accounted for 30 % of the flux, that is, two to three times less

than in treatment B, where the entire flux was inclined. The deviation angle, however, proved to be smaller not by a factor of three but by a factor of four (5.0° as against 20.1°). This points to a non-linearity of the phototropic response: the presence of a powerful vertical component does not merely "dilute" the lateral signal but actively counteracts it, since the shoot apex receives a strong symmetrical signal from above which partly offsets the lateral redistribution of auxin [15, p. 44; 10, p. R387]. From a practical point of view this is an extremely valuable regularity: it means that a substantial share of the advantages of inclined lighting can be obtained at the cost of a disproportionately small deformation.

The crown asymmetry index confirms the same logic from a different angle. In the control it changed practically not at all, rising from 1.000 to 1.022, so the crown remained symmetrical. In treatment B the index rose sharply by day 7 (1.382), continued to rise to 1.592 on day 14 and 1.733 on day 21, and reached 1.824 on day 28. This means that at the end of the experiment the crown projection radius on the side of the light source exceeded the radius on the shaded side by a factor of 1.8 – the crown had in effect lost its symmetry and acquired a one-sided, "flag-like" form. In treatment C the asymmetry index rose only to 1.060, that is, an excess over the control of 3.7 %, which from a practical point of view may be regarded as technologically neutral.

The methodological limitation should be emphasised once more: the asymmetry index was recorded as an averaged characteristic of the treatment, so the differences reported describe a trend and are not the result of analysis of variance. The scale of the difference between treatment B and the others (0.76–0.80 units), however, so far exceeds any reasonable estimate of within-treatment variation that the biological reality of this effect is beyond doubt.

The mechanism by which asymmetry is formed requires a separate explanation. It is not reducible to the bending of the axis alone. The crown projection radius is determined by the length and orientation of the lateral shoots and petioles, and these in turn respond to the local illuminance of their own node. The illuminated side receives a signal that stimulates the unfolding of the leaf blades and their extension to the periphery, whereas the shaded side responds by weakening these processes. The asymmetry index is therefore a composite characteristic combining the bending of the axis,

uneven branching and differences in leaf orientation. This explains why in treatment B the asymmetry index (1.824, that is, +82 % relative to symmetry) rose relatively more strongly than would be expected from the axis deviation angle of 20.1° alone.

Assessing the technological acceptability of the deformation observed requires a separate criterion. For pepper, which forms fruits weighing 20–60 g on lateral shoots, the critical point is reached when the bending of the axis, combined with the fruit load, creates an overturning moment sufficient to cause lodging. A deviation of up to 10–12° is empirically regarded as the acceptable limit for unsupported growing systems, so treatment B with its 20.1° already exceeds this limit twofold on day 28, and if growing were continued to technical ripeness of the fruits it would inevitably require tying or supports. Treatment C with its 5.0° remains within limits that call for no additional measures. This circumstance is decisive in choosing between the two experimental schemes.

It should also be noted that part of the phototropic bend in treatment B occurs in the lower, already lignified part of the stem and is irreversible. Moving the luminaire into a vertical position at later stages of vegetation will not straighten the plant but will merely change the direction of growth of the younger internodes, as a result of which the axis will acquire an S-shape. This means that the decision on lighting geometry must be taken at the beginning of vegetation and cannot be revised painlessly in the middle of it.

6. Biomass Accumulation and Allocation

Biomass indicators are the final integral criterion of the efficiency of any agronomic scheme, since it is in them that the entire balance of assimilation and expenditure over the growing period is summed. Within this experiment, biomass was recorded once, on day 28, with separate determination of the mass of the shoot and of the root system in the fresh and dry state.

In terms of total fresh mass the plants ranked as follows: C (79.0 g) > B (71.1 g) > A (61.2 g) at LSD_{05} = 3.28 g. The excess over the control was 16.2 % in treatment B and 29.1 % in treatment C, and all pairwise differences were significant. The same ranking was retained for total dry mass: 10.33 g in treatment C, 9.33 g in treatment B and 7.85 g in the control at LSD_{05} = 0.42 g, corresponding to an excess over the control of 18.9 and 31.6 %.

