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AN OVERVIEW ON BLUE LIGHT BENEFITS ON PLANTS PHYSIOLOGICAL PERFORMANCES AND ON PLANT PRODUCTS QUALITIES

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Abstract

Light is one of the external factors of crucial importance for the plants growth and development in normal environmental conditions, as well as in the case of stress factors incidence. It is important not only the presence of light, because, the quality or the light spectra plays a major role throughout the all ontogenetic cycle of the plant. Therefore, especially in the current period, the use of light emitting diodes (LEDs) in indoor farming systems is one of the technological procedures applied in order to modify the light spectral composition, to regulate plants growth and last but not least to obtain value-added crops that are high in nutritional or nutraceutical contents. In view of the above, the purpose of this review is to present some of the newer results regarding the effects of blue light emitted by diodes (LEDs) on the physiological parameters of plants during vegetation period, which result in quantitative yield improvement, but also in terms of nutritional quality, including its preservation during the post-harvest period.

***Key words**: light spectra, LEDs, physiological effect.*

INTRODUCTION

Light is one of the external factors of crucial importance for plants growth and development in normally environmental conditions (Smith, 1982), as well as in the case of stress factors incidence (Hoffman et al., 2015; Klem et al., 2019; Kovtun et al., 2019).
Under natural conditions of life, the amount and quality of light vary over the course of a day (Spitschan et al., 2016), but also with the unfolding of the seasons (Menzel and Fabian, 1999). The effects of these changes are not only related to the photosynthesis (Kreslavski et al., 2018), but also the light signalling pathways are interconnected that mediate the acclimatization to the various environmental conditions, or modulation of growth and development processes, thanks to the influence of the pathways to achieve physiological and biochemical processes (Kami et al., 2010; Paik et al., 2019).
Besides the cultivation of plants in the open field (Dunea et al., 2019), light effects are also important for in vitro cultures (Manivannan et al., 2017), greenhouses cultures (Pennisi et al., 2019), tunnels (Dou et al., 2017), including post-harvest effects (Jensen et al. (2018).
It is important not only the presence of light, because, the quality or the light spectra plays a major role throughout the all ontogenetic cycle of the plant, including germination, photomorphogenesis and floral induction (Smith, 1982). At the same time, the spectral composition of light has significant effects on the response of plants to the action of different stress factors, either abiotic (Courbier and PieriK, 2019; Kovtun et al., 2019) or biotic (Kim et al., 2013; Ballester et al., 2017).
In protected spaces (but not only), besides the possible use of different sources of additional lighting, to improve climate control, there are also effects on solar radiation due to climate screens and nets (including in the case of fruit tree plants growth in orchards) (Zoratti et al., 2015; Asănică et al., 2017) and their light transmittance is affected by the properties of the material used (Bastias et al., 2012;

Martinez-Gutierrez et al., 2016; Kotilainen et al., 2018).

In order to reduce the costs, at the same time with the increase of the yield and the enhance of the quality of the harvested products in a plant factory, Chang et al. (2016) noticed that it is necessary to implement an intelligent system for the automatic control of the lighting, so called "cloud-based lighting management system", considered to be of interest in the future for use in greenhouses.

Therefore, especially in the current period, the use of light emitting diodes (LEDs) in indoor farming systems (e.g. vertical farms) is one of the technological procedures applied in order to modify the light spectral composition, to regulate plants growth and development (Pennisi et al., 2019) and last but not least to obtain value-added crops that are high in nutritional or nutraceutical contents (Tan et al., 2019).

As Morrow (2008) emphasised, among the advantages of LEDs in lighting techniques in horticulture are: their ability to control the spectral composition, the production of very high light levels with low radiant heat output and the possibility to maintain their proper functioning for many years, without needing by their replacement.

Consequently, there is a major interest in this issue, not only from a scientific point of view, but also for practical reasons, as evidenced by the recent synthesis prepared by Zheng et al. (2019), with reference to horticultural plants (vegetables or ornamentals).

Moreover, not only can the quantity of the production obtained under such conditions be increased, but also its quality can be significantly improved by lighting supplemented by an adequate spectral composition (Kim et al., 2011; Bian et al., 2016).

