

Article

Differentially Colored Photosensitive Nets as a Sophisticated Approach to Improve the Agronomic and Fruit Quality Traits of Potted Blueberries

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Abstract: The usage of photosensitive anti-hail nets is a modern approach to protect crops from adverse climatic factors with additional beneficial effects on orchard performance. Therefore, this study explored the impact of photosensitive nets (blue, red, pearl, and yellow net) and the black net on the microclimate, plant growth, yield, ripening time, and fruit quality attributes of the blueberry cultivar ‘Duke’. The Photosynthetic Photon Flux Density values were elevated under the pearl and yellow nets in both years studied. Average daily air temperatures did not differ between the nets in 2022, while a slight decrease was registered under the black net in 2023. The red net enhanced the average number of younger and total number of shoots per bush and also caused a notable increase in the fruit number and yield per bush, as well as fruit weight, compared to the other tested nets. The pearl net accelerated the onset of ripening in both years studied, while the blue and yellow net delayed ripening in 2022 and 2023, respectively. The blue net was distinguished by the increased blueness of fruit skin and total soluble solids/titratable acidity ratio, while individual sugar types and organic acids were more influenced by the season. The findings indicate that the red net performed the best in terms of most agronomic and biometrical fruit traits of the potted highbush blueberry cultivar ‘Duke’.

Keywords: microclimate; bush architecture; yield; fruit color; texture; primary metabolites



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1. Introduction

Blueberries have become a top choice for consumers due to their high nutritional value, distinctive flavor, and widely recognized health-promoting benefits [1–4]. As a result, the global production of this crop has increased in recent years, reaching 1,220,665 tons in 2023 [5]. In the Republic of Serbia, the northern highbush blueberry (*V. corymbosum*) is cultivated to meet the growing market demand for fresh blueberries. Modern soilless cultivation technology has also contributed to the intensification of production and protection against the adverse effects of climatic factors [1]. In this regard, global climatic changes resulting in a more frequent occurrence of hailstorms, heavy rains, extreme heat, and solar radiation pose a serious threat to the sustainability of blueberry production. To counterbalance these challenges, plastic nets are increasingly being used in blueberry plantations to protect

the yield and preserve the fruit quality [6,7]. Plastic nets made of high-density polyethylene threads are characterized by different properties, such as the type and dimensions of threads, texture, mesh size, weight, colors, shading factor, transmissivity, reflectivity, air permeability, and durability [8]. Among these traits, mesh size and color were considered the crucial factors determining net capacity for light quality and quantity, moderately changing the microenvironment within the orchard [9]. More recently, differentially colored photoselective nets have been developed as a new technological approach to improve the utilization of solar radiation for cultivated plants [10]. The main goal was to create different mixtures of unmodified light and spectrally modified scattered light, enabling the better penetration of modified light into the canopy, which can stimulate specific physiological and photo-morphogenetic plant responses [11,12]. Therefore, colored photoselective nets have a unique ability to both spectrally modify and scatter the transmitted light, surpassing the ability of traditionally used black nets [7]. According to the available literature, black nets greatly reduce the incidence of solar radiation and, more remarkably, reduce PAR (photosynthetically active radiation) or PPFD (Photosynthetic Photon Flux density) in comparison to white nets [13–15].

The quality of light is the most direct factor affecting the efficiency of photosynthesis, indicating that the red, followed by the blue light spectrum, is the most efficient [16]. In a few studies, it can also be outlined that the pearl net has the greatest light scattering potential and the gray net the least, while red, blue, yellow, white, and green nets are in between [11,15,17]. According to the aforementioned studies, it is evident that through the manipulation of the quantity and quality of light, colored anti-hail nets also change the orchards' microenvironment conditions, causing a decrease in average air temperature and an increase in relative humidity [6,7,11,18], followed by wind speed reduction by up to 50% [6,19]. However, there are conflicting results regarding the ability of these nets to reduce air temperature, with reports that the blue net tends to elevate the mean or maximum temperature [20], which was not the case in other studies conducted with differentially colored nets for blueberries, apples, peaches, and kiwi [6,11,21]. The different net properties (shading factor, color, etc.), agroecological conditions, and experimental methodologies may contribute to such conflicts between studies [6,7,18]. Lobos et al. [22] reported a positive relationship between the PAR values modified by net application and fruit yield, finding that shading by about 50% contributed to the maximum yield. This is probably due to the potential of shading in stressful conditions to increase the fruit size by reducing solar radiation and, thus, lowering temperature stress. High levels of shade have also positively affected fruit firmness, which is an important internal quality parameter of blueberry fruit [22]. Contrary to this, shading causes the limitation of carbohydrates as the main products of photosynthesis, which is a light-dependent process [7,23]. An increase in PAR positively affected photosynthetic efficiency, revealing the red spectrum of light as the most efficient method for carbohydrate synthesis [24]. Generally, the effect of nets on fruit size and the chemical composition of different fruit species cultivated underneath can be described by a net potential to influence photosynthetic efficiency and vegetative and reproductive growth; these are all factors that influence carbohydrate availability and the source–sink relationship [6,7,9,14,17,20,25].

Presently, only a few studies address the impact of photoselective nets on the field performance and fruit characteristics of highbush blueberries grown as a soilless culture [22,23]. Therefore, our study aimed to explore the effects of differentially colored photoselective anti-hail nets, including blue, red, pearl, and yellow nets, and traditionally used the black net on microclimate change, bush architecture, yield-related traits, ripening time, and external and internal fruit quality traits of the blueberry cultivar 'Duke' grown in pots.

2. Materials and Methods

2.1. Experimental Design and Net Properties

The research was carried out in a highbush blueberry plantation of the company 'Gruža agrar' located in the municipality of Knić, central Serbia [43°55' N, 20°43' E, 271 m above sea level (a.s.l.)] from 2022 to 2023, when the plants were 6 and 7 years old, respectively. This region is characterized by temperate continental climate, with a mean annual air temperature of 13.6 °C and mean annual precipitation of 659.7 mm [26]. The 2-year-old nursery plants of the 'Duke' cultivar were planted in pots during the spring of 2017. Pots of 113 L volume were filled with sawdust from conifers and white peat (50:50 ratio), with a distance of 0.8 m in a row and 3.0 m between rows (4170 plants/ha). Irrigation and fertigation were provided by 4 spear drip emitters with a maximum water amount of 4 L h⁻¹ per pot. Mature plants were moderately pruned by removing unproductive shoots in the central part of the canopy and weak and excessively fruiting branches at the top of the bushes, which stimulated the development of new vigorous shoots to prevent a decline in productivity and promote the formation of larger fruits. Fertigation was conducted 7 times a week to supply crops by each phenological stage, maintaining an irrigation cycle from late April to late September in both studied years. The average Electrical Conductivity (EC) of the fertilizer solution was 1.2 mS cm⁻¹, while a pH value was adjusted at a level of 5.0 using sulfuric acid.

The differentially colored photoselective anti-hail nets (blue, red, pearl, and yellow) and the black net (Figure 1) produced by Agrinova (Cassina de' Pecchi, MI, Italy) were placed over the plants, which were 6 years old. All investigated nets weighed 47 g m⁻² with a mesh size of 2.8 × 8.7 mm and a thread thickness of 0.32 mm. Shade level varied depending on the net color: black net—22%; red net—20%; blue net—18%; pearl—without shading; and yellow—16%. Fifteen rows of 50 m long were covered with 5 different colors of the nets at 3.3 m above the ground. Each color of the net covered 3 rows of 150 highbush blueberry plants. The nets were set up slightly before flowering in both studied years (mid-April of 2022 and 2023) and supported on four-meter-high concrete poles placed at a distance of 10 m. The experiment was designed as a completely randomized plan with 3 replicates and 10 plants per replicate for each colored net (the total number of plants per net treatment was 30).