Table 6

Biomass indicators of hot pepper plants on day 28 of vegetation

Indicator	A (90°)	B (45°)	C (70+30 %)	LSD_{05}
Shoot fresh mass, g	48.20±0.71	55.10±0.85	61.30±0.78	2.40
Root fresh mass, g	13.00±0.21	16.00±0.28	17.70±0.35	0.89
Total fresh mass, g	61.20±0.92	71.10±1.13	79.00±1.13	3.28
Shoot dry mass, g	6.10±0.07	7.15±0.11	7.92±0.10	0.29
Root dry mass, g	1.75±0.04	2.18±0.04	2.41±0.05	0.13
Total dry mass, g	7.85±0.11	9.33±0.15	10.33±0.15	0.42
Shoot-to-root ratio	3.488±0.030	3.281±0.015	3.288±0.027	0.076
Dry matter content, %	12.83±0.02	13.12±0.01	13.08±0.01	0.04
Share of the root system in dry mass, %	22.29±0.15	23.36±0.08	23.32±0.14	0.40
Dry mass per 1 cm of height, g/cm	0.385±0.003	0.512±0.005	0.489±0.004	0.013

Note. Means ± standard error of the mean are given (n = 5).

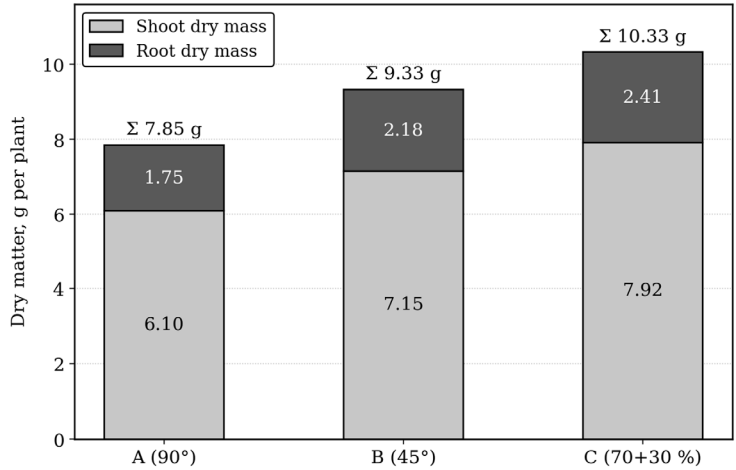


Figure 5. Structure of the dry biomass of hot pepper plants depending on the geometry of the light field

Separate analysis of the organs shows that the biomass gain was not uniform. Shoot dry mass increased by 17.2 % in treatment B and by

29.8 % in treatment C, whereas root dry mass increased by 24.6 and 37.7 % respectively. The root therefore responded to the change in light geometry more strongly than the shoot, and this applies to both experimental treatments.

The consequence was a predictable decrease in the shoot-to-root ratio: from 3.488 in the control to 3.281 in treatment B and 3.288 in treatment C at LSD_{05} = 0.076. Both differences from the control were significant, whereas the experimental treatments did not differ from one another in this indicator. The share of the root system in total dry mass rose correspondingly from 22.29 to 23.36 and 23.32 % at LSD_{05} = 0.40 %.

Interpretation of this result calls for caution. The classical functional equilibrium implies that the root share increases under a deficit of root-zone nutrition and decreases under a light deficit [20, p. 40]. In this experiment nutrition was not limiting and the light regime was equalised in intensity, so the increase in the root share is not a response to a deficit. The key point is that the absolute mass of the shoot in the experimental treatments did not decrease but rose substantially. In other words, what is observed is not a redistribution of a limited resource in favour of the root, but an improvement in the overall carbon balance of the plant, in which the increment of both organs was positive while the root received a somewhat larger share of the additional resource.

The most probable explanation is better light interception by the lower leaf layers. In the control a substantial part of the lower leaves was in deep shade created by the upper layer and in effect operated close to or below the compensation point, consuming more assimilates than they produced. Under inclined and combined lighting these leaves received additional photons, returned to net assimilation and became donors rather than acceptors of carbon. Since it is the lower leaves that are anatomically most closely linked to the conducting pathways supplying the root system, the additional assimilates were delivered primarily to the root. This logic is consistent with results obtained for tomato under intracanopy supplementary lighting, where an increase in root system activity was likewise recorded [18, p. 9].

