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Measuring light spectrum as a main indicator of artificial sources quality

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ABSTRACT

Objective: To compare different artificial light sources in different places where plant breeding is conduced.

Methods: Measurements were conducted outdoor, in room, in greenhouse, under four panels with light emitting diodes, in phytotron, in dark room with various light sources and inside Sanyo versatile environmental chamber. The measurements were made by using SpectraPen SP100 (PSI, Czech Republic) device.

Results: Our result showed that spectrum measured outdoor during sunny day had only one peak at the wavelength of 485 nm (ca. 60000 relative units). On cloudy day, the trend of light spectrum curve was similar, but with lower values. At room conditions, the curve was more flat than outdoor. Under greenhouse conditions, the curve was similar to that measured outdoor. A few additional peaks on the curve appeared by adding high pressure sodium lamp. There were changes of curve under LED panels.

Conclusions: It must be underlined that the most similar spectrum curve to daylight light has incandescent bulb and this light source should be preferred as support of daylight in greenhouses and as main source in phytotrons. Using high pressure sodium lamp in greenhouses as support of daylight cause increase in the red/far-red ratio and occurrence of a new peak on spectrum curve. The new possibilities are creating by LED panels with red and blue diodes.

1. Introduction

Light is one of the most important environmental factor for plant growth. The intensity and quality of light are essential for growth, morphological features and other physiological responses of plant[1]. The most important process, which is dependent on light, is photosynthesis. It is a process by which the physical energy of light is used to convert chemical substances to a more energetic state. The energy of a photon of light is captured by substance pigment, formation of an electronic excited state and use to reduce an acceptor substance, which is used to form other, complex organic molecules[2]. However, not all solar radiance is used by plants. Photosynthetically active radiation (PAR) is a solar radiance available for plant and it occurs in spectral band from 400 to 700 nm wavelength. Plant pigments, chlorophyll and carotenoids absorb PAR best at specific wavelength. Chlorophyll a has a peak spectral absorption at 430, 460 and 660 nm. Chlorophyll b absorb most effectively at 430, 455 and 640 nm. Carotenoids, including xanthophyll absorb most effectively in bands near 450 nm[3].

Considering the above, PAR can be divided into high active and low active wavelength based on pigment absorption bands. PAR in range from 400 to 500 nm, called blue light affect many aspects of plant growth and development, including inhibition of hypocotyl elongation, stimulation of cotyledon expansion, regulation of flowering time, phototropic curvature, stomatal opening, entrainment of the circadian clock and regulation of gene expression[4]. The light from 600 to 700 nm (red light), are active for photosynthesis, photomorphogenesis, and chlorophyll synthesis[3]. Under red light,

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leaves undergo elongation and show reduced chlorophyll content[5]. Growth parameters including specific leaf mass, thickness, and leaf density were also lowest in plants of *Alternanthera brasiliana* grown under red light[6]. Blue light induced the largest number of leaves/plant, and the largest thickness and area of the leaf. Red light leads to randomization of hypocotyl orientation[7]. The percentage absorption of blue or red light by leaves is about 90%[8]. The combination of red and blue light is used nowadays more and more in research because they are the most photosynthetic effective wavebands. PAR ranged from 500 to 600 nm, called green light, is inactive for plant growth and development. However, green light can play main role in shade avoidance responses as well as other plant developmental and physiological processes[9]. Far red irradiance occurs from 700 to 800 nm and is not active for photosynthesis but strongly influences photomorphogenesis[10]. It is shown that red/far red (R/FR) ratio is also important factor, because it can enhance biomass partitioning to shoots and reduce ability of plant to response to environmental triggers[11]. Low levels of FR light in the spectrum or a high ratio between R and FR commonly result in short, compact plants[12]. Plants are usually more sensitive to R and FR light at the end of the day.

The light is also one of the main environmental factors required for efficient plant development along with temperature and humidity. Light sources such as fluorescent, metal-halide, high-pressure sodium, and incandescent lamps are generally used for plant cultivation. LEDs have recently been introduced as an irradiation source for plant to facilitate vegetative growth. Advantages of LEDs in comparsion with other electric sources include longevity, safety, small mass and being solid state device[13]. These sources are applied to increase photosynthetic photon flux levels but contain unnecessary wavelengths located outside the PAR[14]. Light can be also modified by the optical properties of the greenhouse cover. These qualitative changes in the radiation transmitted inside the greenhouse induce morphogenetic effects and can modify the architecture and shape of the plants, which influence the value of the crop in some cases[15,16]. In other hand, most of the available solar spectral data on light emitted by standard light sources were obtained under laboratory conditions. These laboratory results are not really representative of the natural light distribution in greenhouses and phytotrons. To compare different artificial light sources in different places where plant breeding is conduced was the main aim of this study.

