

Research Paper

Does photoselective netting influence ripening, maturity parameters and chemical composition of highbush blueberry (*Vaccinium corymbosum* L.) fruit?

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ABSTRACT

The use of photoselective nets in highbush blueberry orchards has attracted much interest in recent years. In our 2-year experiment, we evaluated the effect of black, red, yellow and white exclusion nets and an uncovered control on light quantity and quality, fruit maturity parameters and chemical composition at harvest. Significant differences between treatments were noticed in fruit peel color, firmness and total soluble solids (TSS) content in both experimental years. The content of total volatiles in 2022 was the highest under the red net (2.67 mg kg⁻¹) and the control (2.63 mg kg⁻¹), to which the contents of hexanal and (E)-2-Hexenal contributed the most. No significance in total volatiles was determined in 2023. The sugar/organic acid ratio was the lowest in fruit under the yellow net (4.62) and the highest under the black net (7.74). Total phenolic, total anthocyanin and petunidin-3-O-glucoside contents were the highest in fruit under the black net (3606 mg kg⁻¹) and lowest in fruit under the white exclusion net (2072 mg kg⁻¹). According to our results, the black net performed the best, regarding the internal quality parameters, while the yellow net negatively affected the sugar/organic acid ratio and the white exclusion net negatively affected the total phenolic content.

1. Introduction

At present, blueberries are considered one of the healthiest foods due to their high nutrient content (phenolics, minerals and vitamins), which has a positive effect on human health through preventing various diseases (Barcia et al., 2010; Skrovankova et al., 2015). Reaching high yields and simultaneously achieving optimum fruit quality (i.e., high secondary metabolite content) are therefore two of the main concerns in highbush blueberry (*Vaccinium corymbosum* L.) fruit production.

The use of anti-hail netting is currently considered an indispensable element in intensive blueberry production (Milivojević et al., 2016), as it protects the plants from hail, heavy rain, snow, strong wind, insects and birds (Lobos et al., 2013; Shahak et al., 2004). However, nets alter the quality, quantity and direction of light that reaches the plants beneath, modifying their generative traits (Lobos et al., 2013, 2012; Shahak et al., 2004).

According to Ilić and Fallik (2017), the traditionally used black net absorbs light over the entire radiation spectrum. As far as the direction of light is concerned, no scattering occurs. Both of the above-mentioned

traits indicate great radiation reduction under the black net (Arthurs et al., 2013). In order to maintain the original anti-hail net function (i.e., protecting the plants from natural disasters) while improving the light properties under the netting, a new technology called photoselective netting was developed. It was first introduced for ornamental plants (Oren-Shamir et al., 2001); however, in recent years, intensive trials have also been taking place in fruit orchards, including blueberry orchards, with the aim of increasing yield and improving fruit chemical composition (Lobos et al., 2013; Milivojević et al., 2016; Retamales et al., 2008).

Light properties are one of the most important environmental factors affecting blueberry plant performance and yield (Milivojević et al., 2016). When solar radiation passes through a photoselective net, a change in light traits occurs. The radiation that comes into contact with the threads is spectrally modified, thus stimulating the desired physiological and photomorphogenic plant response. Light scattering occurs simultaneously, causing the diffuse light to penetrate deeper into the dense blueberry canopy and consequently improving light-dependent processes (Arthurs et al., 2013; Ilić and Fallik, 2017; Shahak et al.,

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Table 1

Mesh size and shading levels of black, red, yellow and white exclusion nets used in the research.

	Mesh size	Shading%
Black net	2.4 mm × 4.8 mm	18%
Red net	2.4 mm × 4.8 mm	17–21%
Yellow net	2.4 mm × 4.8 mm	12–18%
White exclusion net	0.39 mm × 0.83 mm	13%

2004). According to Oren-Shamir et al. (2001), photosensitive nets can increase light scattering by 50 % or more, and this alone may influence blueberry yield and fruit chemical composition. Light that passes directly through the gaps in the net, without hitting the threads, remains spectrally unchanged.

Exclusion nets have been developed to control pest attacks and limit fruit damage. Their mesh size is smaller than the pest (spotted-wing drosophila, *Drosophila suzukii* Matsumura), thus generating a mechanical barrier between the pest and the fruit. Exclusion nets also support organic production, as no insecticides should be used (Cormier et al., 2015).