Dry matter content also differed significantly between treatments: 12.83 % in the control, 13.12 % in treatment B and 13.08 % in treatment C at LSD_{05} = 0.035 %. Although the absolute magnitude of the differences is small (0.25–0.29 percentage points), it is statistically reliable

and biologically meaningful. A higher dry matter content indicates the formation of denser tissues with a lower water content per unit mass, which is usually accompanied by greater mechanical strength and better keeping quality. For pepper this is a favourable circumstance and is consistent with data on the effect of blue light on tissue density [12, p. 3114; 17, p. 7].

Calculation of specific dry mass per unit of plant height yields a further striking result: 0.385 g/cm in the control, 0.512 in treatment B and 0.489 g/cm in treatment C at LSD_{05} = 0.013 g/cm. Each centimetre of height of the plants in the experimental treatments therefore carried 27–33 % more dry matter than in the control. This indicator is essentially a measure of the "density" of the plant and confirms the conclusion already formulated: when the geometry of the light field changes, the plant builds not a longer but a more massive structure.

A comparison of treatments B and C in terms of biomass indicators is unequivocally in favour of the latter. Treatment C exceeded treatment B by 10.7 % in total dry mass, by 10.8 % in shoot dry mass and by 10.6 % in root dry mass, and all these differences were significant at the corresponding LSD_{05} values. Combined lighting therefore proved more efficient than fully inclined lighting not only in terms of preserving architecture but also directly in terms of biomass accumulation.

This observation deserves explanation, since it is not self-evident. It might have been expected that fully inclined lighting would provide maximum penetration of light into the crown and hence maximum growth. Inclined lighting, however, has a reverse side: it creates a pronounced asymmetry of illuminance in which the shaded side of the crown receives considerably fewer photons than it would under vertical incidence. The asymmetry index of 1.824 in treatment B is direct evidence that part of the crown was systematically under-supplied with light. The combined scheme avoids this drawback: the vertical component provides a basic, uniform level of illuminance across the whole crown, while the lateral component adds penetration into its depth without creating large shaded zones. This is why the final balance proved to be in its favour.

7. Formation of the Generative Organs of the Plants

The economic value of pepper is determined not by vegetative mass but by the number and quality of the fruits, so the recording of generative

organs is the most important part of the assessment of any agronomic scheme. Within the 28-day period of the experiment the plants were at the stage of mass bud initiation, flowering and initial fruit set, which makes it possible to assess generative potential, although it does not provide grounds for conclusions about final yield.

Table 7

Indicators of generative development of hot pepper plants on day 28

Indicator	A (90°)	B (45°)	C (70+30 %)	LSD_{05}
Number of buds and flowers on day 14, units	2.6±0.24	3.6±0.24	4.6±0.24	0.75
Number of buds and flowers on day 21, units	5.6±0.24	7.6±0.24	9.6±0.24	0.75
Number of buds and flowers on day 28, units	8.6±0.24	10.6±0.24	13.6±0.24	0.75
Number of set fruits, units	4.6±0.24	6.6±0.24	7.6±0.24	0.75
Realisation coefficient of generative structures, %	53.3±1.36	62.2±0.89	55.8±0.81	3.23
Specific productivity, fruits per 1 g dry mass	0.586±0.032	0.708±0.029	0.736±0.026	0.090
Calculated number of nodes, units	7.85±0.05	7.92±0.05	8.81±0.05	0.156

Note. Means ± standard error of the mean are given (n = 5)

The first generative structures appeared simultaneously in all treatments: on day 7 each of them averaged 0.6 buds per plant, and there were no differences ($F = 0.00$; $p = 1.000$). This is an important fact: the change in the geometry of the light field neither accelerated nor delayed the transition of the plants to the generative phase. Differences began to appear later, at the stage of accumulation of generative structures.

On day 14 the number of buds and flowers was 2.6 units in the control, 3.6 in treatment B and 4.6 in treatment C at $LSD_{05} = 0.75$ units; all pairwise differences were significant. The gap subsequently widened: on day 21 the figures were 5.6 : 7.6 : 9.6 units and on day 28 they were 8.6 : 10.6 : 13.6 units respectively. At the final assessment the excess over the control was 23.3 % in treatment B and 58.1 % in treatment C.