2.2. Microclimate Measurement

The Photosynthetic Photon Flux Density (PPFD) and air temperature were measured with a Galcon PT100 climate sensor (Galcon, Kfar Blum, Kiryat Shmona, Israel), which was placed 1.5 m below the nets in the middle row under each net color. Readings were recorded daily at 5 min intervals in the period from the beginning of the flowering period (20 April) to the end of the harvest season (20 July) in both studied years. Data for PPFD are presented as average daily weekly values (μmol cm⁻²s⁻¹) in the analyzed period, while air temperature values (°C) are presented as average daily and night weekly values in both years of observation. Average daily air temperature values were calculated for the period from 6:00 a.m. to 8:00 p.m., while the data collected for the period from 8:00 p.m. to 6:00 a.m. were used to calculate average night temperatures.

2.3. Vegetative- and Yield-Related Traits

The following vegetative parameters were examined: the number of younger (1 to 2 years old) shoots per bush, the number of older (3 to 5 years old) shoots per bush, the total number of basal shoots per bush, and the diameter of younger and older shoots (mm). The number of basal shoots per bush was determined along with shoot thickness, which was measured at the base using a digital caliper (accuracy ± 0.01 mm) at the end of

each vegetative season. Yield-related components such as the number of fruits per bush, the yield per bush (kg), and per ha (t) were also investigated. The number of fruits per bush was counted to determine the yield potential in each year. Berries were harvested at commercial maturity four times between mid-June and mid-July in both seasons and weighed to determine the yield per bush.



Figure 1. Differentially colored photoselective nets in the blueberry orchard: blue net (a), red net (b), pearl net (c), yellow net (d), and black net (e).

2.4. Fruit Sampling

In the middle of the harvest period, a sample of 60 fully ripe fruits was randomly collected per replicate for each net color treatment (180 fruits per treatment) and transported to the laboratory of the Faculty of Agriculture, University of Belgrade (Serbia), where two-thirds of the fruit samples per replicates were used for the assessment of biometrical characteristics, color, and texture parameters. To prevent the effect of postharvest factors, the rest of the samples were frozen and stored at -20°C up to chemical analysis.

2.5. Biometrical Fruit Traits and Texture Analysis

Measurements of biometrical fruit traits (fruit weight, height, and width) and texture parameters (hardness 1, hardness 2, cohesiveness, and springiness) were performed on twenty berries per replicate within each sample collected in the middle of the harvest

season. The fruit weight was measured using a technical scale (Acom JW-1, ACOM, Seoul, Republic of Korea) with an accuracy of 0.01 g. The fruit height (cm) and width (cm) were measured using a digital caliper (Prowin, Shanghai, China). The fruit shape index was calculated as the ratio of the maximum height and width. Texture profile analysis (TPA) was conducted with the Brookfield CT3 Texture Analyzer (Brookfield Engineering, Middleboro, MA, USA) using a double compression test. The measurements of hardness 1, hardness 2, cohesiveness, and springiness were carried out applying the following parameters: the trigger was set at 5 g, deformation was set at 9 mm, and the speed of the probe was set at $1.7 \text{ mm} \cdot \text{s}^{-1}$ during the penetration, as described by Giongo et al. [27], using a compression Probe TA4 (38.1 mm diameter). Hardness 1 is the maximal force (N) required to complete the deformation of the first compression cycle, and hardness 2 is the force (N) achieved in the second compression cycle. Cohesiveness represents a ratio of energies expanded in compression, while springiness (mm) indicates the sample elasticity or the rate at which the deformed sample returns to its original size and shape. Data were collected using TexturePro CT software 1.9.35 (Ametek, Berwyn, PE, USA).

2.6. Fruit Color Evaluation

The surface color was determined by a CIE $L^*a^*b^*$ system (illuminant D65, observed angle 10°) in the wavelength range of 400–700 nm on twenty randomly chosen berries per replicate using an AMT529 color spectrophotometer (Amtast, Lakeland, FL, USA). The L^* (lightness) is associated with a light/dark scale ranging from 0 to 100, where 0 represents black and 100 represents absolute white, while a^* values denote red vs. green and the b^* values denote yellow vs. blue [28]. The symbol C defines chroma, representing the color intensity. The symbol h (hue angle) shows the color shade expressed in degrees, from 0° to 360° (0° , red; 90° , yellow; 180° , green; 270° , blue). The calibration of the device was ascertained using a white and blackboard.

2.7. Total Soluble Solids (TSSs) and Titratable Acidity (TA) Determination

TSSs were determined by a digital refractometer (Pocket PAL-1; Atago, Tokyo, Japan). The results are presented as a percentage of dissolved solids in the fruit extract. TA was analyzed using a digital burette and 0.1 mol L^{-1} sodium hydroxide (NaOH) to titrate samples to an endpoint, and the results were presented as a percentage of citric acid equivalents. The TSS to TA ratio was also calculated as a key characteristic determining the taste.

2.8. Individual Sugar and Organic Acid Extraction and Determination

The analysis of the extraction of individual types of sugar and organic acids was carried out using frozen fruit samples in three replicates for all the net treatments each year, employing the method previously reported by Milosavljević et al. [29]. Frozen fruit samples were thawed and measured before the extraction of sugar and acids. Extraction was performed by homogenizing 1 g of fruit samples with 3 mL of 80% methanol using a mortar and pestle. Extracts were centrifuged at $13,000 \times g$ for 10 min at 4°C and filtered through $0.22 \mu\text{m}$ nylon syringe filters (Phenomenex, Torrance, CA, USA). The preparation of supernatants was performed in triplicate, and afterward, they were stored at -20°C until the analysis.

HPLC analyses were conducted using a Waters Breeze chromatographic system (Waters, Milford, MA, USA) connected to a Waters 2465 electrochemical detector with a 3 mm gold working electrode and a hydrogen reference electrode. A CarboPac PA1 (Dionex, Sunnyvale, CA, USA) $250 \text{ mm} \times 4 \text{ mm}$ column was used for the separation of sugar, equipped with the corresponding Carbo-Pac PA1 guard column. Analysis was performed at a flow rate of 1.0 mL min^{-1} and a constant temperature of 30°C . Isocratic elution was applied, using 200 mmol L^{-1} of NaOH prepared from 50% *w/w* and low-carbonate

NaOH (J.T. Baker, Deventer, The Netherlands) by adding 10.5 mL to the final volume of 1 L vacuum-degassed deionized water. The pulsed amperometric mode was employed for the detection of signals using the following waveform: E1 = +0.15 V for 300 ms; E2 = +0.75 V for 150 ms; E3 = −0.80 V for 150 ms; and within 150 ms of the integration time. The filter timescale was 0.2 s, and the range was set to 5 μ A for the full mV scale.

The same HPLC system was connected to a 2996 diode array detector, which was adjusted at 210 nm and used for the separation of organic acids. The Supelco C-610H (300 mm $\times$ 7.8 mm) anion exchange column and precolumn (Sigma-Aldrich, Barcelona, Spain) were applied. Organic acids were eluted isocratically with 0.1% phosphoric acid (H_3PO_4) as the mobile phase at a flow rate of 0.5 mL min^{-1} and a column temperature of 40 °C. Data acquisition and quantification for both sugar and organic acid analysis were carried out by Waters Empower 2 Software (Waters).

2.9. Sweetness Index (SI)

The calculation of SI was performed using Equation (1) as the sum of multiplied concentration values of the main individual sugar types with their coefficients (glucose = 1; fructose = 2.3; sucrose = 1.35), according to Keutgen and Pawelzik [30]. The coefficients indicate that fructose is 2.3 times sweeter than glucose, while sucrose is 1.35 times sweeter.

$$\text{SI} = (\text{glucose} \times 1) + (\text{fructose} \times 2.3) + (\text{sucrose} \times 1.35) \quad (1)$$

2.10. Total Quality Index (TQI)

The TQI was obtained based on the determined textural and chemical fruit quality characteristics, in line with Spasojević et al. [31]. The quality index for organic acids, TA, and cohesiveness was calculated using the rule “the nearer to the target value, the better the quality” and Equation (2).

$$\text{QI} = \left| \frac{2 * (x_i - T)}{x_{\max} - x_{\min}} \right| \quad (2)$$

Equation (3) was used to process individual types of sugar, TSS, hardness 1 and 2, springiness, and fruit weight, with the rule “the higher the value, the better the quality”.

$$\text{QI} = \frac{|x_{\max} - x_i|}{x_{\max} - x_{\min}} \quad (3)$$

Finally, TQI was calculated according to Equation (4), and the obtained results were interpreted by the rule “the lower the value, the better the total quality”.

$$\text{TQI} = \sqrt{\sum_{j=1}^N (\text{QI}_j)^2} \quad (4)$$

QI—quality index of each quality characteristic; x_i —the measured value of the quality characteristic; T—target value (the average value in the subset of values); $x_{\max}$ —the maximal value of the quality characteristic; $x_{\min}$ —the minimal value of the quality characteristic; N—the number of quality characteristics.