Photosensitive nets can be classified into two groups: neutral (pearl, white, gray) and colored (red, yellow, green, blue) nets (Shahak, 2008a). For our experiment, nets from both groups were chosen, namely, a white exclusion net and red, yellow and black nets. As mentioned above, photosensitive nets significantly affect the properties of light and, consequently, the performance of the blueberry plants underneath, as this greatly depends on the products of photosynthesis, which is a light-dependent process (Jakopic et al., 2007; Lobos et al., 2012). Consequently, the aim of our study was to investigate the ripening, maturity parameters and chemical composition (individual sugars, organic acids, phenolic and volatile compounds) of blueberry 'Bluecrop' fruit under four different photosensitive nets.

2. Materials and methods

2.1. Plant material and experimental setup

The experiment was conducted in the test field of the Biotechnical Faculty in Ljubljana, Slovenia (latitude, 46 ° 50' N; longitude, 14 ° 47' E; altitude, 295 m a.s.l.) for two consecutive years, in 2022 and 2023. Ljubljana has temperate climate, with hot summers and wet autumn. Uniform 2-year-old plants of the highbush blueberry 'Bluecrop' were planted in 2021 in 40 l black pots. Substrate consisted of peat, soil (distic brown) and pine sawdust (1/3:1/3:1/3, v/v/v). Substrate pH was between 5.0 and 5.3. The plants were grown according to the integrated production guidelines. Each treatment included 6 plants. For the experiment, five treatments were established: control (no net), black, red, yellow, and white exclusion nets. All nets were rolled on top of a structure to cover the plants from leaf senescence to the bud swell stage, and again during flowering for optimal pollination. For the control treatment, no net was used.

In each treatment, six plants were arranged in two rows (each 0.6 m apart). The distance between the rows was 1.5 m. The floor was covered with black agrotexile in order to prevent weed growth. The plants were drip irrigated, using four drippers at each plant and with the flow rate maintained at 900 ml h⁻¹.

Black, yellow and red photosensitive nets were purchased from Agritech Srl Italy. The nets were made of high-density polyethylene. The white exclusion net was purchased from Vetisa (Loznica pri Zalcu, Slovenia). It was made of high-density polyethylene, with dense white threads. Net properties are listed in Table 1.

2.2. Solar radiation measurements

Light measurements were made on a clear sunny day (August 22,

2023) using a spectral light meter Optimum SRI-2000-UV (Optimum optoelectronics Corp., Hsinchu, Taiwan) above the plant canopy, in five replicates per treatment. The light spectrum (from 250 nm to 850 nm) was measured at 12 p.m. At the same time, diurnal change in photosynthetic photon flux density (PPFD; $\mu\text{mol m}^{-2} \text{s}^{-1}$) was monitored for individual treatment, with measurements made at every half hour, from 6.30 a.m. to 7.00 p.m.

2.3. Fruit harvest

In 2022, fruit were harvested and analyzed from all five treatments; in 2023, fruit were only harvested and analyzed from plants covered with nets, due to a hailstorm event which destroyed all of the fruit from plants without netting (control). Fruit were harvested 13 and 10 times in 2022 and 2023, respectively (due to consecutive ripening of the fruit), from each plant separately and placed in plastic containers and immediately transferred to the laboratory for maturity parameter measurements. All fruit from plants under the same treatment were combined in order to retrieve an average sample. For each treatment, 15 randomly chosen fruit were selected for maturity parameter measurements, while 30 fruit were frozen in liquid nitrogen and stored at -20 °C for the analyses of volatile compounds using gas chromatography (GC). The remaining fruit were also stored at -20 °C for individual sugars, organic acids and phenolic compound extractions and analysis using high-performance liquid chromatography (HPLC).

2.4. Fruit maturity parameter measurements

Blueberry peel color was measured once on each fruit at the fruit's equator (Konica Minolta CR-10 portable colorimeter, Tokio, Japan). According to the CIELAB (Commission Internationale de l'éclairage), each color represents an exact point in three-dimensional space and is described using these parameters: L^* , C^* and h° . The L^* value measures lightness on a scale from 0 to 100, where 0 is black and 100 is white. Parameter C^* signifies chroma, meaning the higher the value, the more intense the color is. The h° value represents the color expressed in degrees from 0° to 360°, where 0°–90° is red towards yellow, 90°–180° is yellow towards green, 180°–270° is green towards blue and 270°–360° is blue towards red.