The number of set fruits on day 28 was 4.6 units in the control, 6.6 in treatment B and 7.6 units in treatment C at $LSD_{05} = 0.75$ units, that is,

an excess over the control of 43.5 and 65.2 % respectively, with all pairwise differences significant. This is the largest relative effect among all the indicators recorded – the generative sphere proved more sensitive to a change in light geometry than any of the vegetative traits.

Particularly informative is the calculation of the realisation coefficient of generative structures – the percentage ratio of the number of set fruits to the total number of buds and flowers. It was 53.3 % in the control, 62.2 % in treatment B and 55.8 % in treatment C at LSD_{05} = 3.23 %. The ranking of treatments by this indicator does not coincide with their ranking by the absolute number of fruits, and this discrepancy is of fundamental importance for understanding the mechanism by which the factor under study acts.

Treatment B, while inferior to treatment C in the number of buds initiated (10.6 as against 13.6 units), significantly exceeded it in the share of buds that were realised as fruits (62.2 as against 55.8 %). In other words, these two lighting schemes raise productivity by fundamentally different routes. Inclined lighting acts mainly by improving the conditions for realising generative structures that have already been initiated: better illuminated nodes with a higher local supply of assimilates retain a greater share of their fruit set and shed buds less frequently. Combined lighting acts mainly by increasing the number of initiation sites: it formed 0.96 nodes more than the control, and each additional node is a potential site for the initiation of generative organs.

This difference is consistent with the data of the preceding sections. Treatment C was superior in node number (8.81 as against 7.85 in the control at LSD_{05} = 0.156), whereas treatment B differed practically not at all from the control in this indicator (7.92). Treatment B, on the other hand, had the highest asymmetry index, that is, the greatest unevenness of crown illuminance, and it was evidently on its well-illuminated side that the increased realisation of fruit set was concentrated. A combination of both mechanisms – a greater number of nodes together with higher realisation – could give a still better result, and this is an obvious direction for the further search for an optimum ratio of the overhead and lateral components of the flux.

Calculation of specific productivity, that is, the number of fruits per unit of plant dry mass, gives values of 0.586 fruits/g in the control, 0.708 in treatment B and 0.736 fruits/g in treatment C at LSD_{05} = 0.090 fruits/g.

Both experimental treatments significantly exceeded the control, while not differing from one another. This means that a change in light geometry raises not only the absolute number of fruits but also the efficiency with which the plant converts accumulated dry matter into generative organs. The gain in fruiting is not simply a consequence of the plant having become larger – the very structure of assimilate allocation changes in favour of the generative sphere.

The mechanism of this effect is most probably linked to the activation of axillary buds. In pepper, every fork of the stem is a site of flower initiation, and the release of an axillary bud from dormancy is largely controlled by the illuminance of the corresponding node. In the control treatment the lower and middle nodes were in the shade of the upper layer, so a proportion of their buds remained inactive. Inclined and combined lighting raised the illuminance of these nodes, as a result of which a greater proportion of them entered active development. Such a mechanism explains well why the effect on generative traits (43–65 %) proved considerably stronger than that on vegetative mass (19–32 %).

The limits within which these results may be interpreted should be clearly defined. What was recorded was the number of set fruits and young fruits on day 28, not the marketable yield at technical or biological ripeness. Between fruit set and ripening lies a long period during which some fruits may be shed because of competition for assimilates, and mean fruit mass may change substantially. The data presented should therefore be treated as an assessment of generative potential and not as a yield forecast. Verifying whether the advantage identified is retained until harvest requires a separate experiment covering the full growing cycle.

8. Correlations Between Traits

Correlation analysis makes it possible to move from a description of individual differences between treatments to an understanding of the internal structure of the relationships between traits. The calculations were performed on the pooled sample of 15 plants from all treatments on day 28, which allows the relationships to be assessed across the range of variation created by the factor under study.