Thus, manipulation of light quality in horticulture via photo-selective netting or films is applied with a view to improve not only the yield, but also quality (including chemical composition of cultivated plants (Yahia and Carillo-Lopez, 2019). Because the environmental changes have a negatively impact on the vegetables yield and quality, nowadays, but also in the future, indoor farming under LED lighting can be a sustainable farming system under controlled environment (Scheelbeek et al., 2018).

In view of the above, the purpose of this review is to present some of the newer results regarding the effects of blue light emitted by diodes (LEDs) on the physiological parameters of plants during vegetation period, which result in quantitative yield improvement, but also in terms of nutritional quality, including its preservation during the post-harvest period.

Blue light emitting diodes (LEDs) effects on plant physiology

Theoretically, the effects of the presence of light and its spectral composition are well known even on seed germination and seedling growth. Some plants seeds do not germinate under light condition, with other words, these are negatively photoblastic (light-induced dormancy), as is also the *Cleome gynandra*, a vegetable used in South Africa. However, the use of blue light has been shown to promote germination ($<=35\%$), while red light had an inhibitory effect ($<=8\%$). Moreover, the treatment with the blue light associated with the application of organic bio stimulants has determined biochemical changes in the seeds, such as an increase in the content of protein and carbohydrates, as well as increased activities of alpha-amylase, superoxide dismutase and catalase, which favoured seeds germination and seedlings growth (Nemahunguni et al.,2019).

Fantini et al. (2019) demonstrated the key role of cryptochrome in tomatoes, starting from the influence on seed mass, following the ability to control the early growth of seedlings, respectively the hypocotyl elongation and the root development of young plants. On the other hand, by "*in vitro*" studies, Burescu et al. (2015) reported that green light stimulated the spruce seed germination and plant growth, while the hypocotyl elongation has been inhibited by blue light.

The presence of specific photoreceptors, as light quality "radars" (Courbier and Pierik, 2019) that capture informational cues from sunlight (e.g. the phytochrome-PHY, cryptochrome-CRY, and phototropins -UVR8 that perceive red/far-red, blue/UV-A, and UV-B light, respectively (Wang et al., 2015; Podolec and Ulm, 2018; Fantini et al., 2019), as well as the existence of interconnected signalling networks allow the coordination of photomorphogenesis responses (Doroshenko et al., 2019) and regulation at the plant level of numerous molecular and physiological reactions (Kreslavski et al., 2018; Paik et al., 2019) during the ontogenetic cycle. Besides possible influences in terms of morphological (van Ieperen, 2012) and growth changes (Brazaitytė et al., 2010; Zheng et al., 2018), the researchers' interest was focused on the effects on the functioning of the photosynthetic apparatus, including modifications regarding the chloroplast, the content of assimilatory pigments, but also on the efficiency of the photosystems (PS) located in the tilacoidal membranes (Zheng et al., 2018). For instance, blue light has been shown to have multiple effects, both when applied with red light, in different ratios, but also if it is provided alone.

Blue light contribution during the early steps of photomorphogenesis (the early stages of the seedlings de-etiolation), as well as the cytokinin (CK) dependent greening, has been demonstrated in *Arabidopsis thaliana* L. In this respect, Doroshenko et al. (2019) proceeded to inactivate CRY1, CRY2 and HY (components of signalling due to blue light), which caused the delay of chlorophyll accumulation. In contrast, the application of cytokinin resulted in acceleration of de-etiolation and an increase in chlorophyll fluorescence.

From the morphological view point, internode or petiole elongation growth, as well as leaf expansion directly impact light absorption and consequently plant productivity via photosynthesis process. Leaf deformations and epinasty due to light quality may determine a reduction of the biomass yield caused by a reduction of light interception. More, in the case of ornamentally plants, their final ornamental value decrease (van Ieperen, 2012).

Cryptochrome also has major effects on adult plants, as demonstrated in tomatoes (Fantini et al., 2019), when in the absence of functionally cryptochromes (CRY1a and CRY2), an acceleration of flowering time was induced, and the possible explanation was that the process was mediated by repression SELF PRUNING (SP)5G gene, previously proven as an inhibitor of tomato flowering. The authors concluded that the two types of cryptochromes should be named "master controllers" of tomato development, with reference to their influence on plant architecture, on flowering time and also on the tomato fruits composition. Consequently, they can represent successful molecular targets for the manipulation of the physiological processes in this species.