2. Materials and methods

Measurements were conducted at Warsaw University of Life Sciences – SGGW (Poland) under different light conditions. Firstly, measurements were conducted outdoor on sunny and cloudy days. Measurements were made also in room under the same conditions with and without presence of fluorescent lamp. Moreover, measurements were carried out in greenhouse (also during sunny and cloudy days) with or without high pressure sodium (HPS) lamp. The measurements of light spectrum under four panels with LED were also carried out in the greenhouse during sunny day and without external day light - at night. The diodes were red and blue. Panels had always this same number of red diodes, but numbers of blue diodes were changed. First panel has proportion of red/blue diodes as 1:1, second panel 1:0.5, third 1:0.25 and fourth has only red diodes (no blue). Red diodes emitted light at 640 nm and 660 nm of wavelengths (640/660 = 2/1). Blue diodes emitted light at 440 nm of wavelengths. Measurements carried out in phytotron were made in presence of HPS lamp alone and in presence of a combination of HPS lamp and fluorescent lamp. Measurements were also carried out

Table 1

The PAR, red, far red light energy and R/FR ratio measured in different places.

Place		PAR (W/m^2)	Red ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Far red ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	R/FR
Outdoor - Daylight	Sunny day	161.00	54.80	52.90	1.05
	Cloudy day	36.40	11.70	11.00	1.05
Room	Daylight (sunny day)	7.96	2.40	1.9	1.09
	Daylight (cloudy day)	0.92	0.34	0.26	1.27
	Daylight (sunny day) + Fluorescent lamp	9.60	2.80	2.10	1.26
	Daylight (cloudy day) + Fluorescent lamp	2.23	0.51	0.35	1.40
	Fluorescent lamp (night)	1.34	0.19	0.11	1.63
Greenhouse	Daylight (sunny day)	50.20	12.20	11.10	1.10
	Daylight (cloudy day)	13.70	4.50	4.10	1.08
	Daylight (sunny day) + HPS lamp	118.70	13.80	8.90	1.50
	Daylight (cloudy day) + HPS lamp	45.10	11.20	5.70	1.90
	HPS lamp (night)	25.30	4.10	1.60	2.63
Greenhouse +LED + Daylight	Red/Blue = 1:1	116.70	38.2	12.30	2.57
	Red/Blue = 1:0.5	102.30	42.00	13.40	3.62
	Red/Blue = 1:0.25	50.30	30.20	7.70	3.92
	Red/Blue = 1:0	47.80	32.40	8.80	3.69
Greenhouse + LED (Night)	Red/Blue = 1:1	19.47	15.20	0.00	-
	Red/Blue = 1:0.5	15.30	15.80	0.00	-
	Red/Blue = 1:0.25	12.20	13.10	0.00	-
	Red/Blue = 1:0	9.10	13.30	0.00	-
Phytotron	HPS lamp	78.60	22.61	8.20	2.74
	HPS lamp + Fluorescent lamp	85.20	29.30	6.50	4.35
Dark room	Fluorescent lamp	15.80	2.74	0.69	3.58
	HPS lamp 400 W	54.60	17.72	6.08	2.89
	Mercury lamp	32.80	16.43	2.28	7.25
	Incandescent bulb 500 W	16.30	13.04	18.14	0.70
Sanyo versatile environmental chamber	6.69	1.15	0.18	6.19	

in dark room with various light sources (performed at 0.5 m distance from source): light emitted by fluorescent lamp (250 W), HPS lamp (400 W), mercury lamp (400 W), incandescent bulb (500 W) and white LED. Measurements inside Sanyo versatile environmental chamber were also carried out. This chamber was equipped in 15 adjustable fluorescent lamps, 40 W each.

To compare light spectrum under different environmental conditions and various artificial light sources, SpectraPen SP 100 (PSI, Czech Republic) was used. To compare the PAR energy, SKE 510 sensor was used. PAR was measured at 400-700 nm of wavelengths. To compare R, FR light and R/FR proportion, SKR 110 sensor was used. Measurement was made at 660 and 730 nm of wavelengths. Both sensors were made by Skye Instruments Ltd (U.K.).

3. Results

3.1. The PAR, red, far red energy and R/FR ratio measurements

Results of PAR, red, far red energy and R/FR ratio had been demonstrated in Table 1. The PAR energy outdoor measured in sunny day was 161.00 W/m^2. The red light energy was equal to 54.80 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) and far red light energy was 52.90 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$). R/FR ratio was equal to 1.05. PAR energy measured in cloudy day was only 36.40 W/m^2, red light energy was 11.70 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) and far red was 11.00 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$). The R/FR ratio was similar in both treatments and was equal to 1.05.

