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THE EFFECT OF SELECTIVE LIGHT ON MORPHOGENETIC AND BIOSYNTHETIC REACTIONS IN CALLUS CULTURE OF *PISUM SATIVUM* L.

O.O. AVKSENTIEVA, Y.D. BATUIEVA, M.G. HANZENKO, O.G. KUTSYK

V.N. Karazin Kharkiv National University
4 Maydan Svobody, Kharkiv, 61022, Ukraine
e-mail: avksentyeva@karazin.ua

Light quality is a key environmental factor regulating plant growth, development, and metabolic activity, particularly under controlled *in vitro* conditions. The widespread use of light-emitting diode (LED) systems enables precise modulation of spectral composition, and provides new opportunities for regulating photomorphogenesis and biosynthetic processes in plant tissue cultures. This study investigated the effects of monochromatic LED irradiation with different spectral compositions — red (RL, 660 nm), green (GL, 525 nm), and blue (BL, 470 nm) — on morphogenetic responses and metabolic activity in the callus culture of *Pisum sativum* L. Callus cultures of the pea of Macenat variety at the 2nd—3rd subculture passages were used. Photoactivation was performed using Korobov-modified LED matrices with defined spectral characteristics, while control cultures were maintained in darkness. The effects of selective light irradiation on callus growth, morphogenesis, and the accumulation of primary and secondary metabolites were evaluated. Monochromatic LED irradiation induced spectrum-specific responses in pea callus tissues. Red light stimulated active cell proliferation, increased the growth index, and promoted the formation of morphogenetic structures. Blue light was the most effective inducer of morphogenesis, enhancing callus cell differentiation and protein accumulation. Green light had little effect on callus growth and morphogenesis but caused pronounced changes in metabolic activity, particularly in carbohydrate and flavonoid accumulation. Overall, the results demonstrate that selective monochromatic light differentially modulates photomorphogenic pathways and biosynthetic processes in *P. sativum* callus culture, highlighting the potential of light spectrum manipulation as a tool for regulating morphogenesis and metabolic profiles in plant *in vitro* systems.

Key words: *Pisum sativum* L., *in vitro* culture, monochromatic LED light, callusogenesis, morphogenesis, soluble carbohydrates, proteins, phenols, flavonoids.

One of the most important environmental factors determining plant growth, development and metabolism is light irradiation. Light not only performs an energetic function, ensuring the process of photosynthesis, but also acts as a universal regulatory signal that coordinates the photomorphogenesis programme [1], regulates the expression of genes associated

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with growth [2], tissue differentiation [3] and the biosynthesis of primary and secondary metabolites [4]. The ability of plants to perceive various characteristics of light signals (intensity, direction, photoperiod, spectral composition etc.) is provided by a complex of specialised photosensory systems — photoreceptors [5], which include phytochromes [6], cryptochromes [7], phototropins [8], F-box proteins ZTL/FKF1/LKP2 [9] and the ultraviolet B receptor — the UVR8 protein [10].

The spectral composition of light significantly affects the processes of photomorphogenesis. Previous studies have shown that phytochromes, receptors of red and far-red light, control growth processes, flowering, photoperiodic regulation, and reactions to shading [11, 12]. Cryptochromes and phototropins, receptors of blue light, are involved in the regulation of phototropism, leaf formation, chloroplast development, and circadian rhythm regulation [7, 8]. At present, green light photoreceptors have not been identified, but its effect on photomorphogenic and biosynthetic reactions in plants is being actively studied [13]. The combination of light from different spectral ranges provides a subtle mechanism for regulating plant development, allowing targeted control of the morphogenesis and biochemical profile of plant tissues [1, 14].

The widespread introduction of light-emitting diode (LED) light sources in *in vitro* studies has made it possible to modulate the spectral characteristics of light with high precision, which has significantly expanded the potential for controlling photomorphogenesis and regeneration processes in *in vitro* tissue culture [15]. It has been proven that the light regime is one of the key factors determining the ability to form callus [16], the rate of cell proliferation [17], and their differentiation [18]. It has been established that different light spectra can initiate various pathways of plant cell development *in vitro* through the regulation of phytohormonal balance and the expression of transcription factors associated with regeneration [19].

Callus culture, as a mass of undifferentiated plant cells, retains a number of properties of the original plant organism, but at the same time acquires new properties that are formed *in vitro*, making it a valuable experimental model for studying the mechanisms of cell differentiation, morphogenesis induction, and regulation of metabolite biosynthesis. It is widely used in plant physiology research, as well as for the industrial production of biologically active substances with pharmacological and antioxidant effects [19, 20]. It has been proven that the dynamics of accumulation of secondary metabolites, such as phenolic compounds, flavonoids, anthocyanins, and alkaloids, in response to irradiation with light of different spectra depends on the species and even the variety of plants [1, 21]. For example, combined red-blue light enhances the production of biologically active compounds in the callus of *Gynura procumbens* [22] and *Camellia japonica* [23], while green light enhances antioxidant activity and phenolic metabolism in *Vitis davidii* grape callus [24], demonstrating the multicomponent nature of light regulation. Along with modifying metabolism, the light spectrum also determines the morphogenetic response of plant tissues. Red light typically stimulates cell proliferation and callus biomass increase, whereas blue light may cause partial differentiation or growth retardation

[17, 25]. This indicates that the photomorphogenetic and metabolic pathways of tissue development *in vitro* are closely integrated through the light perception system and depend on the plant species.

Pea (*Pisum sativum* L.) is one of the important legumes in global agriculture and is valuable as a source of food protein, amino acids, vitamins, and biologically active substances, including flavonoids, saponins, and phenolic acids [26]. Pea tissue culture can be considered a promising platform for the biotechnological production of secondary metabolites and the study of regulatory mechanisms of morphogenesis. In addition, pea tissue culture is actively used in breeding programmes [27], but the issue of using pea callus culture in the biotechnology industry as a source of protein remains unresolved [28, 29]. However, unlike many other crops, the effect of selective light on photomorphogenesis and biosynthetic activity of *Pisum sativum* L. callus has not been sufficiently studied.