The alleviation effects of blue light on the so is named "red light syndrome" were noticed by Miao et al. (2019) on cucumber plant exposed to red light for a longer period of time. This negatively effect of continues red light was described by a reduction of the photosynthetic capacity, an unresponsive stomatal conductance, as well as low value for the maximum quantum yield of chlorophyll fluorescence (F-v/F-m). The blue light dependent alleviation was done by changes in chloroplast ultrastructure, as well as nutrient accumulation. The use of red (R) and blue (B) LEDs (with an RB ratio <3) in the case of the lettuce culture (using a ten layer vertical farming system) had the effect of increasing the photosynthetic quantum efficiency, the increase of the stomata conductance (associated with the increase of their densities, although their size was smaller), while the leaves chlorophyll and flavonoids content was lower.

There was also registered an increase of water use efficiency (WUE) up to 75 g FW L^{-1} and energy use efficiency (EUE) (up to 91 g FW $kW^{-1}h^{-1}$) in the case of a ratio of RB = 3, as well as a high production (45 g $plant^{-1}$), generating a potential land surface use efficiency (SUE) of 3110 g m^{-2} d^{-1} for indoor cultivation of basil (Pennisi et al., 2019).

In the case of spinach, Agarwal et al. (2018) highlighted that the use of blue monochromatic light caused the photosynthetic apparatus to deteriorate as a result of the photooxidation process. In contrast, there was an elicitation of the antioxidant defence system, both of the enzymatic and non-enzymatic type, but, nevertheless, the growth of the plants was below an optimal level, when there was not used a proper ratio between red and blue light.

On the other hand, for *Fagus sylvatica* L., Košvancová-Zitová et al. (2009) showed that a ratio of 3/1 (B/R radiation) caused a faster induction of photosynthesis, corresponding to an increased sensitivity of the electron transport process to the quality of light, resulting in a faster activation of the enzyme ribulose-1,5-

bisphosphate carboxylase/oxygenase (RuBisCO) and a reduction of non-photochemical quenching (NPQ) loss. Besides this, no kinetic dependence of the opening of the stomata on the quality of the incident light was observed.

Studies conducted by Zheng et al. (2018) also highlighted the combined effects of light intensity and its quality on *Chrysanthemum* plants. Regarding the application of 100% blue light using LED, at a low intensity (40 micromoles m^{-2} s^{-1}), this caused a decrease of the leaf thickness, respectively in the case of an increased intensity (100 micromoles m^{-2} s^{-1}), also there were observed favourable effects on the evolution of leaf anatomy. At the same time, the reduced light intensity induced a decrease in the value of the stomatal index and implicitly of the stomatal density, while in the white light and in the case of the red + blue combination, the stomata surface increased. Light quality had an effect on the efficiency of photosynthesis, expressed by chlorophyll fluorescence. Moreover, the blue light applied to a high intensity positively influenced the accumulation of biomass, compared to the red monochromatic light.

In the case of some ornamental species (*Cordyline australis* - monocotyledonate; *Ficus benjamina* - dicotyledonate, evergreen leaves; *Sinningia speciose* - dicotyledonate, deciduous leaves) grown in the pot, exposed to LED for 8 weeks, the addition of blue light has been shown to be essential for both normal leaf anatomy development and efficient photosynthetic activity (Zheng and Van Labeke, 2017). Thus, the blue light increased the leaf thickness of *C. australis* and *F. benjamina*, as well as the palisade tissue thickness of the in *S. speciosa*, which made possible a better absorption of the light, but also an increase of photosynthetic quantum efficiency at the PSII level. In has been also found that the stomata conductance was higher in the blue light, compared to the red light, in relation to a higher stomata index and / or a higher stomata density, even though the degree of openness of the stomata was not influenced by the light quality.