2.11. Statistical Analysis

The collected data were analyzed using SPSS 17.0 Statistics (IBM, Armonk, NY, USA) and Microsoft Excel 2019. The significant effect of the factors (net color and year) and their interaction was estimated by a two-way analysis of variance at $p \leq 0.05$. The LSD test at $p \leq 0.05$ was used to establish the significance of the differences between the mean values.

3. Results

3.1. Microclimate Conditions

3.1.1. Effect of Differentially Colored Photoselective Nets on PPFD

Light transmittance was gradually increasing during the vegetation period, from April to July, and the greatest PPFD was recorded at the end of May and June in 2022, while in 2023, the peak was reached on 6–12 June (Figure 2). In both seasons, an increase from the second week of July was also noted. During the monitored period, PPFD values were elevated under pearl and yellow nets in both years due to greater light transmittance compared to the other three nets that showed similar patterns and had slightly reduced values. PPFD ranged from $377.7 \mu\text{mol m}^{-2} \text{s}^{-1}$ (black net, 1–7 May) to $891.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ (yellow net, 27 June–3 July) in 2022 and from $339.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ (blue net, 8–14 May) to $854.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ (pearl net, 11–17 July) in the 2023 season. Considering the average values, it can be observed that light transmission was reduced with the darker color of the photoselective net, in descending order: pearl > yellow > red > blue > black. In relation to the pearl net that transmitted the greatest amount of light, the black net achieved a reduction of 8.0% and 6.9% on average and a maximum of 13.0% and 11.8% in 2022 and 2023, respectively.

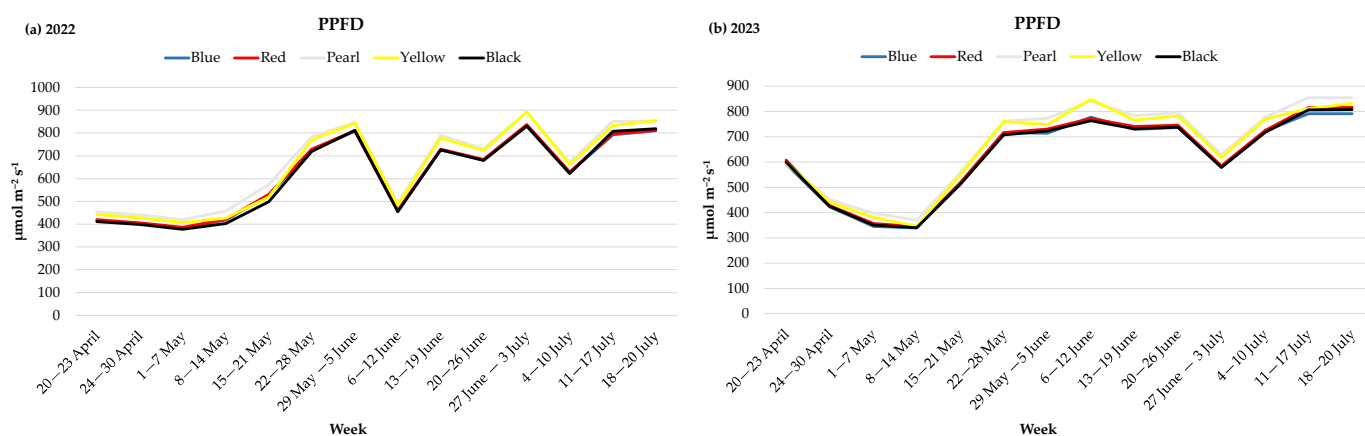


Figure 2. Photosynthetic Photon Flux Density (PPFD) under differentially colored photoselective nets during 2022 (a) and 2023 (b) seasons.

3.1.2. Effect of Differentially Colored Photoselective Nets on Air Temperature

Average daily and night temperatures under photoselective nets in the blueberry orchard during 2022 and 2023 are presented in Figure 3.

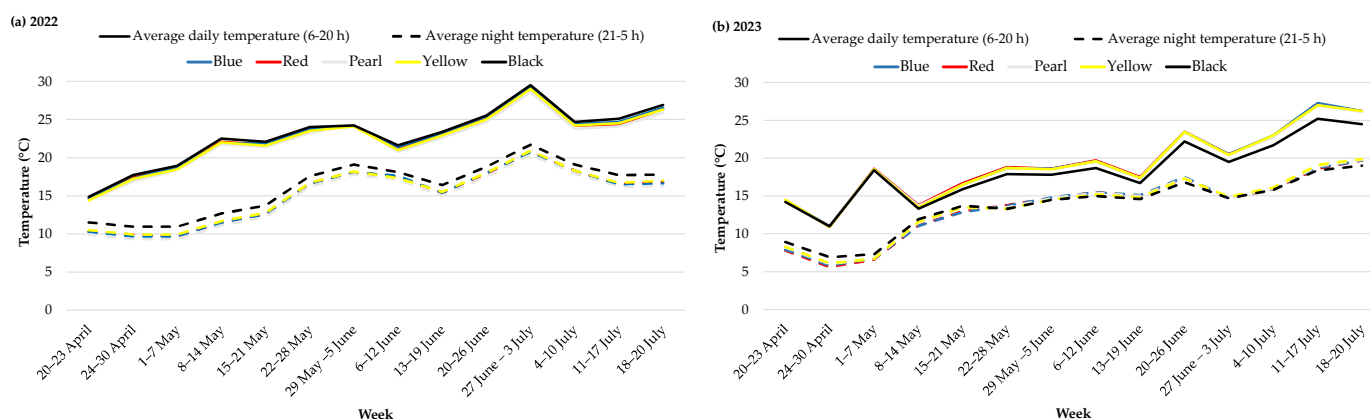


Figure 3. Average daily and night temperatures under differentially colored photoselective nets during the 2022 (a) and 2023 (b) seasons.

In 2022, there were no pronounced differences in daily temperatures among the tested nets, but temperatures were slightly higher under the black net and reached a peak on 27 June–3 July (29.5 °C). The highest average night temperatures were recorded under the black net as well, with temperatures increasing from 1.0 to 1.6 °C, on average, compared to other nets. The lowest average night temperatures were recorded under the pearl photoselective net throughout the 2022 season (Figure 3a). Conversely, in 2023, average daily and night temperatures were reduced under the black net, which was more prominent in the warmest period, from the end of May toward the summer. Although, in contrast to the previous season, night temperatures were similar for all net colors, the daily temperature differences were pronounced. The average daily temperature was reduced under the black net by an average of 0.9 °C for the whole period and up to 2.1 °C at the temperature peak (11–17 July) in comparison to the blue net (Figure 3b).

3.2. Vegetative- and Yield-Related Characteristics

The red photoselective net influenced a significant increase in the average number of younger shoots per bush (6.42 ± 1.57), as well as the total number of shoots per bush (14.67 ± 2.44) in comparison to the other tested nets (Figure 4). The number of younger shoots and the total number of shoots per bush significantly increased in 2023, while the number of older shoots per bush was similar between the two examined years.