Thus, studying the effect of light of different spectral composition on the growth and morphophysiological properties of pea callus is relevant both from the point of view of fundamental biology and practical plant biotechnology. Understanding the mechanisms of light regulation can provide an opportunity to optimise *in vitro* cultivation technologies aimed at increasing crop productivity and obtaining plant materials with a high content of valuable metabolites.

Based on the above, the aim of our work was to study the effect of monochromatic red, blue and green light on the morphogenesis and metabolic activity of *Pisum sativum* L. callus culture.

Materials and methods

The callus culture of *Pisum sativum* L. of the Macenat variety was used, which is included in the State Register of Plant Varieties of Ukraine (2020). Seeds were provided by employees of the Yuriev Plant Production Institute of NAAS (Kharkiv, Ukraine).

Obtaining callus culture and conditions for photoactivation with selective light. Primary callus was obtained by inducing callus formation from sterile seeds. Surface sterilisation was carried out according to the standard protocol: preliminary washing in a detergent solution, followed by treatment with 70 % ethanol (1 min) and 15 % potassium hypochlorite solution (15 min). To induce callus formation, seeds were cultured on Murashige and Skoog (MS) nutrient medium with a standard rate of macro- and microelements, vitamins and glycine [30], modified by the addition of synthetic auxin 2,4-dichlorophenoxyacetic acid (2,4-D) at a concentration of 10 mg/L to activate the process of primary callus formation.

Callus cultures were cultivated in a TSO-80 MICROmed thermostat (Ukraine) at a constant temperature of 26 °C in darkness for 4 weeks. Further subcultivation was carried out on MS medium with a reduced concentration of 2,4-D (5 mg/L). To study the effect of photoirradiation, mature callus cultures of the 2nd—3rd passages were used, which ensured the reproducibility of growth and morphogenetic characteristics.

Irradiation was carried out using Korobov-modified LED matrices «Barva-Flex/FM» of various spectral modifications at intensity of 120 mW/m^2 [31]. According to approximate spectral distributions, this corre-

sponds to PPFD as ≈ 94—132 μmol/($m^2 \cdot s$) depending on the peak wavelength. Callus cultures were irradiated with monochromatic light of different wavelengths: red (λ = 660±10 nm), green (λ = 525±10 nm) and blue (λ = 470±10 nm). Control samples were cultivated without irradiation. Photoinduction was carried out daily for 30 min in a light-tight box for 7 days, after which the cultures were additionally incubated in a thermostat for three weeks to synchronise metabolic processes (Fig. 1).

Evaluation of morphogenetic and biosynthetic reactions. After completion of cultivation, a comprehensive analysis of morphogenetic and metabolic parameters was performed, in particular:

– morphological characteristics of calli (colour, homo/heterogeneity, presence of morphogenic structures);

– the frequency of morphogenesis, assessed as the ratio of calluses that formed morphogenetic structures to the total number of calli (in percent);

– growth dynamics, assessed by the growth index (*GI*), which was determined as the ratio of the callus area after cultivation (S_2) to the initial area (S_1). The callus area was determined using ImageJ 1.52k software;

$$GI = (S_2 \,/\, S_1) \times 100\ \%;$$

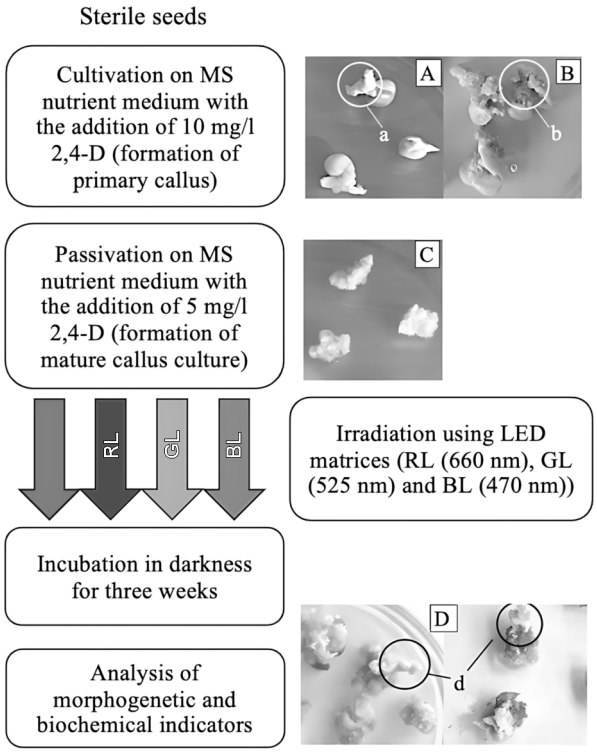

Fig. 1. Scheme of the study of the effect of selective light on morphogenetic and biosynthetic reactions in callus culture of *Pisum sativum* L. variety Macenat: A — pea seedlings on MS nutrient medium with the addition of 10 mg/L 2,4-D (a — altered seedling); B — primary callus on cotyledons and from germs (b); C — mature callus on MS nutrient medium with the addition of 5 mg/L 2,4-D; D — formation of morphogenic structures on experimental calluses after irradiation (d)

– biosynthetic activity, which included determining the content of soluble carbohydrates, soluble proteins, total phenolic compounds, and flavonoids.

Biochemical analysis methods. The soluble carbohydrates content was determined using a photocolorimetric micro method with potassium ferricyanide [32]. Soluble carbohydrates were extracted using 80 % ethyl alcohol. The amount of monosaccharides was determined by reaction with potassium ferrocyanide in an alkaline medium under heating using a Photoelectric Photometer KFK-2MP (λ = 670 nm). To determine the total carbohydrates, part of the extract was subjected to acid hydrolysis followed by repeated measurement. The amount of carbohydrates was determined using a calibration curve constructed for glucose (Sigma-Aldrich, Germany) according to the formula:

$$A = (c \times k) / m, \text{ where}$$

c — soluble carbohydrates concentration in the test solution according to the calibration curve, mg/mL;
k — dilution coefficient;
m — sample weight, g.