In room, PAR energy measured in sunny day was 7.96 W/m^2. Red light energy was 2.40 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) and far red light energy was 1.90 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$). R/FR ratio was 1.09. Values of PAR, red and far red energy measured in cloudy day were lower than in sunny day, but R/FR ratio was higher (1.27). Additions to daylight light from fluorescent lamp cause increase in the values of light energy. Moreover, the R/FR ratio was increased in cloudy day to 1.40 and to 1.63 without daylight (in night).

In greenhouse, PAR energy in sunny day was 50.20 W/m^2, red light energy was 12.20 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) and far red light was 11.10 ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$). The R/FR ratio was 1.10. All of light energy parameters were lower in cloudy day than in sunny day, but R/FR ratio was similar (1.08). Additions to daylight HPS lamp caused increase in the values of light energy, but caused (similar to values measured in room) increase in the R/FR ratio to 1.50 in sunny day and 1.90 in cloudy day. In night, ratio was equal to 2.63. In comparsion to values measured in daylight, additional light from LED's panels' with diodes red/blue = 1:1 and 1:0.5 caused increase in the PAR energy. Light from panels' with diodes red/blue = 1:0.25 and 1:0 had similar PAR energy to daylight. All panels caused increasing red light energy, but far red energy values were not changed. In this situation, R/FR ratio values were higher under the panels.

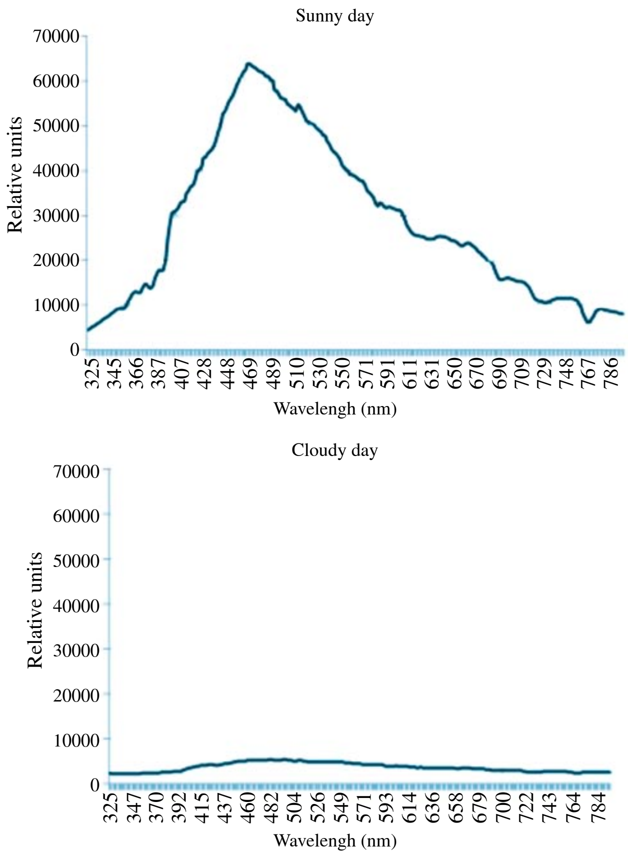

Figure 1. Light spectrum measured outdoor.