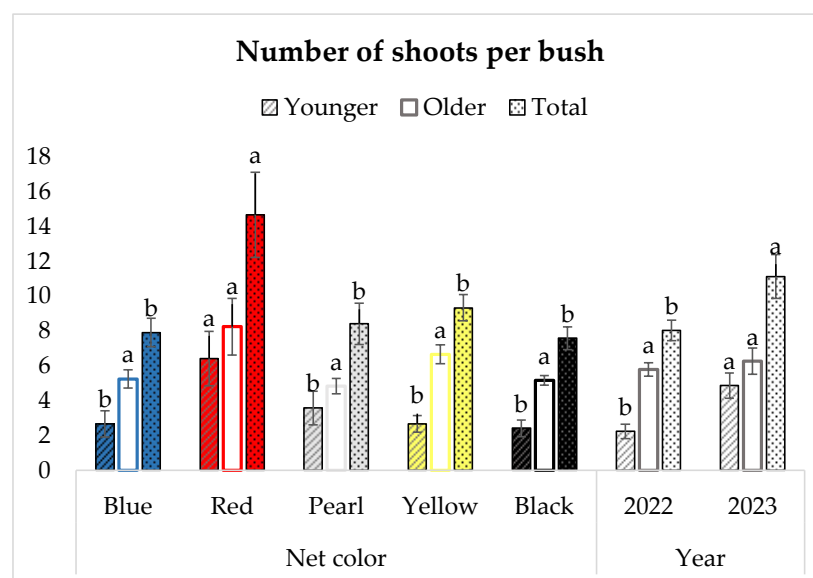


Figure 4. Number of younger, older, and total shoots per bush of blueberry cv. ‘Duke’. Data are the means ($n = 3$) $\pm$ standard error. The same letters assigned for each parameter for the net color and year denote no significant differences according to the LSD test at $p \leq 0.05$.

The diameter of the younger basal shoots in the bush did not differ significantly among the tested nets, while the diameter of the older shoots significantly increased under the black net (20.16 ± 0.83 mm). No significant difference was observed in the average diameter of older and younger shoots in the bush between the two examined years (Figure 5).

The red net significantly increased the average number of fruits per bush (2642.17 ± 144.56 bush⁻¹), the yield per bush (5.80 ± 0.28 kg bush⁻¹), and correspondingly the yield per ha (24.15 ± 1.19 t ha⁻¹) compared to all other tested photoselective nets, among which no significant difference was observed (Table 1). A significant increase in all yield-related parameters was observed in 2023, while the net color $\times$ year interaction significantly affected only the number of fruits per bush. Moreover, the pearl net only expressed a significant increase in the number of fruits per bush in the second year of the

study, while no significant differences were registered with the other colored nets between the two years studied.

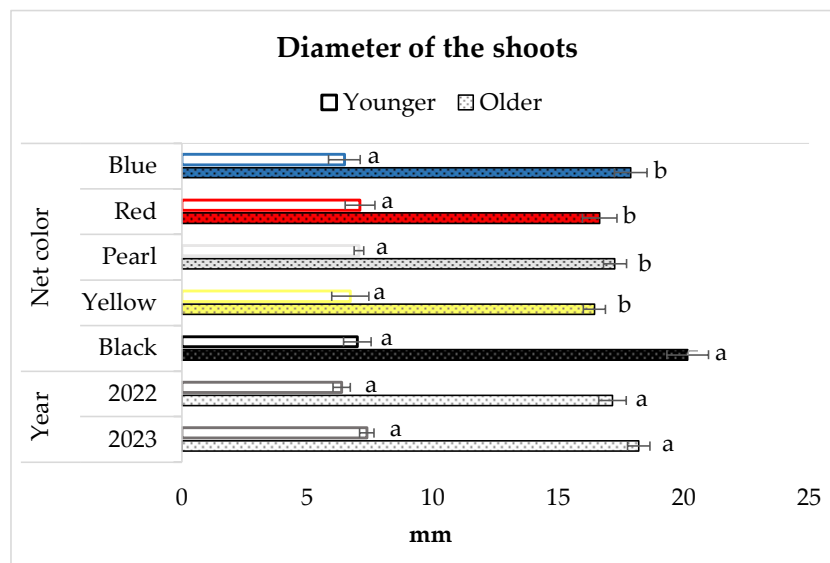


Figure 5. Diameter (mm) of the basal shoots in the bush of blueberry cv. ‘Duke’. Data are the means ($n = 3$) $\pm$ standard error. The same letters assigned for each parameter within net color and year denote no significant differences according to the LSD test at $p \leq 0.05$.

Table 1. Yield-related parameters of blueberry cv. ‘Duke’ grown under differentially colored photoselective nets over two seasons (2022–2023).

Net Color	Number of Fruits per Bush	Yield per Bush (kg)	Yield per Ha (t)
Net color			
Blue	2224.58 $\pm$ 157.18b	3.87 $\pm$ 0.28b	16.13 $\pm$ 1.18b
Red	2642.17 $\pm$ 144.56a	5.80 $\pm$ 0.28a	24.15 $\pm$ 1.19a
Pearl	1824.22 $\pm$ 219.56b	3.62 $\pm$ 0.55b	15.12 $\pm$ 2.29b
Yellow	1970.5 $\pm$ 192.72b	3.91 $\pm$ 0.50b	16.32 $\pm$ 2.10b
Black	2037.33 $\pm$ 141.89b	4.12 $\pm$ 0.35b	17.13 $\pm$ 1.46b
Significance	*	*	*
Year			
2022	1966.00 $\pm$ 155.01b	3.63 $\pm$ 0.31b	15.12 $\pm$ 1.29b
2023	2313.52 $\pm$ 67.98a	4.9 $\pm$ 0.23a	20.42 $\pm$ 0.96a
Significance	*	*	*
Interaction			
Blue $\times$ 2022	2048.83 $\pm$ 275.34bcd	3.48 $\pm$ 0.41	14.50 $\pm$ 1.73
Blue $\times$ 2023	2400.33 $\pm$ 129.71ab	4.27 $\pm$ 0.27	17.77 $\pm$ 1.12
Red $\times$ 2022	2868.67 $\pm$ 229.63a	5.53 $\pm$ 0.55	23.07 $\pm$ 2.32
Red $\times$ 2023	2415.67 $\pm$ 21.42ab	6.06 $\pm$ 0.18	25.23 $\pm$ 0.72
Pearl $\times$ 2022	1425.17 $\pm$ 65.44e	2.63 $\pm$ 0.13	10.93 $\pm$ 0.54
Pearl $\times$ 2023	2223.27 $\pm$ 278.42bcd	4.62 $\pm$ 0.69	19.30 $\pm$ 2.90
Yellow $\times$ 2022	1684.33 $\pm$ 275.19de	2.99 $\pm$ 0.45	12.46 $\pm$ 1.88
Yellow $\times$ 2023	2256.67 $\pm$ 167.59bcd	4.83 $\pm$ 0.45	20.17 $\pm$ 1.89
Black $\times$ 2022	1803.00 $\pm$ 149.78cde	3.51 $\pm$ 0.32	14.63 $\pm$ 1.33
Black $\times$ 2023	2271.67 $\pm$ 152.69bc	4.72 $\pm$ 0.39	19.63 $\pm$ 1.61
Significance	*	ns	ns

Data are the means ($n = 3$) $\pm$ standard error. The same letters within the column denote no significant differences according to the LSD test at $p \leq 0.05$. ns, nonsignificant; * significant effect at $p \leq 0.05$.

3.3. Ripening Time, Biometrical, and Textural Fruit Properties

The earliest onset of ripening was registered under the pearl net in both examined years (8 and 10 June, respectively), while the latest onset was recorded under the blue net in 2022 (13 June) and under the yellow net in 2023 (14 June) (Table 2). The yellow net contributed to the earliest end of ripening in 2022 (July 11), as well as the shortest duration of this phenophase in 2023 (27 days). Contrary to this, in 2022, the shortest duration of

ripening time was registered under the black net (23 days), and the longest was registered under the pearl net (37 days).

Table 2. Ripening time of blueberry cv. ‘Duke’ grown under differentially colored photosensitive nets over two seasons (2022–2023).