The amount of oligosaccharides was determined by the difference between the total carbohydrate and monosaccharide content.

The content of water-soluble proteins was determined by the Bradford method using the Coomassie Brilliant Blue G-250 dye [33]. Extraction was performed with a phosphate-salt buffer (pH 7.4). The optical density was determined by the photocolorimetric method (λ = 595 nm). The amount of protein was determined using a calibration curve constructed according to albumin standards (Chimlaborreaktiv LLC, Ukraine) using the formula:

$$A = (c \times V) / (V_1 \times m), \text{ where}$$

c — protein concentration in the test solution according to the calibration curve, mg/mL;
V — total volume of the extract, mL;
V_1 — volume of the extract taken for analysis, mL;
m — sample weight, g.

The content of total phenolic compounds was determined after triple extraction with 80 % ethanol using Folin-Ciocalteu reagent and sodium bicarbonate by a photocolorimetric method (λ = 760 nm). The amount of phenols was determined using a calibration curve constructed according to pyrocatechin standards (Chimlaborreaktiv LLC, Ukraine) [34].

The flavonoid content was determined in the same extracts by reaction with aluminium chloride. The calculation was performed using the calibration curve for quercetin (Chimlaborreaktiv LLC, Ukraine) by the photocolorimetric method (λ = 510 nm) [35].

The content of phenols and flavonoids was determined using the formula:

$$A = (c \times k) / m, \text{ where}$$

c — concentration in the test solution according to the calibration curve, mg/mL;
k — dilution factor;
m — sample weight, g.

Statistical analysis. Statistical analysis of the obtained data was performed using Microsoft Excel 2019 and Statistica 5.0 software. The significance of differences between variants was assessed using The Mann-Whitney U test. The results of the study were visualised by constructing graphical dependencies of growth and metabolic indices on the spectral composition of lighting using Microsoft Excel 2019 software. The Figures show the mean value and standard error of the mean (x±SE).

Results and discussion

A strongly expressed relation was established between the spectral composition of light irradiation and the growth activity of callus tissue of *Pisum sativum* L. of the Mecenat variety. The observed changes in the growth index (GI) confirm that certain ranges of monochromatic light have a specific regulatory effect on the processes of callus cell proliferation and biomass accumulation *in vitro* (Fig. 2).

In particular, red light (660 nm) provided the highest growth index values — 154.2 % compared to the control value of 129.6 %. This indicates intense stimulation of cell division, which may be associated with the activation of phytochrome-dependent mechanisms of proliferation regulation and metabolic support of growth processes. Similar effects have been described for callus cultures of other species, in particular *Withania somnifera* and *Cymbidium*, where red light promoted both the induction and increase in callus tissue mass [15, 17].

Blue light (470 nm) had a moderate effect: the increase in callus tissue did not exceed the control values (130.7 %). This allows us to interpret its action as maintaining basic metabolic processes without significant activation of proliferation. It is known that blue light activates cryp-

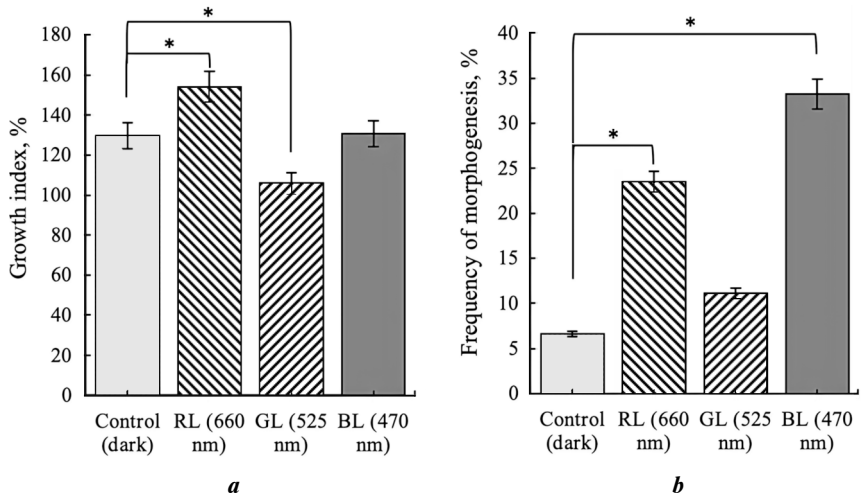

Fig. 2. Callusogenesis and morphogenesis processes in *in vitro* pea culture under photoirradiation with monochromatic light of different spectra RL 660 nm, GL 525 nm, BL 470 nm): *a* — growth index (GI) of mature callus culture after 4 weeks of cultivation under photoinduction of RL, GL, BL; *b* — frequency of morphogenesis of mature callus culture during 4 weeks of cultivation under photoinduction of RL, GL, BL (x±SE, n = 20; * — the difference with the control is significant at $p \leq 0.05$)

tochromes and phototropins, stabilising the photosynthetic and regenerative functions of tissues [36].

Unlike the two previous spectra, the green spectrum (525 nm) caused inhibition of growth reactions compared to the control (105.9 %). Low GI values may be associated with the weak effectiveness of this light in activating photosensory systems or with inhibitory signals that suppress regulatory growth cascades. This may be associated with the ability of green light to deactivate cryptochromes, accompanied by a decrease in growth processes [37, 38].