Individual fruit firmness was measured with a 1 mm diameter tip (digital penetrometer, TR, Turini Italia; N). Total soluble solids (TSS) were determined with a digital refractometer (MA885 wine refractometer, Milwaukee Electronics, Szeged, Hungary).

2.5. Analysis of volatile compounds

The profile of blueberry fruit volatile constituents was determined using gas chromatography analyses (HS-GC-MS; Shimadzu GC-MS QP2020, Kyoto, Japan) connected to a single-quadrupole MS with an EI detector. Fruit were ground to a fine powder in an analytical mill (IKA A11 basic, Staufen, Germany). Then, 2 g of sample and 10 μL of internal standard (3-nonanone, 2.7 mg ml⁻¹ in acetonitrile) were transferred into 20 ml glass vials and thoroughly sealed with a screw cap with a PTFE silicone septum. Three replicates were made for each treatment. The vials were put into a Shimadzu AOC-20 s Autosampler, where they were incubated for 10 min at 50 °C with constant stirring at 250 rpm. The headspace portion (2000 μL) was injected into the injection port for 0.4 min at 250 °C in 1:10 split mode. The injection rate was 25 mL min⁻¹. The separation of volatile compounds took place in a ZB-wax PLUS capillary column (30 m x 0.25 mm, 0.5 μm film thickness). Helium was used as carrier gas and its flow rate was maintained at 1 mL min⁻¹. Temperature fluctuation during analyses was set as follows: initially, the temperature was set at 45 °C for 3 min, then it increased to 150 °C at a rate of 4 °C min⁻¹, followed by a further increase to 220 °C at a rate of 10 °C min⁻¹ and finally held at 220 °C for 5 min⁻¹. The scan rate was 2.0 scans, interface and ion source MS temperature were held at

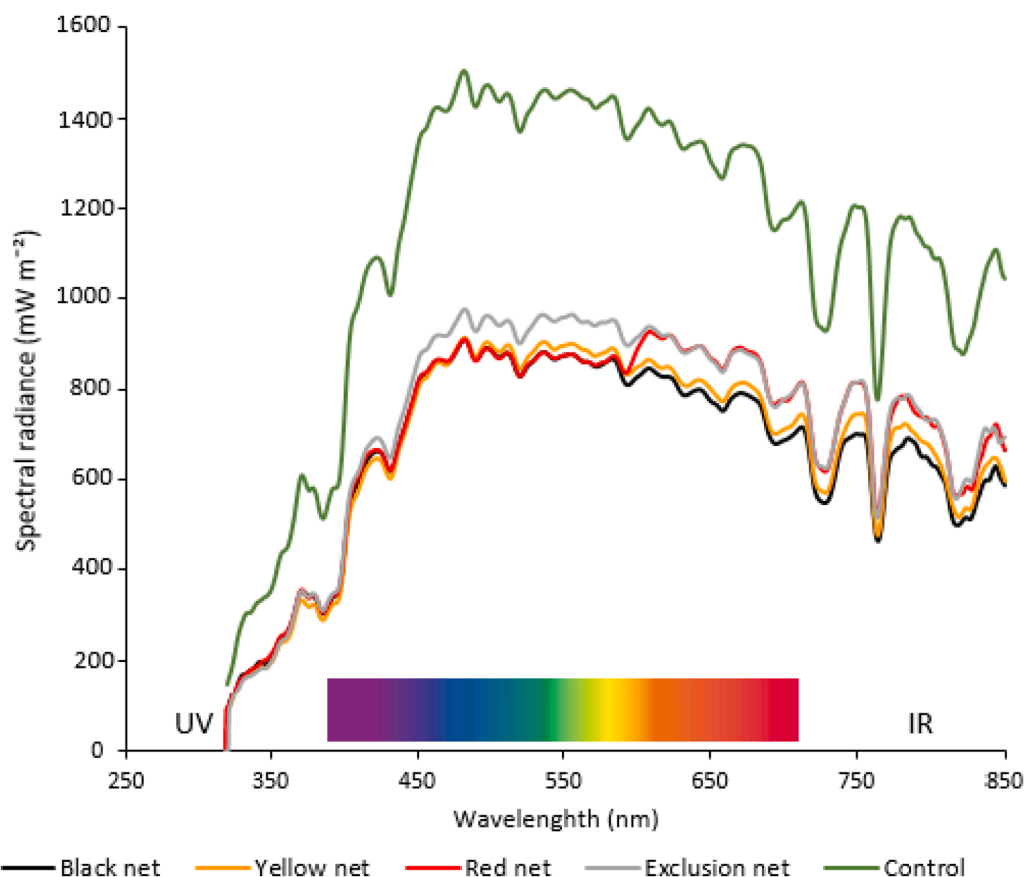


Fig. 1. Light spectrum (from 250 nm to 850 nm) under the black, red, yellow and white exclusion net and the control at 12.00 p.m. on a clear sunny day.