Table 8

Correlation coefficients between morphometric indicators and productivity of hot pepper plants (n = 15, day 28)

Pair of traits	*r*	*p*	Assessment of the relationship
Stem diameter – total dry mass	+0.982	< 0.001	significant
Stem diameter – root dry mass	+0.966	< 0.001	significant
Number of buds – number of fruits	+0.948	< 0.001	significant
Stem diameter – number of fruits	+0.908	< 0.001	significant
Total dry mass – number of fruits	+0.897	< 0.001	significant
Root dry mass – number of fruits	+0.888	< 0.001	significant
Compactness index – total dry mass	−0.843	< 0.001	significant
Stem deviation angle – total dry mass	+0.299	0.279	non-significant
Plant height – total dry mass	+0.176	0.530	non-significant
Asymmetry index – total dry mass	+0.148	0.599	non-significant

Note. The critical value of the correlation coefficient for n = 15 at the five per cent significance level is 0.514.

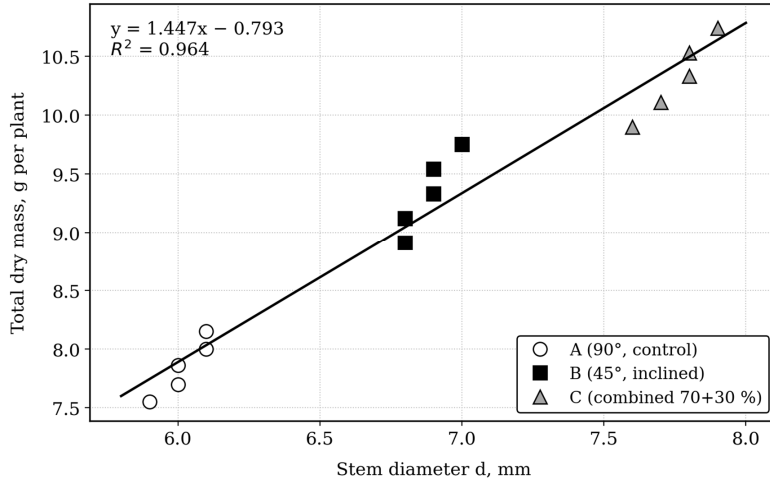


Figure 6. Dependence of the total dry mass of hot pepper plants on stem diameter

The closest relationship was found between stem diameter and total plant dry mass: r = +0.982 at a significance level below 0.001. The coefficient of determination of the corresponding linear regression equation is 0.964, that is, stem diameter explains more than 96 % of the variation in dry mass. The equation takes the form:

$$M = 1.447 \times d - 0.793,$$

where M is the total dry mass of the plant, g, and d is stem diameter, mm. The practical significance of this relationship is difficult to overstate: it makes it possible to assess accumulated dry mass non-destructively, from a single caliper measurement, which is critically important for crop monitoring under production conditions, where cutting plants for weighing is unacceptable.

Stem diameter is no less closely related to the dry mass of the root system (r = +0.966). This is to be expected anatomically: stem diameter reflects the development of the conducting system, which is common to the shoot and the root. In practical terms this means that stem diameter is a reliable indicator of the condition of the root system, which in hydroponic systems is particularly difficult to assess without disturbing the operation of the module.

In sharp contrast to these results stands the relationship between plant height and dry mass: r = +0.176 at p = 0.530, that is, the relationship is statistically non-significant and practically absent. This is one of the most important results of the entire work. Height – the most accessible indicator and the one most often used in production practice – carries no information whatsoever about accumulated biomass within the range of variation created by a change in light geometry. The explanation is simple: treatment B combined the lowest height with an intermediate mass, while the control combined an intermediate height with the lowest mass, and these opposing combinations cancelled the correlation out.

The compactness index, by contrast, showed a close negative relationship with dry mass: r = −0.843 at $p < 0.001$. Since the index is calculated as the ratio of height to diameter, and height does not correlate with mass, this entire relationship is in fact provided by the diameter in the denominator. The practical value of the index is not diminished by this, however: the lower the compactness index, the greater the accumulated dry mass, and

this dependence can be used as a rapid criterion for assessing the condition of a crop.