At the same time, irradiation with monochromatic light contributed to the appearance of morphological structures in the studied callus cultures. In the control variant, the frequency of morphogenesis reached 6.6 %, which was the minimum level of differentiation in the absence of the stimulating effect of photoirradiation. Under the influence of red light, the frequency of morphogenesis increased to 23.5 %, which indicates its significant activation. Obviously, such morphogenetic changes are mediated by phytochromes, which, when irradiated with red light, turn to an active form and induce the expression of genes involved in light-dependent development [37]. The most intense morphogenetic changes were observed under blue light (470 nm), where the proportion of morphogenic structures reached 33.2 %. This indicates active cell differentiation and induction of organogenic primordia, consistent with the known effects of the blue spectrum aimed at activating cryptochrome-mediated signalling cascades and stabilising HY5, which regulate the transcription of key morphogenetic genes [3, 39]. Green light irradiation had the lowest efficiency in triggering morphogenesis — 11.1 %. Thus, blue and red light were the most active in stimulating callus tissue morphogenesis. The green spectrum provided only partial morphogenetic activity, while darkness caused inhibition of differentiation processes. The results confirm the important role of blue and red spectrum photoreceptors in regulating morphogenesis *in vitro* in *Pisum sativum* L. culture.

Irradiation with selective light not only promoted the appearance of morphogenetic elements, but also led to changes in the appearance of the calli studied (Table). In the control variant (without irradiation), the calli had a pale yellow colour with dark brown inclusions and were characterised by medium density. Under the action of red and blue light, the calli acquired a brown colour with dark elements, maintaining medium density, while under the action of green light irradiation, the calli retained a pale yellow colour, as in the control variant. The absence of pronounced morphogenic structures, the amorphous gel-forming consistency of the tissue, and the low level of differentiation indicate an inhibitory or neutral effect of this spectrum. According to the literature, green light is capable of inducing a 'shadow' state of photomorphogenesis and weakening cryptochrome-mediated signals, which is confirmed by the results obtained [36, 40].

It is known that photoactivation of photoreceptor systems in callus tissues contributes to changes not only in growth and morphogenesis, but also affects biosynthetic activity, in particular the content of water-soluble carbohydrates, proteins, and phenolic compounds [14, 22—24].

Morphological characteristics of callus culture in vitro under the action of selective light of different spectra: RL 660 nm, GL 525 nm, BL 470 nm

Cultivation conditions	Density	Heterogeneity	Colour	Appearance
Darkness (without irradiation)	Medium density, watered	Heterogeneous, with new callus elements	Pale yellow with dark brown elements	
RL 660 nm	Dense, compact	Heterogeneous, with morphogenic structures	Brown with dark elements	
GL 525 nm	Medium density, watered	Heterogeneous, with new callus elements	Pale yellow with dark elements	
BL 470 nm	Dense, compact	Heterogeneous, with morphogenic structures	Brown with dark elements	

The total soluble carbohydrates content in the control calli reached 99.7 mg/g of fresh weight (FW), of which 42.9 mg/g were monosaccharides. Irradiation with selective light contributed to an increase in the content of soluble carbohydrates, both monosaccharides and oligosaccharides. The highest content of soluble carbohydrates was found in calli irradiated with green light — 14.7 % more than in the control (Fig. 3). This is probably due to the accumulation of reserve carbohydrates in response to the low rate of growth and morphogenetic processes. This trend is consistent with morphological observations and reduced growth rates in this group (Fig. 2, Table). Under the action of red light, a slight increase in the content of soluble carbohydrates was also noted — by 5.9 % compared to the control. Irradiation with blue light led to a 7.6 % decrease in the content of carbohydrates, both mono- and oligosaccharides, which may be associated with an increase in the rate of biosynthetic processes and, consequently, energy expenditure due to morphogenesis.

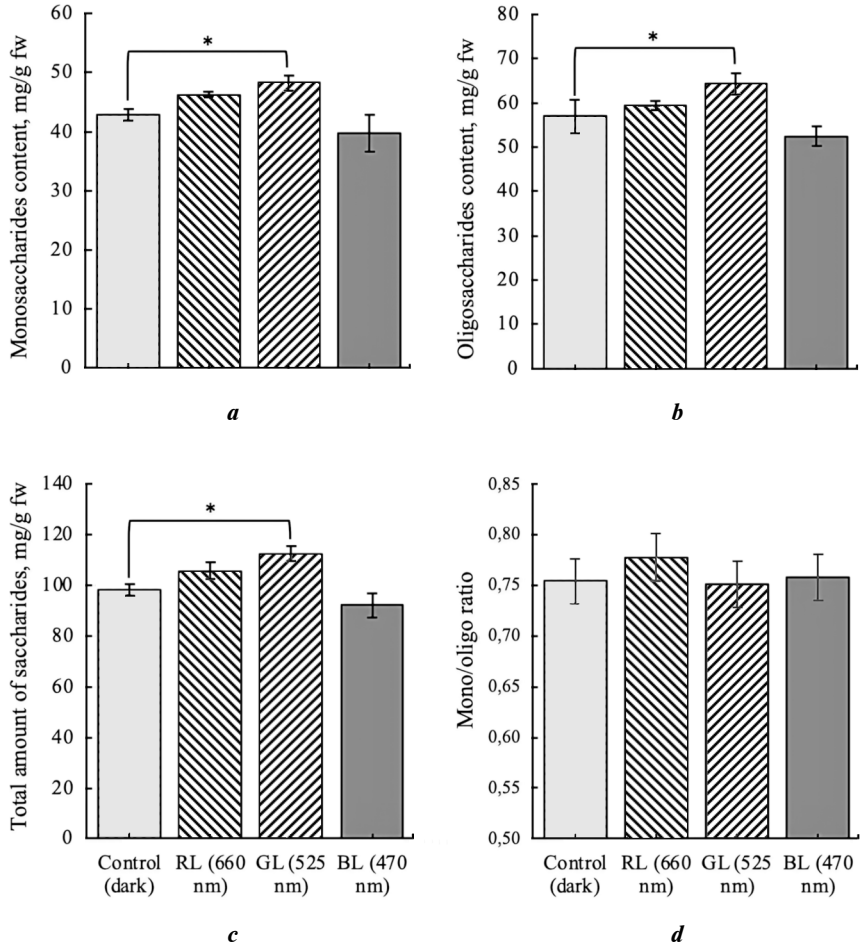

Fig. 3. Soluble carbohydrates content in pea calluses of the Macenat variety under the influence of selective light of different spectra (RL, GL and BL): *a* — total amount of soluble carbohydrates, *b* — monosaccharide content, *c* — oligosaccharide content, *d* — monosaccharide/oligosaccharide ratio ($x \pm SE$, n = 20; * — the difference with the control is significant at $p \leq 0.05$)