Net Color	Year	Ripening Time		
		Beginning	End	Duration (Days)
Blue	2022	13 June	11 July	28
	2023	12 June	16 July	34
Red	2022	10 June	7 July	27
	2023	13 June	14 July	31
Pearl	2022	08 June	15 July	37
	2023	10 June	13 July	33
Yellow	2022	10 June	15 July	35
	2023	14 June	11 July	27
Black	2022	12 June	5 July	23
	2023	13 June	18 July	35

Most of the parameters of biometrical fruit characteristics, except the fruit shape index, were affected by net color, year, and their interaction effect (Table 3). The red net resulted in a significant increase in fruit weight compared to other tested nets (2.47 ± 0.05 g), while the blue net caused the lowest fruit weight (1.98 ± 0.09 g), followed by the black net (2.01 ± 0.04 g). The average fruit weight significantly decreased under the blue and pearl nets in the second year of the study (1.78 ± 0.03 g and 2.06 ± 0.06 g, respectively), while the other nets did not contribute to a significant variation in the fruit weight between the examined years. There were also considerable changes in the fruit length, which ranged from 11.37 ± 0.38 mm (blue net) to 12.45 ± 0.15 mm (red net). The fruit width showed a similar trend, indicating that the red net contributed to the highest value (17.58 ± 0.19 mm) and the blue and black net contributed to the lowest value (16.0 ± 0.43 and 16.05 ± 0.15 mm, respectively). The index of the fruit shape did not differ significantly among the tested colored nets corresponding to roundish or flattened forms. A decrease in all fruit biometrical parameters was recorded in 2023, except for the fruit shape index. The net color $\times$ year interaction showed a significant effect on the fruit weight, length, and width, whereby the blue and pearl net significantly decreased the results in 2023. No significant differences were seen in the results of biometrical fruit traits between the two experimental years under the red, yellow, and black nets.

Table 3. Biometrical fruit characteristics of blueberry cv. ‘Duke’ grown under differentially colored photosensitive nets over two seasons (2022–2023).

	Fruit Weight (g)	Fruit Length (mm)	Fruit Width (mm)	Index of Fruit Shape
	Net color			
Blue	$1.98 \pm 0.09c$	$11.37 \pm 0.38c$	$16.00 \pm 0.43c$	0.71 ± 0.01
Red	$2.47 \pm 0.05a$	$12.45 \pm 0.15a$	$17.58 \pm 0.19a$	0.71 ± 0.01
Pearl	$2.19 \pm 0.06b$	$12.03 \pm 0.21b$	$16.82 \pm 0.30b$	0.72 ± 0.01
Yellow	$2.23 \pm 0.08b$	$12.22 \pm 0.12ab$	$16.92 \pm 0.36b$	0.71 ± 0.00
Black	$2.01 \pm 0.04c$	$11.92 \pm 0.10b$	$16.05 \pm 0.15c$	0.74 ± 0.01
Significance	*	*	*	ns
	Year			
2022	$2.24 \pm 0.05a$	$12.23 \pm 0.09a$	$17.07 \pm 0.17a$	0.72 ± 0.00
2023	$2.11 \pm 0.07b$	$11.77 \pm 0.19b$	$16.27 \pm 0.25b$	0.72 ± 0.01
Significance	*	*	*	ns

Table 3. *Cont.*

	Fruit Weight (g)	Fruit Length (mm)	Fruit Width (mm)	Index of Fruit Shape
	Interaction			
Blue × 2022	2.17 ± 0.07cd	12.17 ± 0.07abc	16.90 ± 0.15ab	0.72 ± 0.01
Blue × 2023	1.78 ± 0.03f	10.57 ± 0.28d	15.10 ± 0.26d	0.70 ± 0.02
Red × 2022	2.43 ± 0.08ab	12.53 ± 0.24a	17.57 ± 0.23a	0.72 ± 0.01
Red × 2023	2.51 ± 0.05a	12.37 ± 0.23a	17.60 ± 0.35a	0.71 ± 0.00
Pearl × 2022	2.31 ± 0.03bc	12.33 ± 0.15ab	17.43 ± 0.07a	0.71 ± 0.01
Pearl × 2023	2.06 ± 0.06de	11.73 ± 0.32c	16.20 ± 0.26bc	0.74 ± 0.01
Yellow × 2022	2.33 ± 0.13abc	12.33 ± 0.18ab	17.43 ± 0.32a	0.71 ± 0.00
Yellow × 2023	2.14 ± 0.08cde	12.1 ± 0.15abc	16.40 ± 0.51bc	0.7 ± 0.01
Black × 2022	1.95 ± 0.03ef	11.77 ± 0.15bc	16.03 ± 0.23c	0.73 ± 0.01
Black × 2023	2.07 ± 0.03de	12.07 ± 0.03abc	16.07 ± 0.23bc	0.74 ± 0.00
Significance	*	*	*	ns

Data are the means ($n = 3$) ± standard error. The same letters within the column denote no significant differences according to the LSD test at $p \leq 0.05$. ns, nonsignificant; * significant effect at $p \leq 0.05$.

The results of fruit textural attributes show that hardness one significantly increased under the pearl and red net compared to the other tested nets (Table 4). Hardness 2, cohesiveness, and springiness did not significantly differ among the tested nets. Interestingly, fruit hardness 1 and 2 were significantly higher in the first year, while cohesiveness and elasticity increased almost 4–5 times in the second year. No significant interaction effect between the net color and year was observed.

Table 4. Textural fruit characteristics of blueberry cv. ‘Duke’ grown under differentially colored photosensitive nets over two seasons (2022–2023).

Net Color	Hardness 1 (N)	Hardness 2 (N)	Cohesiveness	Springiness (mm)
	Net color			
Blue	22.79 ± 1.45b	5.8 ± 0.18	0.14 ± 0.05	5.17 ± 1.39
Red	27.28 ± 1.54a	6.8 ± 0.81	0.13 ± 0.05	5.20 ± 1.32
Pearl	28.17 ± 1.22a	8.53 ± 1.68	0.20 ± 0.06	5.44 ± 1.38
Yellow	21.51 ± 1.08b	7.89 ± 1.39	0.16 ± 0.05	5.03 ± 1.34
Black	20.77 ± 1.22b	5.8 ± 0.61	0.17 ± 0.07	4.93 ± 1.20
Significance	*	ns	ns	ns
	Year			
2022	26.24 ± 1.14a	8.49 ± 0.79a	0.05 ± 0.01b	2.23 ± 0.13b
2023	21.96 ± 0.77b	5.44 ± 0.23b	0.26 ± 0.03a	8.08 ± 0.13a
Significance	*	*	*	*

Data are the means ($n = 3$) ± standard error. The same letters within the column denote no significant differences according to the LSD test at $p \leq 0.05$. ns, nonsignificant; * significant effect at $p \leq 0.05$.

3.4. Fruit Color

The colorimetric parameters of blueberry fruit, including lightness (L), greenness (a), blueness (b), and hue angle (h), were significantly influenced by the color of the net, while none of the parameters were affected by the year (Figure 6). The highest L values were found under the black net (35.90 ± 0.27), followed by the yellow net (34.72 ± 0.99), indicating the brightest color of the fruit. The red net resulted in the lowest blueness (-4.22 ± 0.74), while the black net contributed to the lowest h value (238.57 ± 12.14). All other colorimetric parameters were not significantly affected by the color of the net.

3.5. TSS, TA, TSS/TA, and SI

The changed environmental conditions under the photosensitive nets tested influenced the TSS content, which was significantly increased in fruit harvested under the blue net (Figure 7). The black net was the second contributor to abundant quantities of TSS, while the red, pearl, and yellow nets showed considerably lower values. An opposite trend was observed for TA, with the blue net resulting in a significant decrease, followed by the black net, while the other colored nets contributed to a higher level of TA. TSS and TA also varied

between the years studied, showing a higher accumulation of total soluble solids in 2022 and higher quantities of organic acids in 2023.

