Optimal ratio of spectrum, light intensity and photoperiod to minimize costs when growing microgreens

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Abstract. The paper considers the influence of spectrum and light intensity/photoperiod ratio on the energy intensity of production and financial costs of consumed electricity. This influence is caused not only by the yield obtained, but also by the different energy efficiency of light-emitting diodes of different spectrum and the price of electricity at different hours of the day. Considering the influence of the spectrum, it was found that the costs decrease with increasing the proportion of red light for all microgreen varieties under consideration. Laboratory studies were carried out on microgreens of cabbage of the "Mitsuna" variety and radish of the "Octave" variety. A long photoperiod at low intensity is better than a short photoperiod and high light intensity in terms of energy and financial efficiency. Combining the results on dry weight as a quality indicator, energy consumption and financial cost per fresh weight, we consider a lighting system with parameters B:R:FR=29:58:13%, PPFD= 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ / 16 h as the preferred option for growing microgreens.

1 Introduction

It is predicted that by 2050 the global population will be over 9 billion people, of which 70% will live in cities [1]. With continued urbanization, the development of highly efficient food production is necessary to provide food for the growing population. Moving food production to places with high demand will reduce the cost of production by eliminating transportation costs. The most promising urban technology for vegetable production is the vertical farm (VF) with a controlled environment [2]. It is possible to obtain a crop all year round without interruptions due to climate change, season or adverse natural events. Closed vertical farms with controlled environments provide higher yields per unit area compared to traditional greenhouses and require less water when irrigating plants [3]. However, vertical farm technology requires several times more energy [4]. In order to grow quality plants with minimal energy consumption, quality lighting is necessary. VF artificial lighting conditions allow selecting optimal parameters of light intensity, radiation spectrum and photoperiod for efficient production. The most promising technologies for the formation of optimal lighting parameters are LEDs. The advantages of LED irradiators compared to

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other artificial light sources for use in light-culture are the possibility of forming a more effective spectrum of radiation, flexible control, low dependence of electrical characteristics on the deviation of the supply voltage [5, 6]. Microgreen production appears to be interesting for VF. Microgreens have a content of useful phytochemicals more than for their mature plants [7], as well as a short growing period of 7-10 days. Available studies on the effect of light on microgreens are contradictory. Under blue LEDs the highest raw and dry weight of amaranth and turnip microgreens was obtained compared with white and red LEDs [8]. The efficiency of increased blue light (1R:2B) was shown for basil microgreens compared to white and red-blue light in the ratio of 2R:1B and 1R:1B [9]. The total concentration of anthocyanins increased in proportion to the percentage of blue light applied up to 30% in all species of microgreens [10]. Other studies report an advantage of red light for microgreens. The highest fresh weight and highest total flavonoid content was obtained with an R:B=5:1 ratio [11]. Plants treated with light at a B:R=25:75 ratio had the highest fresh weight and dry weight, and increasing the proportion of blue light (50-100%) in the light spectrum resulted in a higher mineral nutrient content in mustard microgreens [12]. The addition of far red light increased the crude biomass of microgreens [13], increased antioxidants, and decreased nitrates [14]. The level of photocytotic photon flux (PPFD) also affects plant yields and trace elements. The most effective PPFD for arugula and mustard microgreens was obtained by 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [15]. In a study [16], both increasing and decreasing light intensity compared to a value of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for radish and basil microgreens resulted in a decrease in vegetative mass. An intensity of 110-220 $\mu mol \cdot m^{-2} \cdot s^{-1}$ compared to 330, 440 and 545 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was recommended for mustard and kohlrabi microgreens in terms of combined dry weight and beneficial substances [17, 18]. In a study [19], the soluble protein, soluble sugar, free amino acid, flavonoids, vitamin C, and glucosinolates in broccoli microgreens were higher when exposed to 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ being the optimal light intensity to enhance plant growth. Thus, the most effective PPFD for microgreens was in the range of 100-200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Presumably, the variation in the intensity value is due to the different photoperiod in the experiments (8 to 20 hours/day). Studies of the ratio of light intensity to photoperiod within a single daylight integral have not been found. It should be noted that an important issue is the cost of purchased electricity, because they determine the cost of production. Vertical farms with controlled environment allow the use of any hours during the day. The use of a differentiated electricity tariff is interesting in this direction. There are no studies examining the issue of energy and financial costs in the cultivation of microgreens. The purpose of this study is to determine the optimal spectrum and light intensity/photoperiod ratio to minimize energy consumption and financial costs of growing microgreens in vertical farms.