At the same time, the ratio of monosaccharides to oligosaccharides remains almost unchanged under the action of selective light, which may indicate the presence of mechanisms that maintain a relatively stable balance between the synthesis, breakdown and transport of carbohydrates in the test plants (Fig. 3, *d*). Only under the action of red light a slight shift in the ratio towards monosaccharides was observed.

Irradiation with selective light also affected the soluble protein content in the studied calli. In the control calli, the soluble protein content was 10.9 mg/g (FW). Irradiation with blue light contributed to a twofold increase in this index (Fig. 4). This is consistent with the morphogenesis rate (Fig. 2) and the increased demand for protein synthesis during the formation of organogenic structures. An increase in protein content under the influence of blue light has also been described for calli of other species, in particular *Lactuca sativa* [41]. A similar reaction was observed when calli were irradiated with green light — an increase in soluble protein content

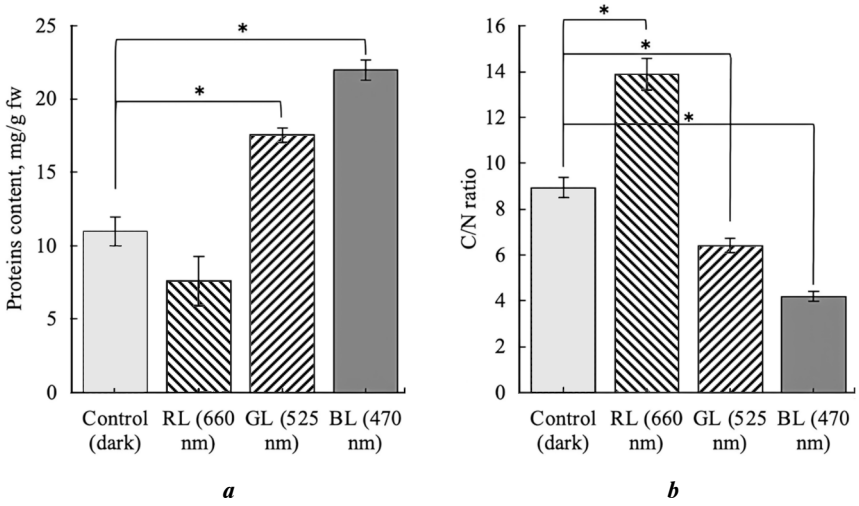

Fig. 4. Content of water-soluble proteins (*a*) and C/N ratio (*b*) in pea callus culture of the Macenat variety under the influence of selective light of different spectra (RL, GL and BL) (x±SE, n = 20; * — the difference with the control is significant at $p \leq 0.05$)

by 60 %, which allows us to assume the involvement of cryptochrome-dependent signalling pathways in the response of plants to green light.

Selective light exposure also causes changes in the C/N ratio, i.e. the ratio of soluble carbohydrates to soluble proteins (Fig. 4, *b*). Under red light, there is a balance shift towards soluble carbohydrates, indicating the predominance of carbohydrate synthesis over protein biosynthesis and the active accumulation of energy resources, which may be associated with meeting the energy and structural needs of cell division without significant synthesis of specialised proteins necessary for morphogenesis. Under blue light, on the contrary, the C/N ratio decreases compared to the control, which may indicate the active use of soluble carbohydrates in biosynthetic processes associated with morphogenesis.

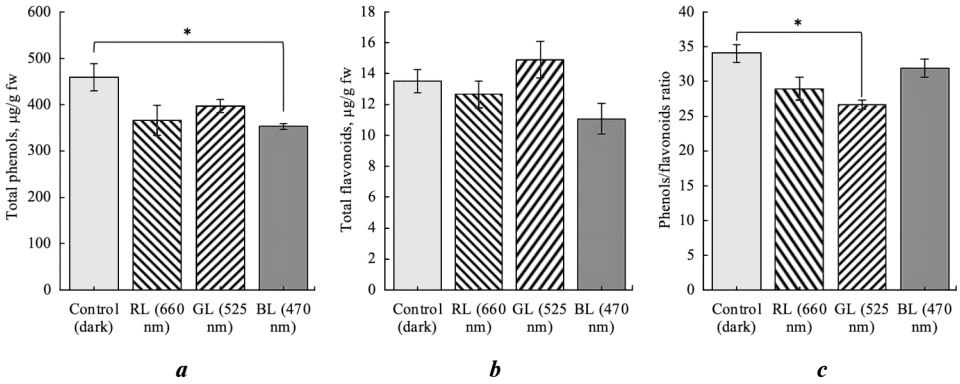

Fig. 5. Phenolic balance in pea callus culture of the Macenat variety under the influence of selective light of different spectra (RL, GL and BL): *a* — phenols content, μg/g FW, *b* — flavonoids content, μg/g FW, *c* — phenols/flavonoid ratio (x±SE, n = 20; * — the difference with the control is significant at $p \leq 0.05$)