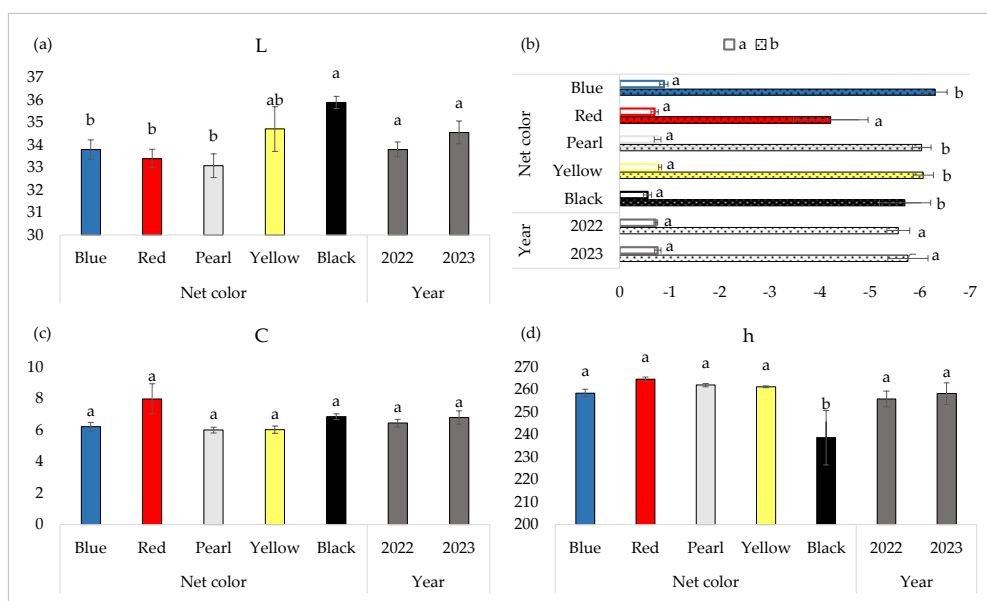


Figure 6. Blueberry fruit CIE L*a*b* color parameters for cv. 'Duke' grown under different photoselective nets over two seasons (2022–2023): L—lightness (a), a—greenness and b—blueness (b), C—chroma, (c) and h—hue angle (d). Data are the means ($n = 3$) $\pm$ standard error. The different letters within net color and year indicate statistically significant differences according to the LSD test at $p \leq 0.05$.

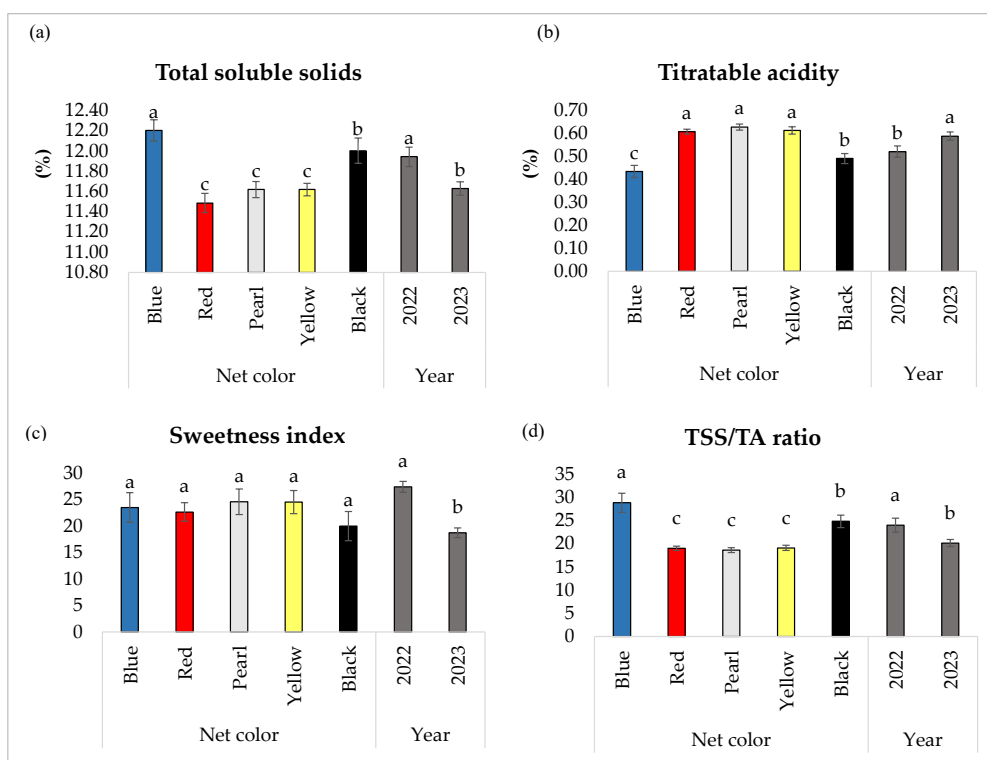


Figure 7. Blueberry fruit TSS (a), TA (b), SI (c), and TSS/TA ratio (d) for cv. 'Duke' grown under differentially colored photoselective nets over two seasons (2022–2023). Data are the means ($n = 3$) $\pm$ standard error. The different letters within net color and year denote significant differences according to the LSD test at $p \leq 0.05$.

The data given in Figure 7 show that cultivar ‘Duke’ responded differently to the tested photosensitive nets in terms of the TSS/TA ratio. The highest TSS/TA ratio was seen for the fruit harvested under the blue net compared to the other four nets. In line with the increased content of TSS in 2022, the same trend was noted for the TSS/TA ratio, which showed a significant decrease in 2023. Interestingly, the sweetness index (SI) also showed a significant decrease in 2023, although the effect of the tested nets on SI was not significant.

3.6. Content of Individual Sugar Types and Organic Acids

The content of individual types of sugar is presented in Figure 8a and Supplementary Material, Table S1. The major sugar types found in blueberry fruit were glucose and fructose, which were represented almost equally, while sucrose showed a much lower content. The fructose content was elevated under the blue, pearl, and yellow nets, whereas a significant decrease in both glucose and fructose content was detected under the black net (Table S1). The sucrose content was positively affected by the blue, red, and black nets in comparison to the yellow net, which caused the lowest sucrose content. Myoinositol was also detected in trace amounts, representing 1% of the total of all detected sugar. Significant differences were noted for all identified sugar types between the two experimental years, showing an increase in concentration in 2022. The net color $\times$ year interaction was not statistically significant, but an increase in the content of all identified sugar was recorded under all net colors in 2022.

Figure 8b shows that the most abundant organic acids were citric and malic, with 66% and 33% of total detected acids, respectively, while tartaric, shikimic, and fumaric acids were detected at almost trace amounts. Although net color did not cause significant differences for organic acids, a higher content of the most represented acid was observed under the black and blue nets. The malic, tartaric, and shikimic acid contents were significantly influenced by the year, recording an elevated content in the 2022 season. This interaction factor significantly affected only the citric and shikimic acid content, with the greatest differences among seasons under the red net, while other net colors showed consistency. The greatest content of citric acid was found in blueberry fruits cultivated under the black net in 2022 ($2.54 \pm 0.32 \text{ g kg}^{-1}$) and under the blue net in 2023 ($2.34 \pm 0.34 \text{ g kg}^{-1}$) (Supplementary Material, Table S2).

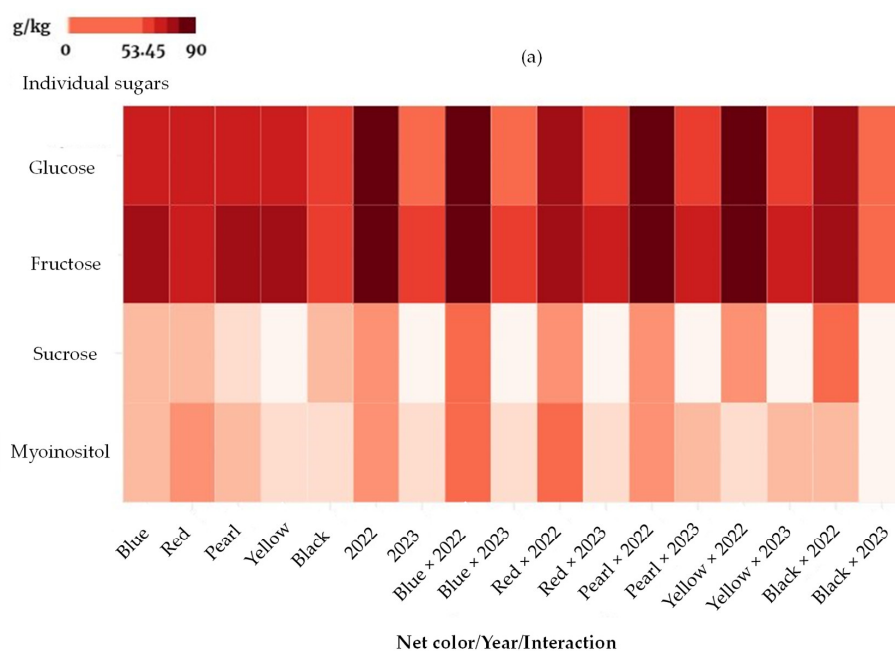


Figure 8. Cont.