2 Materials and methods

The studies were conducted in an enclosed chamber without access to natural light. Air temperature during the experiment was 20-23°C with relative humidity of 60-70%. Metal trusses with racks, irrigation system, lighting system and automation of technological processes in growing microgreens were installed in the chamber (Figure 1).

One installation included three racks, each of which contained plastic containers with peat. Seeds of microgreens of cabbage "Mitsuna" and radish "Octava" were sown into the containers with peat. The period of cultivation of microgreens was 7 days.

The water supply system consisted of 90-liter tanks, OASIS DN 110/6 drainage pumps, and an extensive network of water pipes. The solution was fed automatically 4 times a day for 5 minutes (00.00; 6.00; 12.00; 18.00).

Artificial lighting began to be applied from the first day.

Fresh weight of the microgreen harvest ($kg \cdot m^{-2}$):

$$m = \frac{\sum_{i=1}^{n} m_i}{n \cdot S_i}$$

m_i – fresh weight of the harvest of microgreens one plastic container, kg; n – number of containers, pcs.; S_i – container area, m^2.

Dry weight obtained by drying the fresh weight of microgreens in a drying chamber (Premed,Poland). Weight was measured using a BK-300 scale (Massa-K, Россия).

Energy use efficiency (EUE) lighting systems to produce a unit of product ($kWh \cdot kg^{-1}$):

$$\mathrm{EUE} = \frac{P \cdot T}{m}$$

P - electric power consumption of lighting systems, (kW); T - operating time of lighting systems, (h).

Costs of purchased electricity ($euro \cdot kg^{-1}$):

$$\mathrm{CE} = \frac{\sum_{i=1}^{24} Wi \cdot Ci}{m}$$

Wi – electricity consumed by the lighting system for each hour during the day, (kWh); *Ci* - the cost of electricity in each hour during the day, (euro/ kWh).

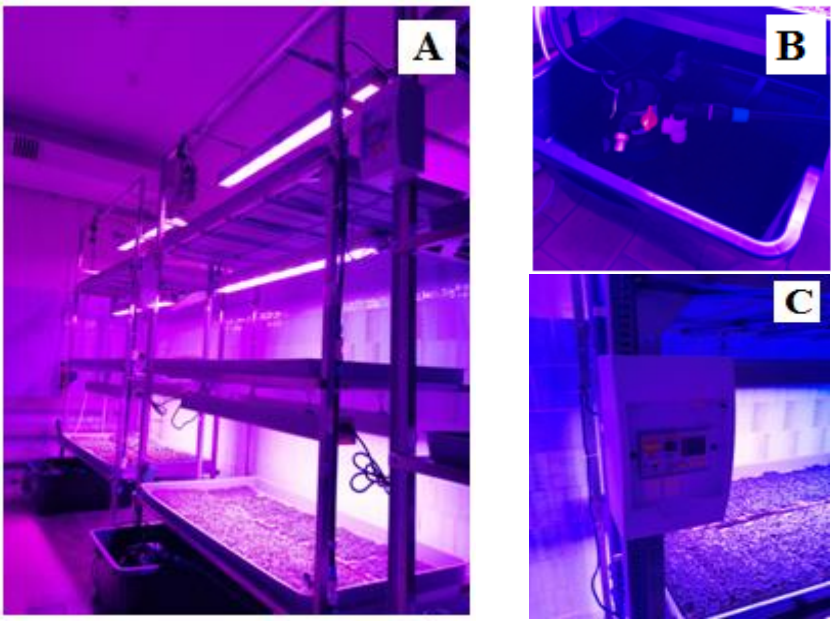
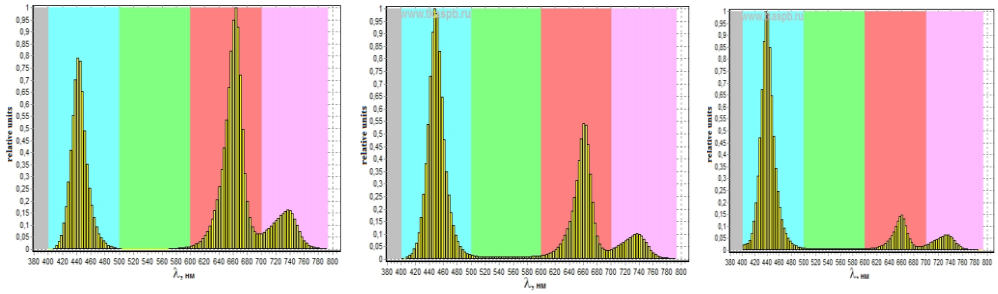