Total dry mass is closely related to the number of set fruits (r = +0.897), and the corresponding regression equation takes the form:

$$N = 1.139 \times M - 4.182,$$

where N is the number of fruits, units, and M is total dry mass, g; the coefficient of determination is 0.804. The negative intercept has a clear biological meaning: it corresponds to the minimum plant mass below which fruiting does not begin. According to the equation, this threshold mass is approximately 3.67 g of dry matter per plant. It should be emphasised that extrapolating the equation beyond the range of masses studied (7.55–10.75 g) is not valid, and the threshold estimate given is illustrative only.

The number of buds and flowers on day 28 correlates closely with the number of fruits (r = +0.948), which is to be expected, since one follows from the other. The practical significance of this relationship, however, is that bud counting, which is performed non-destructively and quickly, gives a reliable forecast of the number of set fruits.

The absence of a significant relationship between the phototropic indicators and productivity is telling. The stem deviation angle correlates with dry mass at r = +0.299 (p = 0.279) and the asymmetry index at r = +0.148 (p = 0.599). Both relationships are non-significant. This result has important applied significance: deformation of architecture and biomass gain are not rigidly coupled, and there is therefore no fundamental obstacle to the search for a lighting configuration that delivers a high gain in mass with little deformation. Treatment C of this experiment is practical confirmation of that possibility: it provided the highest mass at a deviation angle of only 5.0°.

A substantial reservation should be made about the interpretation of all the coefficients presented. The sample of 15 plants consists of three clearly separated groups of five plants, so a large part of the calculated coefficients reflects primarily between-treatment differences rather than within-population relationships. Formally, this is a manifestation of the fact that the experiment was designed as an analysis-of-variance study rather than a correlation study. The coefficients given should therefore be treated as a description of the structure of relationships specifically within the range of variation created by the factor under study, and not as

universal characteristics of the cultivar. Obtaining genuinely population-level estimates would require a sample with natural variation, taken within a single treatment on a considerably larger number of plants.

9. Practical Application of the Results Obtained

A comparison of the three lighting schemes studied across the complex of indicators makes it possible to formulate well-founded practical recommendations suitable for implementation in modular hydroponic units without additional capital expenditure.

The main practical conclusion is that the combined lighting scheme with a flux distribution of 70 % from above and 30 % from the side at 45° is the best of the treatments studied across the set of traits. It provided the highest total dry mass (+31.6 % over the control), the largest stem diameter (+28.9 %), the greatest number of generative structures (+58.1 %) and of fruits (+65.2 %), while the stem deviation angle rose only to 5.0° and the crown asymmetry index only to 1.060, so that both indicators remained within limits requiring no additional technological measures such as tying or the installation of supports.

Fully inclined lighting at 45° also provided a significant gain in productivity relative to the control (+18.9 % in dry mass, +43.5 % in fruit number), but at the cost of a deformation that must be regarded as technologically unacceptable for most practical applications. A deviation angle of 20.1° on day 28, at an unchanging rate of increase of about 0.65° per day, means that by the time the fruits reached technical ripeness the deviation could have exceeded 40°. Moreover, a substantial part of the bend occurs in the already lignified part of the stem and is irreversible. This scheme can therefore be recommended only for special applications: short-cycle crops, production for greens, and systems with inclined or horizontal plant arrangement, in which the bending of the axis is a desirable feature rather than a defect.

Classical vertical lighting, despite its structural simplicity and the complete absence of deformation, was inferior to both experimental treatments in every productivity indicator. This gives grounds for considering that the widespread practice of positioning luminaires strictly above the crop is not optimal for pepper in modular systems and should be regarded as a starting point for improvement rather than as a standard.

The economic dimension of the question deserves particular attention. All three lighting schemes used the same installed power and provided the same photon flux density at the level of the upper leaf layer, that is, they consumed the same amount of electricity. The gain of 31.6 % in dry biomass and 65.2 % in fruit number was obtained exclusively by rearranging equipment that was already in place. In the operating-cost structure of a unit with artificial lighting, where lighting accounts for 40–60 % of energy consumption [14, p. 453], such a gain translates directly into a proportional reduction in specific energy consumption per unit of produce. This makes the scheme proposed one of the cheapest known ways of raising the efficiency of modular hydroponic systems.