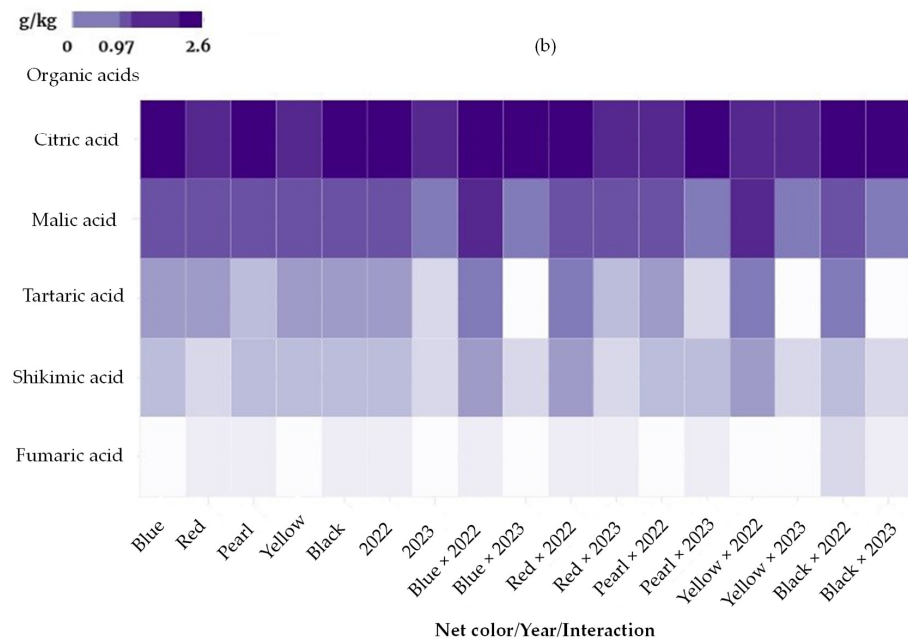


Figure 8. Heatmap for individual sugar types (a) and organic acid (b) contents in the fruit of blueberry cv. ‘Duke’ grown under differentially colored photoselective nets over two seasons (2022–2023).

3.7. TQI

According to TQI, which comprised all previously determined fruit characteristics, the pearl and blue nets showed the best overall quality, while the black net scored the worst (Figure 9).

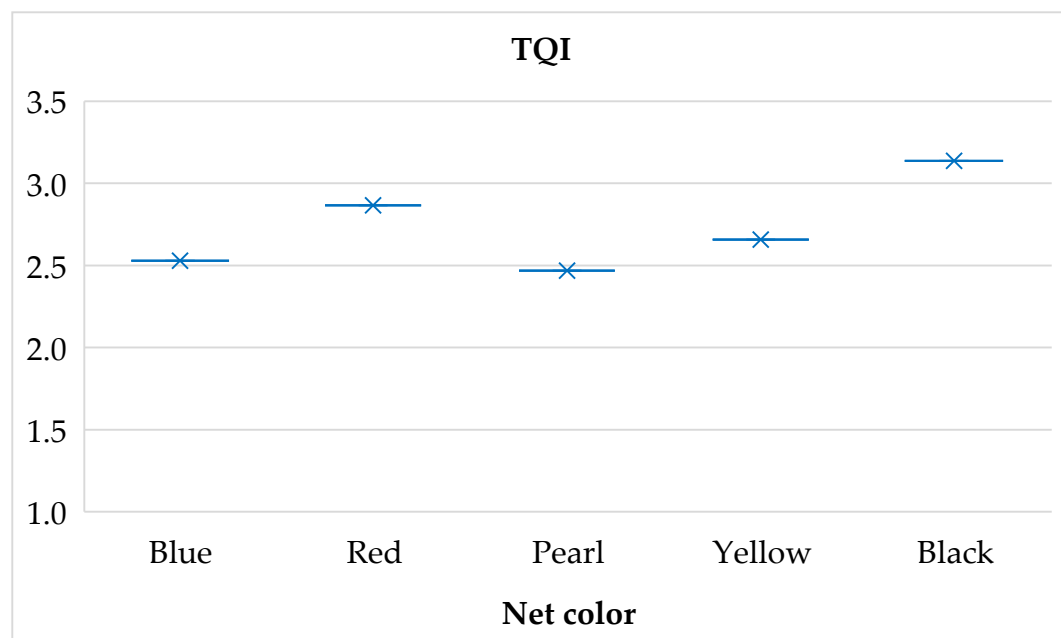


Figure 9. Total quality index of the blueberry fruit of cv. ‘Duke’ grown under differentially colored photoselective nets.

4. Discussion

Photoselective colored nets represent an emerging technological concept that could prevent the harmful effects of climate extremes faced by blueberries in field conditions [22]. Light is a significant environmental factor that affects blueberry growth, yield, and fruit

quality [6]. Solar radiation that passes through the threads in photosensitive nets becomes spectrally modified and scattered, which stimulates specific photo-morphogenic plant responses in contrast to the traditionally used black nets [11,12]. Zhang et al. [32] previously reported that the black net reduced light transmittance in the apple orchard while the white net recorded the greatest values, which is in line with our findings. Namely, we recorded the greatest light transmission through the pearl net as the brightest, which was then reduced up to 2.5-fold with a darker net color. Smrke et al. [23] also confirmed the greatest PPFD reduction in the highbush blueberry orchard under the black net, achieving the greatest amount of light reduction compared to the open field conditions and other net colors (red, yellow, white). As previously reported by Milivojević et al. [6] and Shahak et al. [11], the light transmittance can be reduced by up to 20% under the gray anti-hail net, which absorbs infrared radiation more efficiently than other colored nets, thus contributing to the reduction in air temperatures. Accordingly, in our study, lower light transmittance in 2023 resulted in significantly reduced temperatures under the black net, while differences among the tested nets in 2022 were not notable.

Light modification and shading can cause different plant responses, reflected in elongation and increased vegetative growth, which correlates with higher shading or darker-colored nets [7,33]. The red-to-far red ratio is probably the primary reason for enhancing vegetative growth since it mostly influences the shadow avoidance mechanism. The red net transmits light in the red and far-red spectrum and can modify the blue/red light intensity ratio, which is responsible for increased vegetative growth as the result of the shadow avoidance mechanism [7,33]. In our study, the red net showed the most notable influence on the vegetative and reproductive traits of the blueberry cultivar 'Duke', causing a significant increase in the number of shoots and fruits and also yield per bush as a consequence of new shoot growth. There were no differences in the diameter of younger shoots, while the growth of older shoots was significantly affected by the black net. Similarly, Zhang et al. [32] found a significantly greater shoot diameter in the apple orchard under the green, blue, and black nets in comparison to the white net. Light quality changes under the photosensitive nets also improved the yield in blueberry orchards [22,34], which is consistent with our results. The spectrally modified and scattered light under the red net improved the efficiency of light-dependent processes like flower induction and fruit development, leading to an increase in yield and fruit weight during the second growing season. Increased berry size and weight could be considered the most pronounced effect of the red net since the opposite trend was expected, taking into account the fact that the greatest yield was obtained under this net. Berry weight was also positively affected by modified microclimatic conditions under the gray hail protection net [6] and photosensitive red, blue, and white nets compared to the open field conditions [35].