240 °C, ionization energy was 70 eV and mass scanning was set to 50–500 *m/z*. Volatile compounds in samples were identified using their retention indices (RIs) and commercial spectral libraries (NIST 11 and FFNSC 4). They were semi-quantified considering the peak area of each compound and the internal standard, and the weight of the sample and internal standard (Zamljen et al., 2023).

2.6. Extraction and analysis of individual sugars and organic acids

Sugars and organic acids from fruit were extracted in 2023. Extractions were prepared in accordance with an already-established method (Smrke et al., 2022). Individual compounds were analyzed with high-performance liquid chromatography (HPLC) (Smrke et al., 2022), identified by comparing their retention times with external standards, calculated from standard curves and expressed in g kg⁻¹ of fresh weight (FW).

2.7. Extraction and analysis of individual phenolic compounds

Extraction of individual phenolics was made from the same fruit as primary metabolites, according to the method previously described by Smrke et al. (2022). They were analyzed with HPLC (Smrke et al., 2022). The individual compounds were identified based on their mass fragmentation pattern and their retention times, compared with external standards. Their contents were calculated from standard curves. Individual compounds were combined into individual groups of flavan-3-ols, phenolic acids, flavonols and anthocyanins. They were expressed as mg kg⁻¹ of FW.

2.8. Chemicals and reagents

The following standards and chemicals were used in a present study:

3-nonanone, quercetin-3-galactoside, kaempferol-rutinoside, myricetin-3-galactoside, procyanidin B2, neochlorogenic acid, chlorogenic acid, cryptochlorogenic acid, caffeic acid, ellagic acid, malvidin-3-glucoside, glucose, sucrose, fructose, citric acid, tartaric acid, malic acid, shikimic acid, methanol, formic acid, acetonitrile, sulfuric acid (Sigma-Aldrich), ferulic acid, epicatechin, quercetin-3-rutinoside, quercetin-3-rhamnoside, quercetin-3-glucoside, isorhamnetin-3-rutinoside, delphinidin-3-glucoside, cyanidin-3-glucoside, pelargonidin-3,5-glucoside, cyanidin-3-rutinoside, (Fluka Chemie, Steinheim, Germany). The water used for sample preparation, solutions and analyses was twice distilled and purified (Milli-Q water purification system, Millipore, Bedford, MA).

2.9. Statistical analyses

Statistical analysis of the data was performed in R commander i386 4.3.2. Significant differences between different photoselective nets were determined with one-way analysis of variance (ANOVA) using Tukey's test ($\alpha < 0.05$). Significant differences are represented by different letters. Multivariate analysis was used for data visualization.

3. Results and discussion

3.1. Solar radiation

The spectral composition of light under the different nets is presented in Fig. 1. Light under the black net was similar in composition to that of the control treatment, which means that the light was not spectrally modified. Black nets are completely opaque, which somewhat decreases light intensity without affecting light quality (Arthurs et al., 2013). On the other hand, an increase between the yellow and red parts of the spectrum can be observed under the red net (Solomakhin and