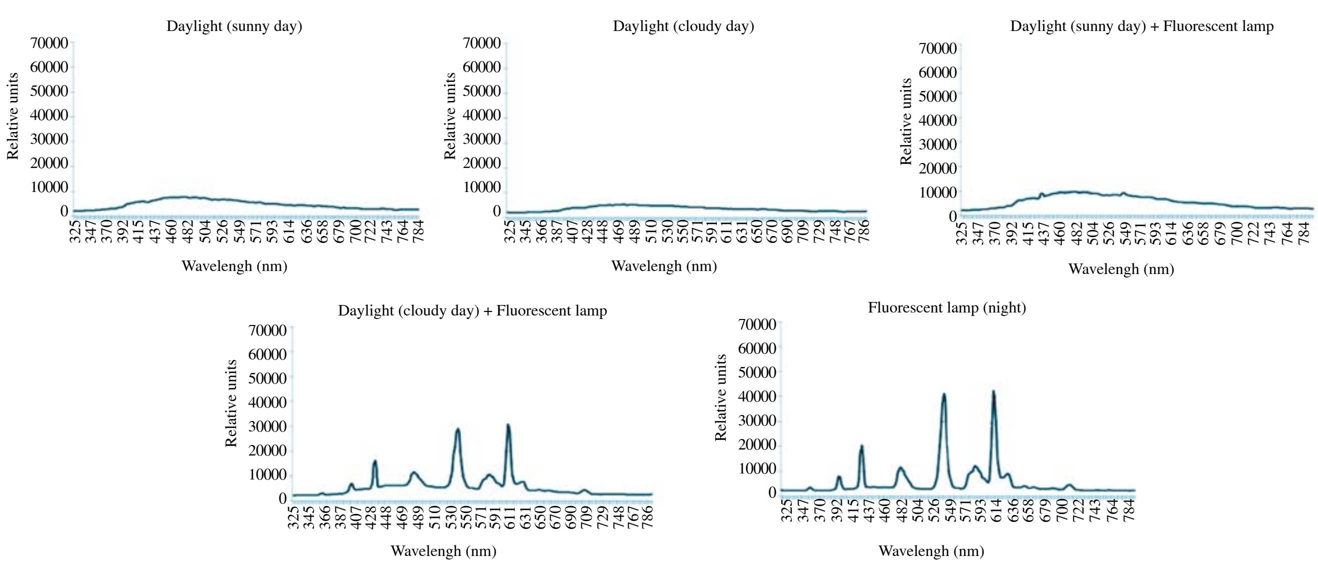

Figure 2. Light spectrum measured in room.

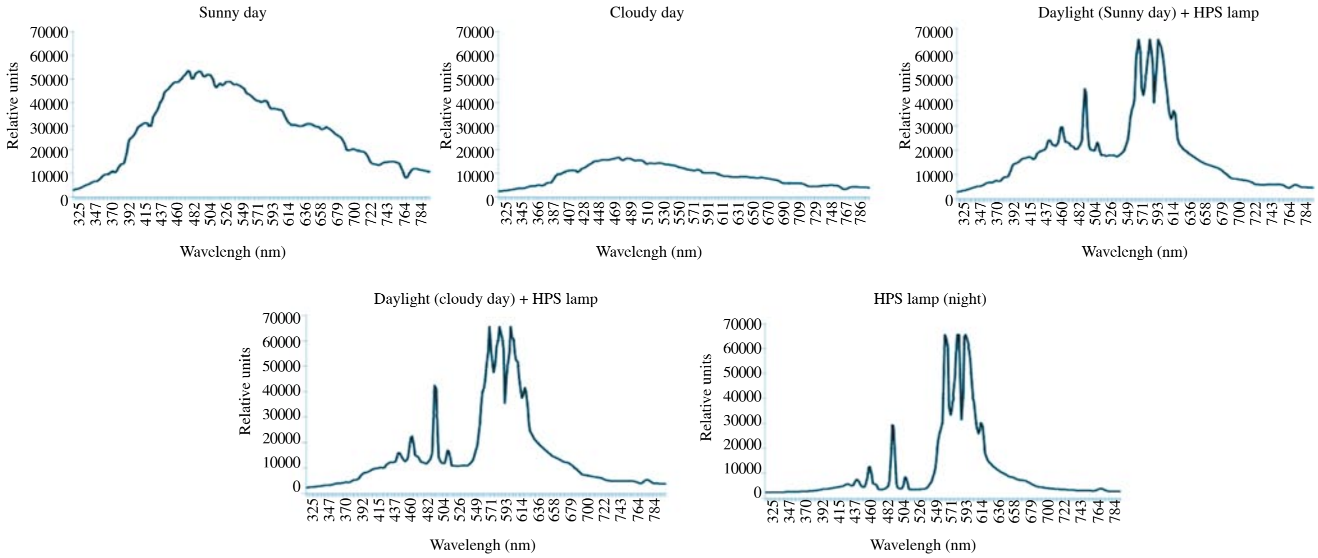

Figure 3. Light spectrum measured in greenhouse.