The effects of light quality are not only limited to the influence on plant physiology during greenhouse cultivation, as it is usually considered, but, as Jensen et al. (2018) noticed, post-harvest physiological changes may also occur. Thus, in basil grown under various types of light radiation (in different ratios) and exposed after harvesting at low temperature conditions it was found that an increased ratio in favour of blue light had negative effects, whereas in the case of the green light the effects were positive from this point of view. The authors' explanation was that an increase in the ratio in favour of blue light led to an increase in stomata density, contrary to the effects of green light. Thus, in basil, the connection between the leaves water retention capacity and post-cultivation chilling tolerance was highlighted.

Regarding the influence of coloured polyethylene nets (red, blue, pearl, black and no net), with a 50% shading coefficient on basil plants, the studies carried out by Martinez-Gutierrez et al. (2016) showed that although indicators such as photosynthetically active radiation (PAR) and the temperature had lower values, compared to the control, the quality expressed by the oil content (ranged from 0.6 up 0.7%) was improved by red, pearl, blue nets and control. On the contrary, the black net reduced the oil content by 34.3%, as against the control (no net).

The use of coloured nets with the aim of changing the microclimate and to provide protection against stress factors has also proved useful in fruit trees (Bastias et al., 2012; Asănică et al., 2017). They assured a manipulation of the photosynthetic and morphogenetic processes. Thus, in the Fuji apple tree variety of 3 years old, the red and blue nets (40% photo-selective) reduced by 27% the photosynthetically active radiation, compared to the control. At the same time, the rate of photosynthesis and the total leaf area were higher by 28%, respectively 30% in the case of the blue net, which demonstrates its positive effect on the net carbon assimilation, as well as on the total dry matter accumulation.

Also, in the case of cultivation of two varieties of strawberries in the low tunnels covered with foil of different colours, there were found differences according to variety regarding the vegetative growth, productivity and quality of the fruit. In contrast, coloured sheets (red, blue, yellow and green) did not significantly improve the studied indicators. So, the use of commercially available transparent and opaque sheets was recommended for further use (Henschel et al., 2017). On the other hand, Nadalini et al. (2017) noticed that in the case of protected strawberry cultivation systems (soilless culture) and blue LED treatment, the accumulation of biomass (especially at the root and crown level) was favoured, a better fruit set was ensured and implicitly a greater final yield was obtained, as against the control.

The effects of light quality are registered not only on the morphology, physiology and biochemistry of the upper part of the plant, but also on the root (Klem et al., 2019), which influences not only the development of the root system, but also its resistance to the action of certain stress factors (e.g. drought resistance). In barley roots, if in the case of white light, it was stimulated the accumulation of secondary compounds with defence effect (e.g. proline, jasmonic acid), respectively the production of abscisic acid (ABA) was reduced, in blue light, Γ-aminobutyric acid (GABA), sorgolactones and others secondary metabolites were accumulated, whose osmolytes activity, antioxidants or growth regulators activities highlight the role of blue light as inductor of the protective mechanisms against abiotic and biotic stress factors.

The effects of light quality are recognized even in the case of "*in vitro*" cultures, as Manivannan et al. (2017) emphasised. The quality of carnation plants propagated "*in vitro*" was improved in both blue and red light (applied for 8 weeks). Both treatments significantly increased the growth, photosynthetic parameters and content in mineral nutrients, compared to conventional growth.

Beneficial effects were demonstrated too by Enache and Livadariu (2016) on *Artemisia dracunculus* L. seed, when there were applied different light treatments (white, red, blue or green) using LEDs, over a photoperiod of 16 hours, for seven days. In controlled cultivated conditions there were registered different reactions as regard as the germination process, development of sprouting plant elements (cotyledons and hypocotyl) and in accumulation of the fresh weight, also of the dry weight of biological material.

Blue light benefits on secondary metabolism and biochemical compounds accumulation

Light quality has important effects not only on plant morphologies or intensity of some on the processes specific to the primary metabolism, but also on the secondary metabolism (Kim et al., 2011; Bian et al., 2016; Lee et al., 2016; Doerr et al., 2019).

Therefore, in addition to the primary metabolism, changes in secondary metabolism can lead to positive effects in terms of increasing antioxidant activity (Raiciu et al., 2018), as one of a defence mechanism that protect plant species from stresses factors incidence (Kim et al., 2013), as well as improving the nutritional and nutraceutical qualities of the obtained products (Sucupira et al., 2012; Dou et al., 2017).