Fig. 1. Farm for growing microgreens: A- metal racks with irrigation and lighting systems, B – water container with a pump; C – automatic pump and light control unit.

Experiment 1: The influence of the spectrum within the light intensity/photoperiod ratio equal to 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$/16 h was investigated. Light intensity (photosynthetic photon flux density) was controlled by spectrophotometer TKA-spectrum (TKA, Russia). LED units with a combination of blue (B): red (R): far red (FR) light were used for illumination. The spectrum of the illumination options is shown in Figure 2. The characteristics of the illumination systems are shown in Table 1.



№1 №2 №3

Fig. 2. Spectrum options for lighting systems.

Table 1. Characteristics of LED installations.

	Electric power consumption, kW	Spectrum, %		
		λ=400-500 nm	λ=600-700 nm	λ=700-800 nm
№1	0.105	29	58	13
№2	0.099	50	37	13
№3	0.090	70	17	13

Experiment 2. A study of the effect of light intensity and photoperiod within one daylight integral was carried out. Parameters and operation modes of the lighting systems are shown in Table 2. The lighting system was turned on automatically according to a preset algorithm using a programmable controller. The price of electricity during the day is shown in Figure 3. (electricity supplier PJSC "TNS Energo NN", Nizhny Novgorod, Russia). LED installations No.3 were used for lighting (Figure 2).

Table 2. Parameters and modes of operation of lighting systems.

№	PPFD, $\mu mol \cdot m^{-2} \cdot s^{-1}$	Light/Dark, h	Working time	DLI, $mol \cdot m^{-2} \cdot d^{-1}$
1	100	16/8	21.00-13.00	5.76
2	134	12/12	19.00-7.00	5.76
3	200	8/16	23.00-7.00	5.76

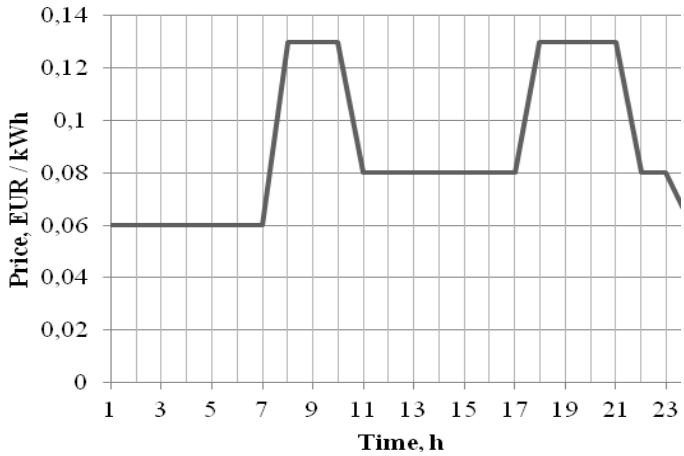


Fig. 3. Price of electricity during the day.