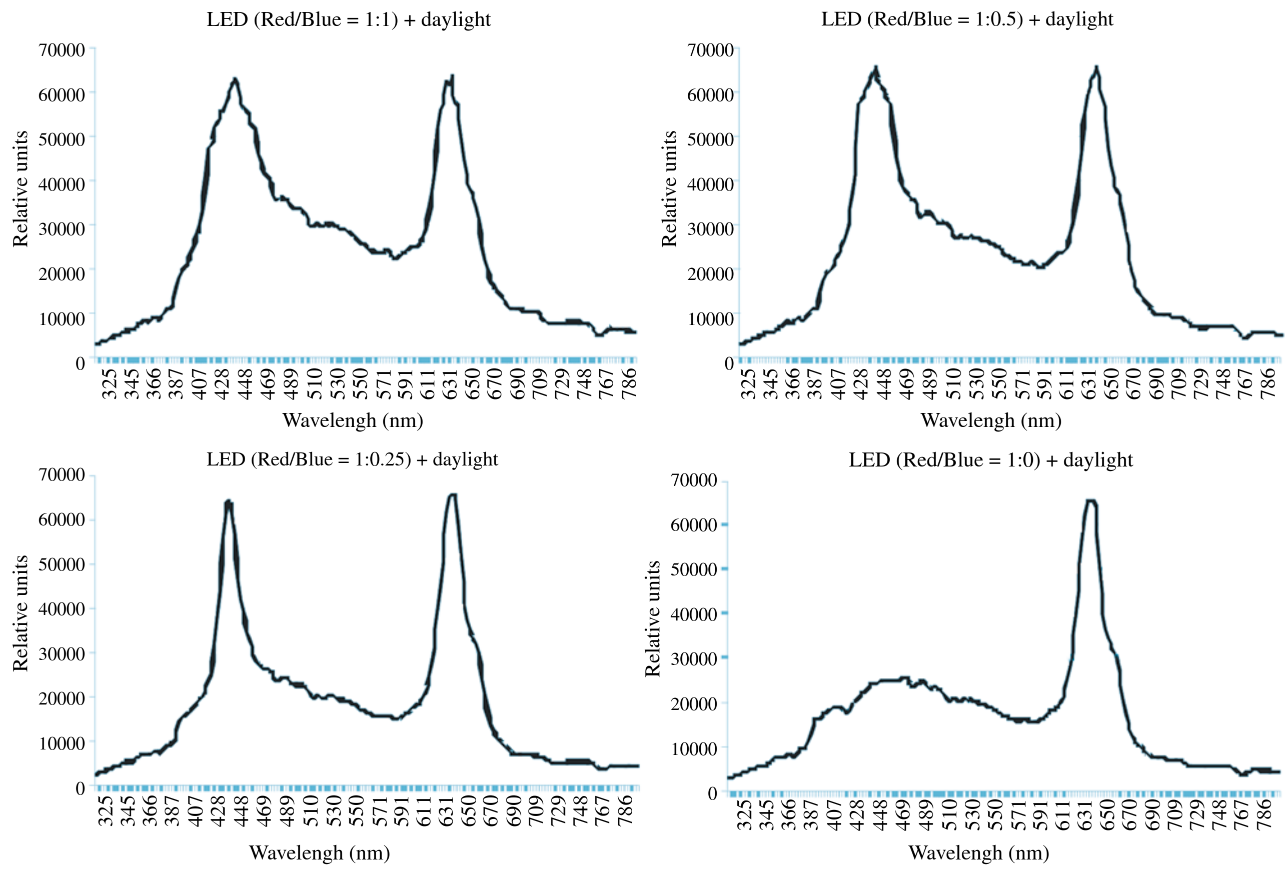

Figure 4. Light spectrum measured in greenhouse under LED's panels with daylight.

Light emitted by HPS lamp in phytotron was 78.60 W/m^2. Red light energy was 22.61 (µmol·m^{-2}·s^{-1}) and far red energy was 8.20 (µmol·m^{-2}·s^{-1}). R/FR ratio was 2.74. Additional light emitted from fluorescent lamp caused increase in the PAR and red light energy, but far red energy decreased. This situation led to increase in the R/FR ratio to 4.35.

In dark room, fluorescent lamp has 15.80 W/m^2 PAR energy, 2.74 (µmol·m^{-2}·s^{-1}) red light energy and 0.69 (µmol·m^{-2}·s^{-1}) far red energy. R/FR ratio was equal to 3.58. HPS lamp has more PAR, red and far red light energy. R/FR ratio was 2.89. Mercury lamp has the highest R/FR ratio (7.29) but PAR and red light energy were lower than in HPS lamp. Incandescent bulb has PAR energy similar to fluorescent lamp, but red and far red light energy were the highest. R/FR ratio of this light source was 0.70.

Light source installed in Sanyo versatile environmental chamber has 6.69 W/m^2 PAR energy, 1.15 (µmol·m^{-2}·s^{-1}) red light energy and 0.18 (µmol·m^{-2}·s^{-1}) far red energy. Inside this chamber, the light conditions were unfavorable because of one of the highest R/FR ratio (6.19).