In addition to the effects on temperature and morphology, changes in secondary metabolism were noted by Doerr et al. (2019) after the exposure of the species *Plectranthus scutellarioides* (*Solenosternon scutellarioides, Coleus bluntel*) to different lamp systems, including LEDs. LEDs favoured strain elongation, possibly due to a greater amount of red light in the spectrum component, but at the same time, the leaf temperature was lower, which favoured the production of rosmarinic acid and flavone glycosides relative to the dry mass. At the same time, the presence of a large amount of blue radiation in the light spectrum has led to the formation of thicker leaves, and consequently the accumulation of a larger quantity of secondary substances at the unit of leaf surface.

The different effects of blue light have been studied especially in the case of vegetables plants, both in terms of the influence on the physiology of the plants during the vegetation period, with implications regarding the productivity and quality of the crop, but also in relation to possible effects regarding the post-harvest behaviour.

It has been proven that the lettuce quality can be improved by reducing the nitrate content. In this context, Bian et al. (2016) reported that by enhanced the duration of the illumination and the pre-harvest spectral composition, this trait can be modified. Thus, the plants exposure for 24 h at red:blue LED light (R:B = 4:1) with an intensity of 200 micromoles $m^{-2}s^{-1}$ determined the marked decrease of the nitrate content and besides it led to the increase of free-radical scavenging activity, as well as to increase the content in phenolic compounds. A promotion of the nitrogen assimilation, a favour of the accumulation of above ground biomass, as well as an improved nutritional quality (including a reduction of nitrate accumulation) in the lettuce was assured by a light ratio of 4R/1B, explained by the effects on the enzymes involved in the metabolism of nitrogen (nitrate reductase, nitrite reductase, glutamine synthetase, glutamate synthase and glutamate dehydrogenase) (Zhang et al., 2018).

A combination of RB light improved the nutritional quality at *Brassica* vegetables (Chinese cabbage and kale) by a better production of polyphenols and flavonoids. Thus, the content in glucoraphanin, glucobrassicin, polyphenols and anthocyanins were improved by culture techniques based on the use of LEDs, as demonstrated by Lee et al. (2016). Also, Kopsell and Sams (2013) showed that in broccoli microgreen tissues, pre-harvest application for the short duration of the blue light, significantly improved the nutritional quality expressed by increasing the content in carotenoids (e.g. β- carotene, violaxanthin), glucosinolates, essential micronutrients (e.g. copper, iron, boron, manganese, molybdenum, sodium and, zinc) as well as essential macronutrients (e.g. calcium, phosphorus, potassium, magnesium and sulfur), which are very useful for consumers.

The highest concentrations of the proteins, polyphenols and flavonoids of sprouts of hemp (*Cannabis sativa* L.) were determined in aseptically culture conditions, by illumination with blue LED, as compared with another two light spectra (red and green) and the control (sunlight), in the study initiated by Livadariu et al. (2019).

Obtaining high quality horticultural products can be achieved by applying biotechnologies based on the use of LED devices, as highlighted by studies conducted by Kang et. (2019), on Chinese cabbage seedlings. Blue light has been shown to increase the accumulation of ascorbic acid (AsA) by activating the expression of the gene involved in AsA biosynthesis. At the same time, there was an increase in antioxidant activity, by activating major reactive oxygen species (ROS) - scavenging antioxidant enzymes.

For soilless cultivated strawberries, Nadalini et al. (2017) determined that the use of blue LED light did not induce changes regarding the main characteristics of the fruit quality, even if in colour, it was weaker and lower level of pelargonidin-3-glucoside has been registered.

In the post-harvest period, blue light led to increased colour index, respiration rate and ethylene synthesis in strawberries stored at 5^0C, increased the activity of antioxidant enzymes (superoxide dismutase, catalase and ascorbate peroxidase), while superoxide anion levels, hydrogen peroxide, and malondialdehyde were kept low. In addition, the free radical-scavenging ability has been improved (Xu et al., 2014).