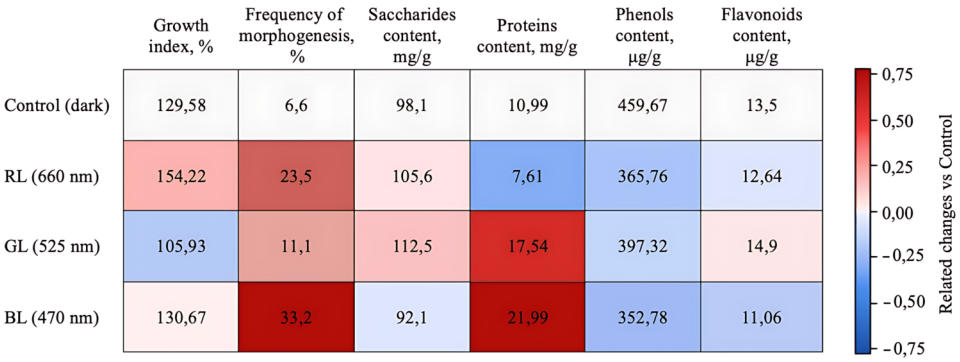

Fig. 6. Assessment of the effect of photoirradiation with monochromatic light of different spectra (RL 660 nm, GL 525 nm, BL 470 nm) on the studied parameters on the thermal map (the colour shows the direction and intensity of changes compared to the control)

Irradiation with selective light also affected the secondary metabolites content. The phenolic compounds content decreased under all irradiation treatments compared to the control (Fig. 5). The most significant decrease in total phenols was recorded under red and blue light irradiation — by 20 % and 23 %, respectively, which may indicate their use in differentiation processes or a decrease in oxidative stress under conditions of increased biosynthetic activity.

The highest flavonoid content was observed in calli irradiated with green light — 14.9 μg/g (FW) — 10.3 % higher than the control, which may indicate the activation of enzymatic pathways of secondary metabolism. It is likely that the green spectrum induces metabolic restructuring that is not accompanied by the formation of organogenic structures.

Under the action of selective light of all studied spectra, a decrease in the phenols/flavonoids ratio was observed, especially under the action of green light. It has been proven that flavonoids act as endogenous negative regulators of auxin transport in the model plant Arabidopsis, which allows us to assume a connection between the increased flavonoid content in the experimental calli and the reduced growth index under green light irradiation compared to the control (Fig. 2) [42].

In summary, it can be stated that monochromatic LED irradiation of different spectral composition has a significant modulating effect on the photomorphogenesis and metabolic profile of *Pisum sativum* L. callus culture (Fig. 6).

Red light mainly stimulates callus growth and cell proliferation, ensuring intensive growth of callus tissue without significantly enhancing morphogenesis processes, while blue light is the most effective inducer of morphogenesis processes, promoting callus cell differentiation and the formation of morphogenic structures, accompanied by the activation of protein metabolism and a metabolic shift towards the use of energy resources in biosynthetic processes. At the same time, green light does not provide callus growth or morphogenesis, but causes pronounced metabolic changes in the studied calli, manifested by the accumulation of carbohydrates and flavonoids. Spectrum-specific changes in the ratio of soluble carbohydrates to soluble proteins (C/N) reflect the integral response of cal-

lus culture to light signals and can be considered as a generalised index of the direction of its development *in vitro*. Thus, *Pisum sativum* L. callus culture demonstrates high sensitivity to the quality of light environment, and is a promising model system for studying the mechanisms of light regulation of growth, morphogenesis, and metabolic activity of plant tissues *in vitro*.

The work was carried out within the framework of the research topic «Study of photoinfluence as a regulator of molecular-genetic, physiological-metabolic processes and plant-microorganism interactions for controlling the productivity of leading leguminous crops under global climate change» State Registration No. 0124U004292.

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Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES

1. Paradiso, R. & Proietti, S. (2022). Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. J. Plant Growth Regul., 41(2), pp. 742-780. https://doi.org/10.1007/s00344-021-10337-y
2. Kami, C., Lorrain, S., Hornitschek, P. & Fankhauser, C. (2010). Light-regulated plant growth and development. Curr. Top. Devel. Biol., 91, pp. 29-66. https://doi.org/10.1016/S0070-2153(10)91002-8
3. Gangappa, S.N. & Botto, J.F. (2016). The multifaceted roles of HY5 in plant growth and development. Mol. Plant, 9(10), pp. 1353-1365. https://doi.org/10.1016/j.molp.2016.07.002
4. Zhang, S., Zhang, L., Zou, H., Qiu, L., Zheng, Y., Yang, D. & Wang, Y. (2021). Effects of light on secondary metabolite biosynthesis in medicinal plants. Front. Plant Sci., 12, 781236. https://doi.org/10.3389/fpls.2021.781236
5. Briggs, W.R. & Olney, M.A. (2001). Photoreceptors in plant photomorphogenesis to date. Five phytochromes, two cryptochromes, one phototropin, and one superchrome. Plant Physiol., 125(1), pp. 85-88. https://doi.org/10.1104/pp.125.1.85
6. Rockwell, N.C. & Lagarias, J.C. (2010). A brief history of phytochromes. Chemphyschem, 11(6), pp. 1172-1180. https://doi.org/10.1002/cphc.200900894
7. Yu, X., Liu, H., Klejnot, J. & Lin, C. (2010). The cryptochrome blue light receptors. The Arabidopsis Book/American Society of Plant Biologists, 8. https://doi.org/10.1199/tab.0135
8. Christie, J.M. (2007). Phototropin blue-light receptors. Annu. Rev. Plant Biol., 58, pp. 21-45. https://doi.org/10.1146/annurev.arplant.58.032806.103951
9. Schultz, T.F. (2005). The ZEITLUPE family of putative photoreceptors. Handbook of Photosensory Receptors, pp. 337-347. https://doi.org/10.1002/352760510X
10. Jenkins, G.I. (2014). The UV-B photoreceptor UVR8: from structure to physiology. The Plant Cell, 26(1), pp. 21-37. https://doi.org/10.1105/tpc.113.119446
11. Eskins, K. (1992). Light-quality effects on Arabidopsis development. Red, blue and far-red regulation of flowering and morphology. Physiol. Plant., 86(3), pp. 439-444. https://doi.org/10.1111/j.1399-3054.1992.tb01341.x
12. Spaninks, K., Van Lieshout, J., Van Ieperen, W. & Offringa, R. (2020). Regulation of early plant development by red and blue light: A comparative analysis between Arabidopsis thaliana and Solanum lycopersicum. Front. Plant Sci., 11, 599982. https://doi.org/10.3389/fpls.2020.599982