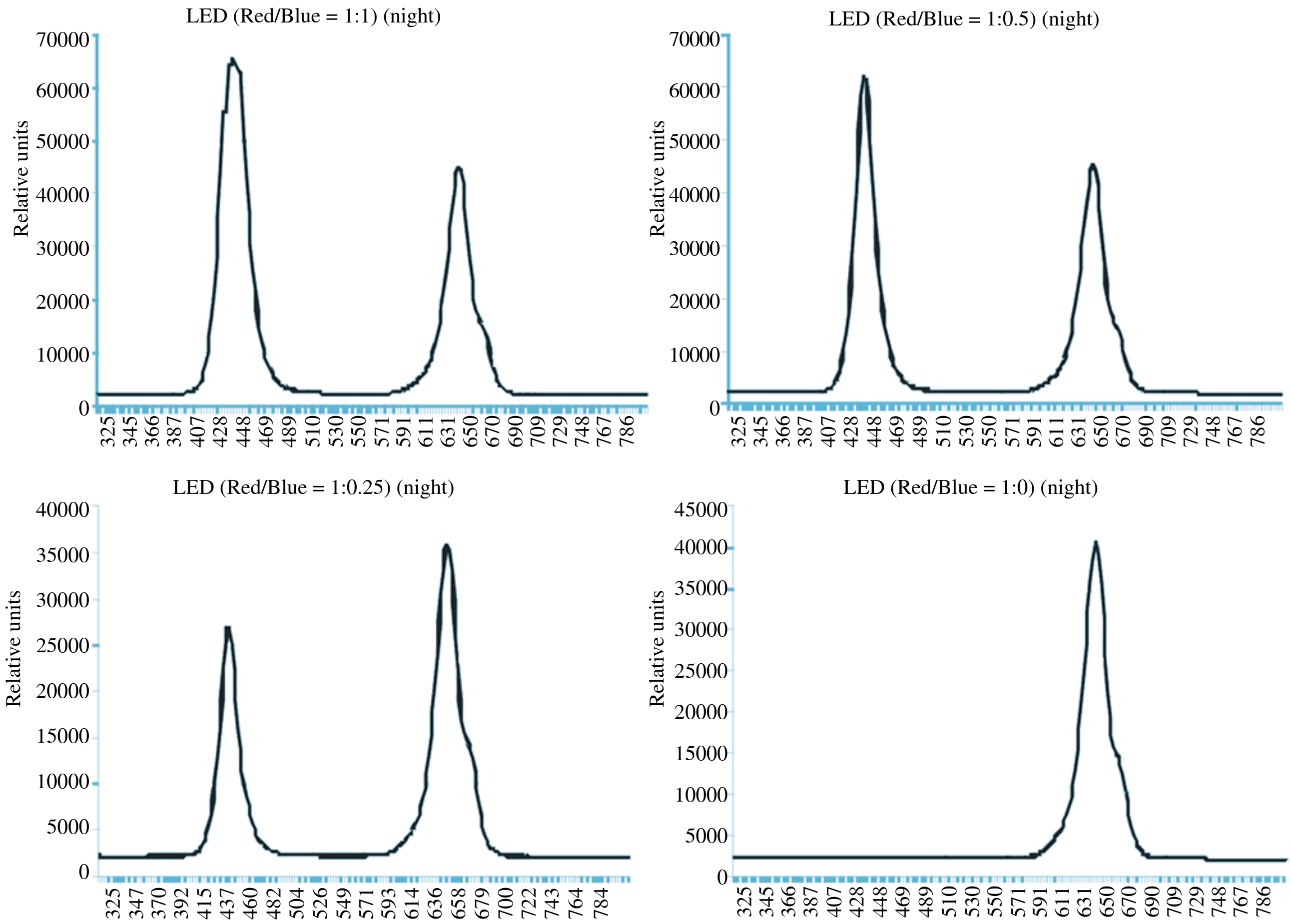

Figure 5. Light spectrum measured in greenhouse under LED's panels in dark.

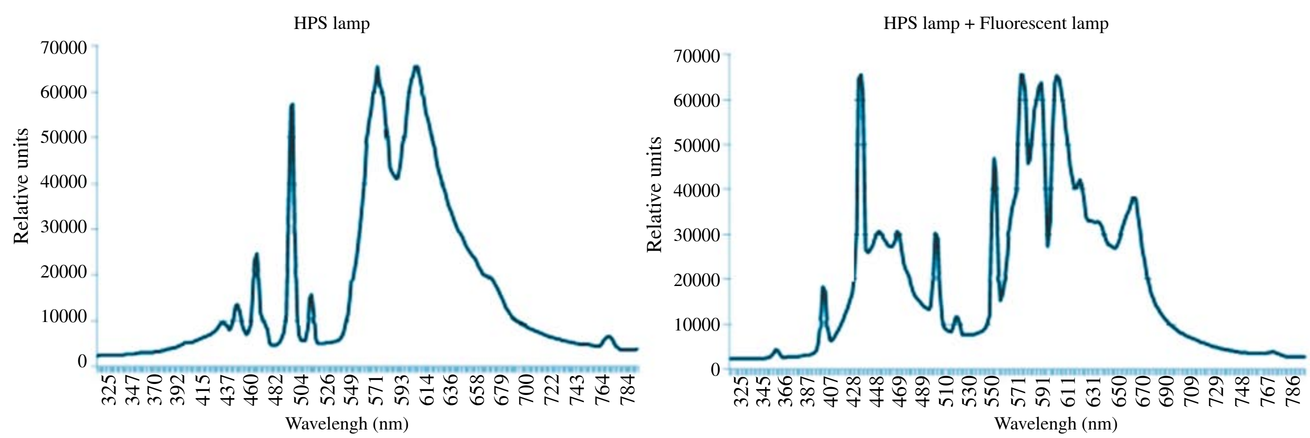

Figure 6. Light spectrum measured in phytotron.