3 Result

Experiment 1. Increasing the proportion of red spectrum increased the fresh weight of both microgreens (Figure 4, A). Increasing the red spectrum from 17 to 58% increased the fresh weight of cabbage and radish microgreens by 20% and 22.5%, respectively. The fresh weight value of radish microgreens was 43% higher than the fresh weight of cabbage microgreens.

For the production of dry weight of microgreens, the efficiency of light use increases by increasing the red region of the spectrum (Figure 4,B). Dry weight value increased by 36% and 33% for cabbage microgreens and radish microgreens, respectively.

Increasing the proportion of red spectrum helped to reduce the energy cost per unit production of both microgreens (Figure 4,C). By increasing the red spectrum, specific energy consumption decreased for cabbage and radish microgreens by 28.8% and 29.3%, respectively. It should be noted that the decrease in energy consumption outpaced the increase in the fresh weight of the microgreens. This is due to more energy-efficient light sources (Table 1). The value of specific energy consumption for radish microgreens is 30.3% less than for cabbage microgreens.

Increased yield and a more energy-efficient light source contributed to lower financial costs for purchased electricity (Figure 4, D). The financial cost of purchased electricity for cabbage and radish microgreens decreased by 15.8% and 18.2%, respectively, when the red region of the spectrum was increased. The financial cost of purchased electricity for radish microgreens compared to cabbage microgreens was 43.8% lower.

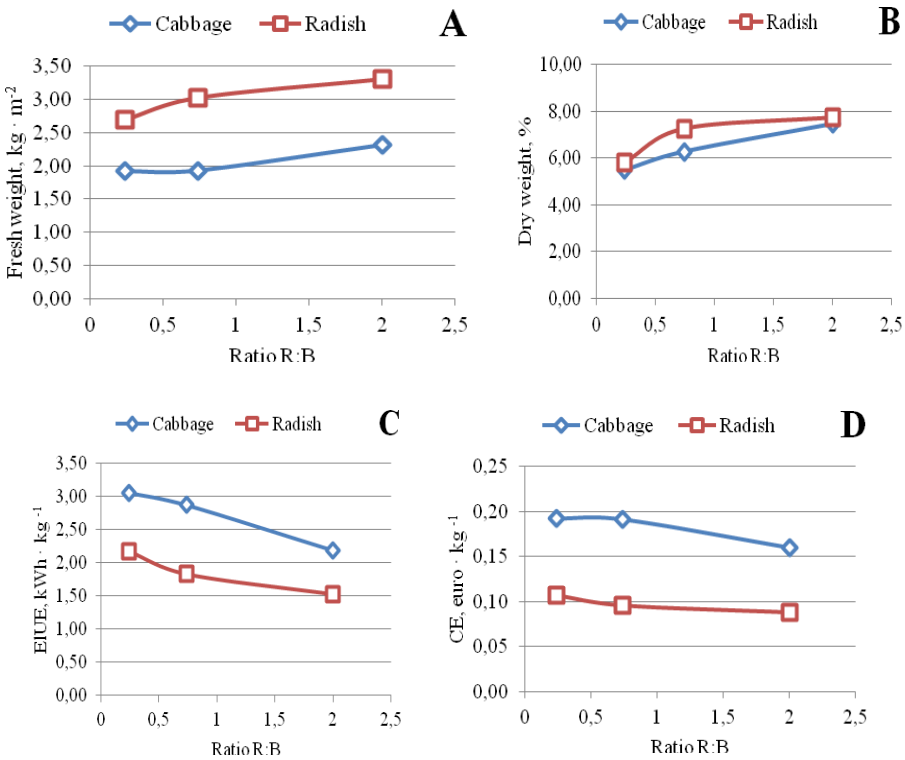


Fig. 4. Fresh weight (A), dry weight (B), energy efficiency (C), and energy costs to produce fresh weight (D) of microgreens at different ratios of red to blue light at constant far red light.