From an engineering point of view, implementing the combined scheme requires no special equipment. It is sufficient to divide the existing light flux between two groups of luminaires: the main group (70 % of the power) is left in the standard overhead position, while the auxiliary group (30 %) is placed at the side of the module with an inclination of 45° to the horizontal. A critically important condition is the monitoring of total photon flux density at the level of the upper leaf layer with a quantum sensor: without such monitoring it is impossible to guarantee that the plants receive the design number of photons, since under inclined incidence the illuminance of a horizontal surface decreases in proportion to the cosine of the angle. Measurements should be repeated weekly, with adjustment of the suspension height as the plants grow.

The regularities established are also important for the organisation of crop monitoring. The close relationship established between stem diameter and dry mass ($r = +0.982$; $R^2 = 0.964$) makes it possible to introduce non-destructive monitoring of biomass accumulation from a single caliper measurement. Plant height, by contrast, which is used most often in production practice, proved unsuitable for assessing crop condition within this range of variation ($r = +0.176$; relationship non-significant). This circumstance should be regarded as an independent practical result of the work: switching from recording height to recording stem diameter requires no expenditure whatsoever but substantially increases the informativeness of monitoring.

The limitations of the study must be clearly stated. First, the experiment was carried out with a single replication in time, that is, the results of one

growing cycle were obtained; definitive conclusions would require the experiment to be repeated over at least two or three cycles. Second, the sample size was five plants per treatment, which is the minimum admissible for analysis of variance; increasing replication would raise the reliability of the estimates, particularly for traits with a high coefficient of variation. Third, the 28-day recording period covers only vegetative growth and the beginning of fruiting, so conclusions about marketable yield lie beyond the data obtained. Fourth, the crown asymmetry and internode length indicators were recorded as averaged characteristics of the treatment, which precluded their analysis of variance. Fifth, only one cultivar of one cultivar type was studied, and transferring the results to other pepper cultivars, let alone to other crops, requires separate verification.

The prospects for further research in this direction are fairly clearly defined. The primary task is to find the optimum ratio of the overhead and lateral components of the light flux: only the proportions 100:0, 0:100 and 70:30 were compared in this experiment, whereas the optimum may lie in the range 50:50 to 80:20 and requires a separate study with a finer step. The second task is to vary the inclination angle of the lateral component: the angle of 45° was chosen a priori and its optimality was not tested. The third is to carry out a full growing cycle through to fruit harvest, with determination of marketable yield, mean fruit mass and produce quality indicators, in particular the content of capsaicin and ascorbic acid, which are of independent economic importance for hot pepper. The fourth direction is to combine the geometric factor with the spectral one: since inclined lighting changes the effective spectral regime of the inner canopy layers, there are grounds for expecting an interaction between incidence angle and the ratio of the spectral components. The fifth task is to verify the regularities identified on other pepper cultivar types and on other protected-cultivation solanaceous crops.

A separate and practically important direction is the development of automated systems for controlling the geometry of the light field. Modern LED luminaires make it possible to vary the distribution of power between groups of emitters, and hence the geometry of the light field, programmatically and in real time. This opens up the possibility of dynamic control in which the share of the lateral component changes according to the developmental phase of the plant: minimal at the stage of transplant

establishment, increased during the phase of active vegetative growth and generative organ initiation, and reduced during the fruit-filling phase in order to prevent lodging. The development of such control programmes is a natural continuation of the study presented here.

CONCLUSIONS

The study conducted on the effect of the incidence angle of the light flux from light-emitting diode sources on the morphometric indicators and productivity of hot pepper cultivar Uhorskyi Zhovtyi in an ebb-and-flow module allows the following conclusions to be drawn.

1. The geometry of the light field is an independent and quantitatively significant agronomic factor. Under equalised photon flux density at the level of the upper leaf layer, identical spectral composition, photoperiod duration and all other growing conditions, a change in the light incidence angle produced an increase in total plant dry mass of 18.9–31.6 % and in fruit number of up to +65.2 %, while the share of factorial variance for most morphometric traits exceeded 0.95.