3.2. The spectrum measurements

Spectrum measured outdoor during sunny day had only one peak at the wavelength of 485 nm (ca. 60000 relative units). On cloudy day, the trend of light spectrum curve was similar, but with lower values. Peak was at the wavelength of 473 nm, but was lower than peak measured during sunny day (ca. 2500 units). Spectrum curves are presented on Figure 1.

At room conditions, the curve was more flat than outdoor. The higher point of curve was at the wavelength of 476 nm (ca. 7700 units) during sunny day and at the wavelength of 473 nm (ca. 5200 units) during cloudy day (Figure 2). The addition of fluorescent lamps in the room caused the increase of curve during sunny day, but during cloudy day the curve has explicit peaks at the wavelength of 432 nm (ca. 14600 units), 482 nm (ca. 10400 units), 541 nm (ca. 27500 units) and 609 nm (ca. 30700 units).

Under greenhouse conditions, during sunny day, the curve was similar to measured outdoor (Figure 3). Peak was at the wavelength of 473 nm (ca. 51000 units). During cloudy day, peak was also at 473 nm, but was with lower values (ca. 16 000 units). A few additional peaks on the curve appeared by adding HPS lamp. During sunny day, there were one peak at the wavelength of 495 nm (ca. 45000 units) and 3 peaks at 507, 582 and 593 nm (ca. 65000 units). During cloudy day, the curve was similar. Curve of HPS lamp only had even higher peaks than the curve of daylight with lamp. Spectrum curve of daylight with light from LED panel (diodes red/

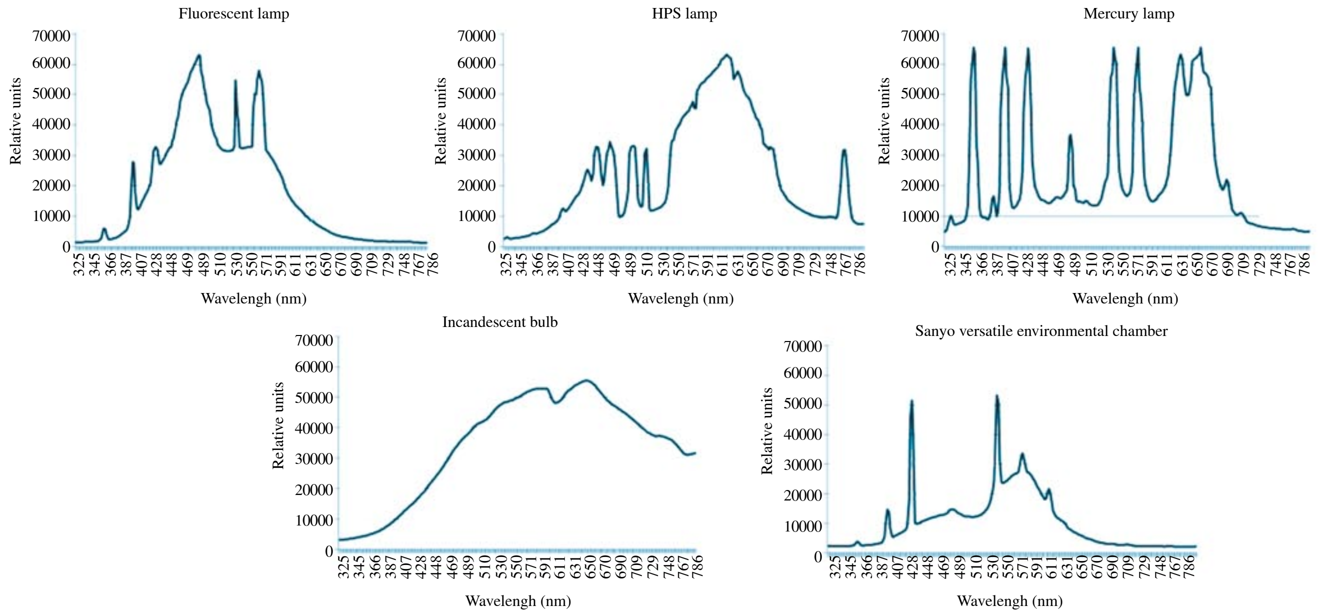

Figure 7. Light spectrum measured in dark room and inside Sanyo versatile environmental chamber.

blue = 1:1) had peaks at the wavelength of 445 nm and 631 nm (Figure 4). Changes of proportion of diodes from 1:0.5 and 1:0.25 did not result in changes of spectrum curve; light from panel with diodes 1:0 had only one peak. Spectrum measured without daylight was similar (Figure 5).

In phytotron, where there was only HPS lamp (Figure 6), the spectrum curve had a few peaks on 495 nm (ca. 56 600 units), 571 nm (ca. 65 500 units) and 600 nm (ca. 62 500 units). Additional light from fluorescent lamp caused the appearance a few new peaks.