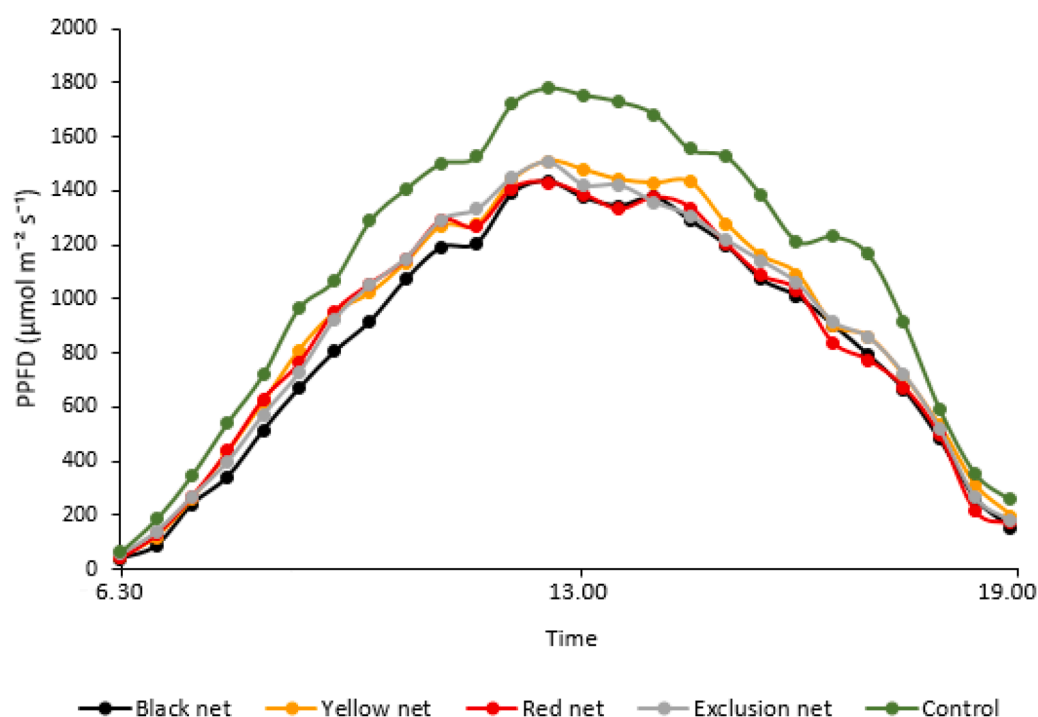


Fig. 2. Photosynthetic photon flux density (PPFD, $\mu\text{mol m}^{-2} \text{s}^{-1}$) under the black, red, yellow and white exclusion nets and the control from 6.30 a.m. to 7.00 p.m. on a clear sunny day.

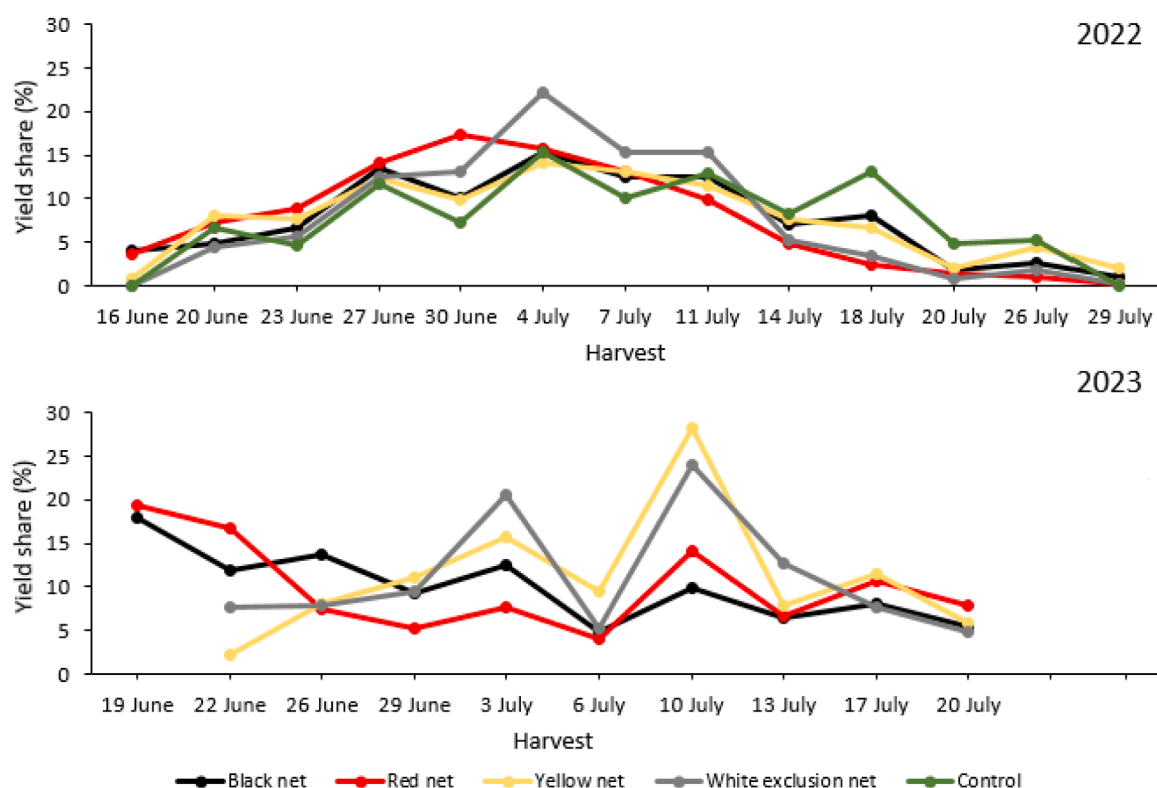


Fig. 3. Yield share (%) at each harvest date on plants under the black, red, yellow and white exclusion nets and the control in 2022 and 2023.