13. Wang, Y. & Folta, K.M. (2013). Contributions of green light to plant growth and development. Amer. J. Bot., 100(1), pp. 70-78. https://doi.org/10.3732/ajb.1200354
14. Zhang, T., Shi, Y., Piao, F. & Sun, Z. (2018). Effects of different LED sources on the growth and nitrogen metabolism of lettuce. Plant Cell Tissue and Organ Culture (PCTOC), 134, pp. 231-240. https://doi.org/10.1007/s11240-018-1415-8
15. Huan, Le & Tanaka, Michio. (2004). Effects of Red and Blue Light-Emitting Diodes on Callus Induction, Callus Proliferation, and Protocorm-Like Body Formation from Callus in Cymbidium Orchid. Environ. Control in Biol., 42, pp. 57-64. https://doi.org/10.2525/ecb1963.42.57.
16. Long, Y., Yang, Y., Pan, G. & Shen, Y. (2022). New insights into tissue culture plant-regeneration mechanisms. Front. Plant Sci., 13, 926752. https://doi.org/10.3389/fpls.2022.926752
17. Cavallaro, V., Pellegrino, A., Muleo, R. & Forgione, I. (2022). Light and plant growth regulators on in vitro proliferation. Plants, 11(7), 844. https://doi.org/10.3390/plants11070844
18. Adil, M., Abbasi, B.H. & ul Haq, I. (2019). Red light controlled callus morphogenetic patterns and secondary metabolites production in Withania somnifera L. Biotechnol. Rep., 24, e00380. https://doi.org/10.1016/j.btre.2019.e00380
19. Hashim, M., Ahmad, B., Drouet, S., Hano, C., Abbasi, B.H. & Anjum, S. (2021). Comparative effects of different light sources on the production of key secondary metabolites in plants in vitro cultures. Plants, 10(8), 1521. https://doi.org/10.3390/plants10081521
20. Bojko, M., Kędra, M., Adamska, A., Jakubowska, Z., Tuleja, M., & Myśliwa-Kurdziel, B. (2024). Induction and characteristics of callus cultures of the medicinal plant Tussilago farfara L. Plants, 13(21), 3080. https://doi.org/10.3390/plants13213080
21. Acharjee, S., Kumar, R. & Kumar, N. (2022). Role of plant biotechnology in enhancement of alkaloid production from cell culture system of Catharanthus roseus: A medicinal plant with potent anti-tumor properties. Industrial Crops and Products, 176, 114298. https://doi.org/10.1016/j.indcrop.2021.114298
22. Lian, T.T., Moe, M.M., Kim, Y.J. & Bang, K.S. (2019). Effects of different colored LEDs on the enhancement of biologically active ingredients in callus cultures of Gynura procumbens (Lour.) Merr. Molecules, 24(23), 4336. https://doi.org/10.3390/molecules24234336
23. Jang, E.B., Ho, T.T. & Park, S.Y. (2020). Effect of light quality and tissue origin on phenolic compound accumulation and antioxidant activity in Camellia japonica calli. In Vitro Cellular & Developmental Biology-Plant, 56(5), pp. 567-577. https://doi.org/10.1007/s11627-020-10121-9
24. Lai, C.C., Pan, H., Zhang, J., Wang, Q., Que, Q.X., Pan, R., Zhong-Xiong, Lai & Lai, G.T. (2022). Light quality modulates growth, triggers differential accumulation of phenolic compounds, and changes the total antioxidant capacity in the red callus of Vitis davidii. J. Agric. Food Chem., 70(41), pp. 13264-13278. https://doi.org/10.1021/acs.jafc.2c04620
25. Fan, C., Manivannan, A. & Wei, H. (2022). Light Quality-Mediated Influence of Morphogenesis in Micropropagated Horticultural Crops: A Comprehensive Overview. BioMed Res. Int., 2022(1), 4615079. https://doi.org/10.1155/2022/4615079
26. Dahl, W.J., Foster, L.M. & Tyler, R.T. (2012). Review of the health benefits of peas (Pisum sativum L.). British J. Nutr., 108(S1), S3-S10. https://doi.org/10.1017/S0007114512000852
27. Abbas, A., Rehman, A.U. & Javed, M.M. (2021). Exploring the potential of in vitro tissue culture in breeding programs of legume and pulse crops: utilization and present condition. Bull. Biol. Allied Sci. Res., 2021(1), pp. 36-36. https://doi.org/10.54112/bbasr.v2021i1.36
28. Efferth, T. (2019). Biotechnology applications of plant callus cultures. Engineering, 5(1), pp. 50-59. https://doi.org/10.1016/j.eng.2018.11.006
29. Tulbek, M.C., Wang, Y.L. & Hounjet, M. (2024). Pea—A sustainable vegetable protein crop. In Sustainable Protein Sources (pp. 143-162). Academic Press. https://doi.org/10.1016/B978-0-323-91652-3.00027-7