Experiment 2. The photoperiod/intensity ratio within one daylight integral affected the yield of both microgreens (Figure 5, A). The highest fresh weight was obtained under the 16/100 regime and was 2.26 kg/m^2 and 3.74 kg/m^2 for cabbage and radish microgreens, respectively. With decreasing photoperiod and increasing light intensity, the fresh weight decreased by 9.8% and 22.8% for cabbage and radish microgreens, respectively.

For the production of dry weight of microgreens, the efficiency of light use increases as the photoperiod increases with decreasing light intensity (Figure 5, B). Dry weight value increased by 1.3 times for all studied varieties of microgreens.

The efficiency of plant light energy utilization influenced the efficiency of electrical energy used by the lighting systems. Electricity consumption was lowest for the production of 1 kg of microgreens with a 16-h photoperiod and 100 μmol·m^{-2}·s^{-1} (Figure 5, C). The energy consumption per unit production of radish microgreens compared to cabbage microgreens is 39.5% lower.

The financial cost of purchased electricity for unit production was 13.4% less for cabbage microgreens and 20% less for radish microgreens with a 16-hour photoperiod than with an 8-hour photoperiod (Figure 5, D).

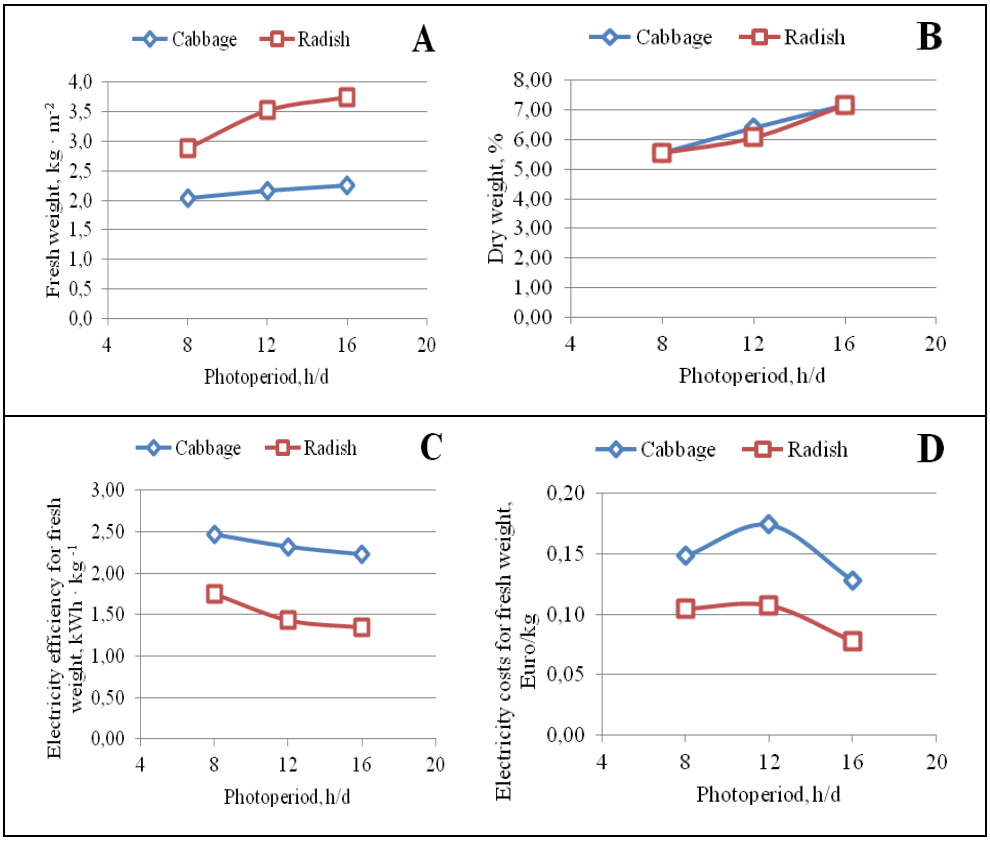


Fig. 5. Fresh weight (A), dry weight (B), energy efficiency (C), and energy costs to produce fresh weight (D) of microgreens under different photoperiods within one daylight integral.