In darkroom, light emitted by fluorescent lamp had three peaks at the wavelength on 488 nm (ca. 60 800 units), 541 nm (ca. 54 700 units) and at the wavelength on 572 nm (ca. 58 000 units). Light emitted by HPS lamp had peaks throughout the curve; the highest peak was on 612 nm (ca. 61 800 nm). Light emitted by mercury lamp had also irregular curve with eight peaks (seven of them were higher than 60 000 units), while incandescent bulb had no any peaks. Inside Sanyo Versatile environmental chamber, light had two peaks, at 433 nm (ca. 51 500 units) and 543 nm (ca. 53 300 units) (Figure 7).

4. Discussion

There are refined photosensitive mechanisms, which are used by plant to capture light energy for photosynthesis[17,18]. Light intensity and quality are important factors for plant growth and development. Changes in light quality strongly affect several plants' anatomical, physiological, morphological, and biochemical parameters[6,19,20].

Because of the non-ideal transmission of light by the cladding material, in the absence of artificial source, the light level inside a greenhouse is normally lower than that outside. In some cases, the properties of the cladding material and the roof structure can even reduce the light level to below its desired value, and change its spatial distribution and spectrum. In general, the reduction in light intensity is dependent on three main factors: the characteristics of the cover material and their clear (accumulation of dust and dirt on the cover), structural elements, internal environment-control systems, roof openings and screens (insect-proof and/or shading), and water vapour condensation on the inner surface of the cover[21]. Results showed in this paper confirm that in greenhouse PAR energy is on lower level than outdoor. Simultaneously, increasing of red and far red energy was observed in comparsion to outdoor. However, the R/FR ratio values measured outdoor were similar to greenhouse.

Conventional high-intensity supplemental lighting in a greenhouse is usually in a fixed installation above the plant canopy. Recently, the technique of moving light fixtures within a greenhouse has been used in Europe and North America. By moving the light source, a higher proportion of the total leaf area, especially beneath the top canopy, is irradiated and therefore better plant growth is achieved[22]. The most common light source is HPS lamp which has a high emission of PAR energy[23]. Our results show, that this source increases the total light energy in greenhouse. However, the light spectrum and R/FR ratio of light emitted from these sources were unfavorable for plant growth and development. The R/FR ratio of daylight in sunny and cloudy day was about 1, but addition of light from HPS lamp caused increase in the ratio to 1.5 in sunny day and 1.9 in cloudy day. Moreover, spectrum curve has the highest peak on the 600-650 nm of wavelength[23].

LEDs are becoming more widely used in greenhouses. In opinion of Islam *et al.*[23], LED with a high proportion of blue light was effective in reducing the stem extension growth of all the poinsettia cultivars tested compared to HPS lamp. It is suggested that LED with a high proportion of F/FR light can be used to control hypocotyl elongation of a commercial cucurbit rootstock[24]. The use of an LED light source was the aim of research conducted by Li *et al*[25]. Author concluded that this light source is good at promoting the differentiation, proliferation and growth of rapeseed plantlets. Fresh and dry masses, concentrations of pigments, sucrose and soluble sugar, stem diameter, leaf stomata length on the abaxial surface and stomata frequency on the adaxial surface were highest in plantlets cultured under red/blue = 1:3 light. Our results show, that in greenhouse LEDs are characterized by higher level of PAR energy, but the R/FR ratio is also very high. Depending on the share of red and blue diodes, the R/FR ratio ranged from 2.57 to 3.69.

Fluorescent lamps and incandescent bulbs are also vilely used in light sources. However, our results made in dark room show, that the light qualities from these sources are very different. Incandescent bulb emits more FR light and has R/FR ratio of 0.7. In compare, fluorescent lamp emits blue and red light, so the emitted R/FR ratio is higher (3.58). These results were fully confirmed by research done by Runkle *et al*[26]. Moreover, results from phytotron show, that the quality of light mixed from fluorescent lamp and HPS lamp is worse than from these lamps work separately. On the other hand, there are obvious benefits of using fluorescent lamps. In compare to incandescent bulbs, they consume about 75% less energy while emitting a similar PAR energy. They also approximately work 6-10 times longer than incandescent bulb. Moreover, the research conducted on *Gerbera jamesonii* plant suggested that, the cold cathode fluorescent lamps affected positively the growth and development of this species[27].

In conclusion, our result show that incandescent bulb has the most similar spectrum curve to daylight light and this light source should be preferred as support of daylight in greenhouses and as main source in phytotrons. Using HPS lamp in greenhouses as support of daylight causes increase in the R/FR ratio and occurrence of a new peaks on spectrum curve. The new possibilities are create by LED panels with red and blue diodes.

Conflict of interest statement

We declare that we have no conflict of interest.

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