30. Phillips, G.C. & Garda, M. (2019). Plant tissue culture media and practices: an overview. In Vitro Cellular & Developmental Biology-Plant, 55(3), pp. 242-257. https://doi.org/10.1007/s11627-019-09983-5
31. Korobov, A.M. (2015). Phototherapy devices by Korobov A. and Korobov V. from the Barva series: popular science publication. Kharkiv: V.N. Karazin Kharkiv Nat. Univ. [in Ukrainian].
32. Avksentieva, O.O., Zhmurko, V.V., Shchogolev, A.S. & Yukhno, Yu.Yu. (2018). Plant physiology and biochemistry — a short practical guide: teaching and learning manual. V.N. Karazin Kharkiv Nat. Univ. [in Ukrainian].
33. Bradford, M.M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Analyt. Biochem., 72(1-2), pp. 248-254. https://doi.org/10.1016/0003-2697(76)90527-3
34. Stanek, N. & Jasicka-Misiak, I. (2018). HPTLC phenolic profiles as useful tools for the authentication of honey. Food Analyt. Methods, 11(11), pp. 2979-2989. https://doi.org/10.1007/s12161-018-1281-3
35. Vitalini, S., Beretta, G., Iriti, M., Orsenigo, S., Basilico, N., Dall'Acqua, S., Iorizzi, M. & Fico, G. (2011). Phenolic compounds from Achillea millefolium L. and their bioactivity. Acta Biochim. Polon., 58, pp. 203-209. https://doi.org/10.18388/abp.2011_2266.
36. Al Murad, M., Razi, K., Jeong, B.R., Samy, P.M. A. & Muneer, S. (2021). Light emitting diodes (LEDs) as agricultural lighting: Impact and its potential on improving physiology, flowering, and secondary metabolites of crops. Sustainability, 13(4), 1985. https://doi.org/10.3390/su13041985
37. Teixeira, R.T. (2020). Distinct responses to light in plants. Plants, 9(7), 894. https://doi.org/10.3390/plants9070894
38. Kim, H.H., Goins, G.D., Wheeler, R.M. & Sager, J.C. (2004). Green-light supplementation for enhanced lettuce growth under red-and blue-light-emitting diodes. HortSci., 39(7), pp. 1617-1622. https://doi.org/10.21273/HORTSCI.39.7.1617
39. Bian, Z., Cheng, R., Yang, Q., Wang, J. & Lu, C. (2016). Continuous Light from Red, Blue, and Green Light-emitting Diodes Reduces Nitrate Content and Enhances Phytochemical Concentrations and Antioxidant Capacity in Lettuce. J. Amer. Soc. Hort. Sci., 141(2), pp. 186-195. https://doi.org/10.21273/JASHS.141.2.186
40. Chen, Y., Bian, Z., Marcelis, L.F., Heuvelink, E., Yang, Q. & Kaiser, E. (2024). Green light is similarly effective in promoting plant biomass as red/blue light: a meta-analysis. J. Exp. Bot., 75(18), pp. 5655-5666. https://doi.org/10.1093/jxb/erae259
41. Jones, M.A. (2018). Using light to improve commercial value. Horticult. Res., 5. https://doi.org/10.1038/s41438-018-0049-7
42. Brown, D.E., Rashotte, A.M., Murphy, A.S., Normanly, J., Tague, B.W., Peer, W.A., Taiz L. & Muday, G.K. (2001). Flavonoids act as negative regulators of auxin transport in vivo in Arabidopsis. Plant Physiol., 126(2), pp. 524-535. https://doi.org/10.1104/pp.126.2.524

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ВПЛИВ СЕЛЕКТИВНОГО СВІТЛА НА МОРФОГЕНЕТИЧНІ ТА БІОСИНТЕТИЧНІ РЕАКЦІЇ В КАЛУСНІЙ КУЛЬТУРІ *PISUM SATIVUM* L.

О.О. Авксентьєва, Є.Д. Батуєва, М.Г. Ганзенко, О.Г. Куцик

Харківський національний університет імені В.Н. Каразіна
61022, Харків, Майдан Свободи, 4
e-mail: avksentyeva@karazin.ua

Якість світла є ключовим чинником навколишнього середовища, який регулює ріст, розвиток і метаболічну активність рослин, особливо в контрольованих умовах in vitro. Широке використання світлодіодних (LED) систем дає змогу модулювати спектральний склад і надає нові можливості для регулювання фотоморфогенезу та біосинтетичних процесів у культурі рослинних тканин. У цьому дослідженні вивчали вплив монохроматичного світлодіодного опромінення з різним спектральним

складом — червоним (ЧС, 660 нм), зеленим (ЗС, 525 нм) і синім (СС, 470 нм) — на морфогенетичні реакції та метаболічну активність у калюсній культурі *Pisum sativum* L. Використовували калюсні культури гороху посівного сорту Меценат 2—3-го пасажу. Фотоактивацію проводили з використанням модифікованих світлодіодних матриць Коробова з визначеними спектральними характеристиками, тоді як контрольні культури утримували в темряві. Оцінено вплив селективного світлового опромінення на ріст калюсу, морфогенез та накопичення первинних і вторинних метаболітів. Монохроматичне світлодіодне опромінення індукувало спектроспецифічні реакції в тканинах калюсу гороху. Червоне світло стимулювало активну проліферацію клітин, збільшувало індекс росту й сприяло формуванню морфогенетичних структур. Синє світло було найефективнішим індуктором морфогенезу, посилюючи диференціацію клітин калюсу та накопичення білка. Зелене світло мало впливало на ріст калюсу й морфогенез, проте спричинювало виражені зміни метаболічної активності, зокрема накопичення вуглеводів і флавоноїдів. Загалом, результати демонструють, що селективне монохроматичне світло диференційовано модулює фотоморфогенетичні шляхи і біосинтетичні процеси в культурі калюсу *P. sativum*, що підкреслює потенціал маніпуляції світловим спектром як інструментом для регулювання морфогенезу та метаболічних профілів у рослинних системах in vitro.

Ключові слова: Pisum sativum L., культура in vitro, монохроматичне LED світло, калюсогенез, морфогенез, розчинні вуглеводи, білки, феноли, флавоноїди.

ORCID

О.О. АВКСЕНТЬЄВА — O.O. Avksentieva https://orcid.org/0000-0002-3274-3410

Є.Д. БАТУЄВА — Y.D. Batuieva https://orcid.org/0000-0003-2532-7141

М.Г. ГАНЗЕНКО — M.G. Hanzenko https://orcid.org/0009-0000-1541-1708

О.Г. КУЦИК — O.G. Kutsyk https://orcid.org/0009-0008-1286-5921