4 Discussion

Experiment 1. In the study [20], the fresh and dry weights of microgreens were greater at a red spectrum fraction of 70-80% than at a red spectrum fraction of 20-30%. In the study [21], microgreen plants had greater fresh and dry weights at 75% red light than at 50% and 25%, respectively. Lots of red light is preferred for the highest yield of microgreens also in a study [22]. Increasing red light above 70% has little effect on increasing yields regardless of the microgreen variety [23]. Our study shows that a high proportion of red spectrum as part of a lighting system can not only increase fresh and dry weight, but also reduce energy consumption and financial costs. This is due to the fact that red LEDs are more energy efficient than blue LEDs. And even if the microgreen crop is the same, energy consumption will decrease with more red light. This is consistent with research on other plants. The lowest energy consumption and best use of light energy in growing spinach was with LED treatments with an R:B=1.2 ratio compared to R:B=0.9 [24]. In a study [25], the lowest energy expenditure in lettuce cultivation was obtained with R:B=3 ratio compared to 0.5-1-2-4 and white light ratios. The same ratio is the most suitable for growing basil with the minimum electricity consumption [26].

Experiment 2. The study [27] obtained opposite results for fluorescent lamps (R:B=1.8) and LEDs (R:B=1.2 and R:B=2.2) with equal daylight integral (DLI), different photoperiod and light intensity (12/200 and 16/150 respectively). When the photoperiod was increased

from 12 to 16 h/d (reducing the light intensity from 200 to 150 µmol-m-2-s-1), the crude mass of lettuce leaves for fluorescent lamps increased from 34.5 to 37.7 g/plant, for LEDs with R:B=1.2 and R:B=2.2 ratios the crude mass decreased from 28.4 to 28.3 g/plant and from 34.9 to 30.7 g/plant respectively. Leaf dry weight decreased from 1.34 to 1.27 g/plant for fluorescent bulbs, increased from 1.35 to 1.37 g/plant for R:B=1.2 LEDs, and decreased from 1.6 to 1.38 g/plant for R:B=2.2 LEDs. In a study [28] at a high DLI of 15.6 $mol \cdot m^{-2} \cdot d^{-1}$, lettuce grown at a lower PPFD and a longer photoperiod had higher fresh and dry weight than lettuce grown at a higher PPFD and a shorter photoperiod, whereas at a lower DLI of 10.4 $mol \cdot m^{-2} \cdot d^{-1}$ this did not occur. In a study [29], aboveground biomass increased by 16.0% in lettuce and 18.7% in mizuna in response to an increase in photoperiod from 10 to 20 h. Thus, extending the photoperiod and reducing PPFD increased the growth of lettuce and mizuna by increasing light interception and quantum yield of the photosystem. Increasing light intensity increases vitamin C and decreases nitrates, while increasing photoperiod has no effect on vitamin C changes and increases nitrates in cabbage and Chinese cabbage microgreens [30]. As we can see, the effect of the light intensity/photoperiod ratio within a single daylight integral is not unambiguous. The analyzed studies show that the response depends on the spectrum and the DLI value. According to the results of our study, we saw that a long photoperiod at low intensity is better than a short photoperiod and high light intensity in terms of energy and financial efficiency.

5 Conclusion

The conducted studies show that the spectrum and the light intensity/photoperiod ratio affect the energy intensity of production. This influence is not only due to the yield obtained, but also to the different energy efficiency of LEDs of different spectrum and the price of electricity at different hours of the day. Combining the results on dry weight as a quality indicator, energy consumption and financial costs for fresh weight, we consider a lighting system with parameters B:R:FR=29:58:13, PPFD= 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ / 16 h as the preferred option for growing microgreens.

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