Also, the results of the studies by Huang et al. (2018) regarding the ripening of bananas in the post-harvest period led to the recommendation of the LED light source as a chemical-free strategy intended to shorten the ripening period. There has been registered a faster de-greening and flesh softening, as well as the increase of the ethylene biosynthesis, and respectively, an intensification of the respiration process, especially due to blue LED. Furthermore, exposure to LED light favoured the accumulation of ascorbic acid, total phenols, and total carbohydrates in banana fruit.

Improvement of the physiological performance (intensification of photosynthesis, enhancement of photochemical efficiency of PSII, decrease of non-photochemical quenching - NPQ, accumulation of flavonols in epidermal cells) of plants exposed to UV stress has been demonstrated by research carried out by Hoffman et al. (2015). The blue light in high amount triggered biochemical and physiological processes meant to ensure the acclimatization and recovery of pepper plants exposed to stress.

The beneficial effects of additional illumination with blue light have also been shown for potato plants exposed to saline stress (Kovtun et al., 2019), possibly due to the accumulation of carotenoids and proline, substances that act as non-enzymatic antioxidants, during the defence reactions. Thus, following the study on the tolerance capacity of potato plants to chlorine salinity, it was found that the protective effect

of the blue light was based on its ability to stimulate the accumulation of organic compounds with low molecular weight and antioxidant activity.
Also, in the case of buckwheat sprouts (known as rich food in nutritional elements destinated for human food, zootechnical industry, apiculture and human medicine) a highest antioxidant activity was induced by illumination with blue LED light (Livadariu & Maximilian, 2017).
In the reinforcement of the aforementioned, also come the results of Kim et al. (2013), who emphasized that tomato seedlings treatment with blue-LED light resulted in an increase of proline content in leaves and stem by about 296% and 127%, respectively, compared to the application of broad-spectrum white LED (BSWL), while in red and green light, the proline content significantly decreased. Also, the total phenolic compounds in leaves and stems significantly increases (1.3-fold, and 1.2-fold, respectively) as against to BSWL conditions.
The inhibition effect of blue LED light on *Botritys cinerea* development on tomato should be explained at least in part by enhanced proline accumulation and antioxidative processes. On the same note, possible effects regarding the elicitation of the resistance of citrus fruits to the attack of the most important pathogen in the post-harvest period (*Penicillium digitatum*) by the blue LED have been studied by Ballester et al. (2017). Although an increase in the content of scoparone phenylpropanoid was determined, it didn't turn out to be the critical factor in inducing resistance by blue LED. At the same time, although there has been an increase in the production of ethylene, it has not been implicated in the elicitation of resistance.
As Alsanis et al. (2019) recently mentioned in a bibliographic synthesis, it is obvious the need to provide artificial lighting to improve the physiological performances of the plants in order to obtain maximum profitability for ornamental plants and to secure the production of vegetables and berries in greenhouse conditions, with low energy consumption and at low costs. Alternative biotechnological measures include light emitting diodes, whose proper use has already been established in urban farms, respectively plant factories. The authors highlight not only the influence of such technology on the plants biotic and abiotic environmental conditions, but also the impact on the plant-microorganism interactions (thereby understanding pathogens, such as bacteria and fungi, control biological agents and respectively, the phyllobiome).

CONCLUSIONS

The presence of light represents a primordial condition for the life of plants, considering first of all its involvement in the unfolding of the greatest phenomenon of nature, photosynthesis. The unfolding under optimum conditions of the whole ontogenetic cycle also depends on the quality of the light or the spectral composition, both under the conditions of cultivation of the plants under field conditions, but, especially under controlled conditions (e.g. "*in vitro*" cultures) and/or protected spaces (e.g. greenhouses, vertical farms etc.).
Besides the general physiologically known effects that blue light has on plant functioning, the use of blue light emitted by diodes has proven to be one of the appropriate technological procedures for modifying the spectral composition of light, in order to regulate the growth process, as well as obtaining products (especially horticultural products in the classical sense, microgreens and herbs) with high added value, characterized by increased nutritional and nutraceutical content.
In addition to these beneficial effects, maintaining products postharvest quality and / or enhancing features that define this attribute (including increased tolerance to abiotic and biotic stressors) may be due to the specific effects of blue light.
Given the experimental results obtained in the field, especially nowadays, when climate change negatively impacts vegetables production, under environmentally controlled conditions, the use of light emitted diodes seems to be a promising technological measure.

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