As previously found, light intensity can significantly influence the ripening period, where the greater shaded areas contribute to a delayed harvest [22]. Accordingly, the pearl net caused fruits to ripen earliest in both experimental years, in contrast to Smrke et al. [23], who reported earlier ripening under the black and red nets. On the other hand, delayed fruit maturation was confirmed in both blueberries and bilberries under the photosensitive nets compared to the open field conditions, and the greatest delay was observed under the black net [35]. Interestingly, in our study, darker net colors (black, red, and blue) did not postpone ripening notably but completed harvest significantly earlier in 2022, resulting in a 10–14 day shorter harvest period. However, in the second season, ripening lasted the longest under the black net, while the yellow net caused the earliest end to ripen. This inconsistency may be caused by higher air temperatures in 2022 under the black net, which likely accelerated fruit ripening.

Fruit quality is defined by physical traits and chemical composition, which can differ greatly depending on environmental factors, such as light and temperature conditions. In addition to being an important parameter for determining maturity and the moment of harvest, fruit color is one of the most important characteristics that affect consumer preferences. Netting is reported to have an inconsistent impact on fruit coloration and has been mostly examined in apples but less in other fruit species [7]. It was found that netting can significantly impact apple fruit color, lowering the presence of the red overcolor [36], which was confirmed by another study in comparison to the open field conditions, where the yellow net contributed to the greatest red color reduction and, conversely, white and red nets increased the proportion of fruits with good overcolor [37]. In contrast, in blueberries under photoselective nets, only minor differences were found for color lightness and chroma [23]; we observed significant effects on L^* , b^* , and h , but C was unaffected by net color. Fruits under the black net had the lightest skin color and the lowest value for the hue angle. This meant that all tested photoselective nets increased h values significantly, showing a blue-purple fruit color, while the black net contributed to a lighter hue of the blue color. The blue net contributed to the bluest fruit color, and the red net had the opposite effect. Both light quality and quantity, including direct and scattered light, UV, red, and blue light, have a significant impact on fruit color development, mostly through pigment synthesis, the effect of which is rather dependent on the species [7]. The anthocyanin content of blueberry fruit under the gray hail protection net was unaffected in relation to the open field but notably conditioned by the harvest date [6]. Likewise, no differences were found in blueberries under the blue, red, and white photoselective nets, while bilberries elevated anthocyanin content under the black and blue nets [35]. This indicates that the blue net, through light spectrum modifications, has the potential to promote the anthocyanin synthesis that caused the bluest color of the fruit observed in our study.

Reportedly, light quantity is critical for blueberry fruit firmness as another essential fruit quality trait, where net color and shade significantly interact, meaning that higher shades contribute to greater fruit firmness [22]. Contrastingly, we found the firmest fruit under the pearl and red nets, while the black net, with the greatest shading level, caused the lowest values. In addition, both fruit hardness 1 and 2 were significantly increased in the first study year, along with an increase in fruit size, which is likely attributable to the reduction in stressful environmental conditions in 2022. According to Pandey et al. [33], fruits grown under covers can elevate their soluble solids content, which consequently can lead to lower firmness. The soluble solids content was the highest under the blue and black nets, which has also been shown to increase during ripening under covers in kiwifruits (*A. deliciosa*) [38]. Fruit grown under the blue and black nets also showed similar patterns regarding TA, which had the lowest content, as opposed to the other three nets. The average TSS in blueberry fruit ranged from 10.55% ('Chandler') to 15.04% ('Bluecrop'), which can be considered a reference since these findings are comparable with reports from Serbia [39], Poland [40], Bosnia and Herzegovina [41], and Romania [42]. The average content of TA ranges from 0.44% ('Chandler') to 1.45% ('Bluecrop') depending on the plant's physiological status, the degree of fruit ripeness, their position in the bush, the microclimate, and the harvest date. The TSS/TA ratio is mainly associated with a fruit's taste. Hancock et al. [43] found that in the northern highbush blueberry cultivars, the TSS/TA ratio ranges from 5.9 to 12.8, with strong environmental effects noted even in the same cultivar. The values for the TSS/TA ratio obtained in our study were considerably higher due to the lower presence of acid, but the values for TSS and TA are in correspondence with previously published results for cultivars 'Duke' and 'Bluecrop' [39]. Zoratti et al. [35] also observed the highest TSS under the blue net, but contrastingly, the lowest value was found under the black net, which can be explained by the specificities of the climatic conditions in different regions of

the study, including different net properties, cultivars, and methods of cultivation. TSS is a complex parameter that comprises (besides carbohydrates and organic acids) proteins, fats, and minerals of the fruit. Thus, its variations in dependence on the color of the net are a result of many factors that contribute to variations in many different classes of metabolites.

In Slovenian climatic conditions, the obtained results from the effects of photoselective nets are quite opposite to our findings, showing an increase in sugar content with the darkening of the net color [23]. Our results are in line with another report, where the brighter net colors (yellow and white) resulted in an elevated glucose and fructose content [44], whereas the black net contributed to an increase in the organic acid content. Basile et al. [44] concluded that white and red nets caused a higher accumulation of dry matter in fruit, leading to an increase in soluble solids concentration. In the same research, the white net elevated the percentage of scattered light in PAR, allowing for better light distribution within the canopy of vines, resulting in a higher photosynthetic rate. The content of organic acids did not change significantly, but at least a similar trend of enhanced content of organic acids was seen in the shade netting of raspberries and blackberries [45]. In a detailed analysis of grape berries, it was reported that reduced irradiation under the darker net correlates positively with the organic acid content [46]. However, our study revealed no significant differences in individual sugar types and organic acid contents affected by net colors, while the seasonal variations were significant. Although not significant, the changes observed in primary metabolites followed the expected trend: the brighter the net, the more sugar was present; organic acids were more abundant with greater shading. Considering the overall fruit quality attributes affected by differentially colored nets, the most positive effect on the mean value of TQI for the two experimental years was observed under pearl and blue nets, while the worst TQI was estimated under the black net.

Our results point out the season as the dominant factor that influences the content of primary metabolites. In this regard, the content of all identified sugar types and some minor organic acids considerably increased in 2022 because the process of primary metabolite synthesis is very intricate where various factors are involved. From our results, it can be seen that the 2022 season is characterized by a lower number of fruits per bush, which contributes to the elevated content of the primary metabolites [41]. Furthermore, the accumulation of sugar is more intense in blueberry fruit if the weather conditions are warmer and dry before and during the ripening season [47]. The above-mentioned fact is supported by meteorological data gathered during our experiment, depicting the 2022 season as the warmer one (Figure 3), especially during the ripening phase.

5. Conclusions

In conclusion, observing the effect of tested nets on the microclimate in the blueberry orchard, the black net remains in use, as it lowers daily temperatures and increases nightly temperatures in the spring, and also decreases high temperatures during fruit maturation, preventing the harmful impact of climate change. By altering the microclimate in the orchard, mainly through light modification, photoselective nets affect the vegetative growth, yield, ripening time, and fruit quality traits of soilless cultivated highbush blueberry. Among the four tested nets, the red net expressed the most positive effect on the bush growth- and yield-related parameters, which also significantly increased the fruit weight, and after the pearl net, the red net was the second highest contributor to the fruit hardness. The blue net may also receive more attention in the future due to its positive effect on the color and chemical composition of the fruit, which also contributed to the high TQI value, placing this net as second only to the pearl net. Overall, given the outstanding effect of red netting on the agronomic traits of the potted blueberries, its application could lead to the faster achievement of higher yields and premium fruit sizes compared to standard

black netting. From this perspective, despite shorter durability, the red net can contribute to increased production profitability in the expected period of up to a maximum of 8 years. However, further research is needed to confirm the long-term effects of photoselective nets on the sustainability of the entire production process.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agronomy15030697/s1>. Table S1: The content of individual types of sugar in the fruit of blueberry cv. ‘Duke’ grown under differentially colored photoselective nets during the 2022 and 2023 seasons; Table S2: The content of individual organic acids in the fruit of blueberry cv. ‘Duke’ grown under differentially colored photoselective nets during the 2022 and 2023 seasons.

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Data Availability Statement: The data presented in this study are available in the article and the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

PPFD	Photosynthetic Photon Flux Density
EC	Electrical Conductivity
TSS	Total soluble solids
TA	Titrateable acidity
SI	Sweetness index

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