2. The responses of linear growth and of stem thickening to a change in light geometry act in opposite directions. Inclined lighting at 45° reduced plant height by 10.7 % relative to the control, while combined lighting raised it by 3.6 %; stem diameter, meanwhile, increased in both experimental treatments, by 14.3 and 28.9 % respectively. The absolute rate of stem thickening rose from 0.121 mm/day in the control to 0.150 and 0.180 mm/day in the experimental treatments.

3. The compactness index I_c proved to be the most sensitive integral indicator of the plant response to the geometry of the light field. In the control it rose over the course of the experiment from 3.258 to 3.389 cm/mm, that is, the plants became elongated, whereas in the experimental treatments it fell to 2.648 and 2.724 cm/mm. The difference from the control exceeded LSD_{05} more than thirtyfold, and the share of factorial variance was above 0.99.

4. The phototropic response of the plants to the lateral component of the light flux is non-linear with respect to its share. Under fully inclined lighting the stem deviation angle reached 20.1° and the crown asymmetry index 1.824; under combined lighting with a lateral share of 30 % these indicators were only 5.0° and 1.060 respectively. A threefold reduction of

the lateral component thus reduced the deformation fourfold, which points to active counteraction of the lateral redistribution of auxin by the strong vertical component.

5. The change in the geometry of the light field increased dry matter accumulation by 18.9 % under inclined and by 31.6 % under combined lighting, with the increment of the root system (24.6 and 37.7 %) exceeding that of the shoot (17.2 and 29.8 %). The shoot-to-root ratio decreased significantly from 3.488 in the control to 3.281 and 3.288 in the experimental treatments which, given the simultaneous increase in the absolute mass of both organs, indicates an improvement in the overall carbon balance of the plant rather than a redistribution of a limited resource.

6. The generative sphere proved more sensitive to the factor under study than the vegetative one. The number of buds and flowers on day 28 increased by 23.3 and 58.1 %, the number of set fruits by 43.5 and 65.2 % relative to the control, and specific productivity (the number of fruits per unit of dry mass) from 0.586 to 0.708 and 0.736 fruits/g. A change in light geometry therefore increases not only the size of the plant but also the efficiency with which accumulated dry matter is converted into generative organs.

7. The two schemes studied raise productivity by fundamentally different mechanisms. Combined lighting acts through an increase in the number of nodes (8.81 as against 7.85 in the control at $LSD_{05} = 0.156$), that is, by increasing the number of potential sites for the initiation of generative organs. Inclined lighting acts through an increase in the realisation coefficient of generative structures (62.2 as against 53.3 % in the control), that is, through better conditions for retaining the fruit set already initiated.

8. A close direct relationship was established between stem diameter and total plant dry mass ($r = +0.982$; $R^2 = 0.964$; equation $M = 1.447d - 0.793$), which makes it possible to introduce non-destructive monitoring of biomass accumulation from a single caliper measurement. Plant height, by contrast, showed no significant relationship with dry mass within the range of variation created by the factor under study ($r = +0.176$; $p = 0.530$) and is unsuitable for assessing crop condition.

9. Phototropic deformation and biomass gain are not linked by a significant correlation (for the deviation angle $r = +0.299$, $p = 0.279$; for the asymmetry index $r = +0.148$, $p = 0.599$). This means that it is fundamentally possible to seek a lighting configuration that combines a high gain in mass

with little deformation of architecture, practical confirmation of which is provided by the combined treatment of the experiment.

10. For practical application in modular hydroponic units, a combined lighting scheme is recommended with a flux distribution of 70 % vertically from above and 30 % laterally at 45°, subject to compulsory equalisation of the total photon flux density at the level of the upper leaf layer. The scheme requires no additional installed power and no additional capital expenditure, is implemented by rearranging existing equipment, and provides a gain of 31.6 % in dry biomass and 65.2 % in fruit number at a technologically acceptable deformation of plant architecture.

11. The results obtained are preliminary and require confirmation in repeated growing cycles on larger samples, with the experiment carried through to fruit harvest. Priority directions for further research are the search for an optimum ratio of the overhead and lateral components of the flux with a finer step of variation, optimisation of the inclination angle of the lateral component, study of the interaction between the geometric and spectral factors, and the development of programmes for dynamic control of light field geometry according to the developmental phase of the plants.

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