Blanke, 2010). As for the yellow net, the light is reduced up to and including the blue part of the spectrum (250 nm to about 475 nm), followed by an increase, when compared with the black and red nets. Colored photoselective nets contain different chromophores that have a reflective function and filter only specific wavelengths of solar radiation

(Zoratti et al., 2015). According to Shahak (2008b), red nets transmit light in the red and far red part of the spectrum, while yellow nets transmit light in the green, yellow, red and far red part. Light under the exclusion net has a similar spectral composition as other treatments between 250 nm and approximately 400 nm, followed by an increase

Table 2

Blueberry peel color parameters (L^* , C^* and h°), fruit firmness and total soluble solids (TSS) from the black, red, yellow and white exclusion nets and the control at harvest in 2022 and 2023.

Treatment	2022				
	L^*	C^*	h°	Firmness (N)	Total soluble solids (°Brix)
Black net	30.76 ± 2.18 b	1.41 ± 0.55 b	291.8 ± 21.35	0.22 ± 0.09	11.43 ± 1.30 bc
Red net	33.66 ± 1.92 a	2.55 ± 0.58 a	278.6 ± 10.53	0.20 ± 0.07	10.97 ± 1.07 c
Yellow net	31.32 ± 2.72 ab	1.69 ± 0.49 b	290.5 ± 23.35	0.29 ± 0.15	11.73 ± 0.68 bc
White exclusion net	31.78 ± 2.69 ab	1.59 ± 0.71 b	266.8 ± 62.55	0.22 ± 0.09	13.43 ± 1.62 a
Control	32.00 ± 2.22 ab	1.98 ± 0.53 ab	276.1 ± 10.68	0.23 ± 0.11	12.39 ± 1.13 ab
Sign.	*	***	NS	NS	***
Treatment	2023				
	L^*	C^*	h°	Firmness (N)	Total soluble solids (°Brix)
Black net	31.60 ± 2.18	2.59 ± 0.61	296.3 ± 12.78	0.16 ± 0.02 a	10.80 ± 1.06
Red net	32.21 ± 1.89	2.44 ± 0.46	285.2 ± 16.55	0.13 ± 0.03 bc	10.57 ± 1.75
Yellow net	31.69 ± 2.56	2.41 ± 0.65	284.4 ± 17.08	0.12 ± 0.03 c	10.46 ± 1.68
White exclusion net	33.27 ± 2.22	2.65 ± 0.94	299.6 ± 25.68	0.16 ± 0.05 a	9.98 ± 0.77
Sign.	NS	NS	NS	**	NS
Sign. black net	NS	***	NS	NS	NS
Sign. red net	*	NS	NS	***	NS
Sign. yellow net	NS	**	NS	***	*
Sign. white exclusion net	NS	**	NS	*	***
Treatment x year	NS	***	NS	*	***

Data are presented as the mean ± standard error calculated from 15 replicates per treatment. Different letters (a-c) indicate significant differences between treatments (Tukey's test, $\alpha < 0.05$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; NS, not significant. Sign. black, red, yellow and white exclusion nets indicate significant differences between both growing seasons.

until around 600 nm. From then on, the light spectrum under the white exclusion net resembles that under the red net.

Fig. 2 illustrates the diurnal change in light quantity under each net from 6.30 a.m. to 7.00 p.m. The highest amount of light was measured in the control, with the highest discrepancy between it and the nets in the middle of the day. Among the nets, the lowest values of PPFD were measured under the black net, indicating that different net colors with the same mesh size lead to diverse shading levels underneath (Lobos et al., 2013). The minimum differences between treatments were detected in the morning and in the evening, conditions with the lowest amount of light. Similar results were obtained in a study conducted by Solomakhin and Blanke (2010). The highest PPFD was found in all treatments measured at 12.30 p.m., and it was reduced by 19.4 % under the black net, 19.6 % under the red net, 15.2 % under the yellow net and 15.6 % under the white exclusion net, when compared with the control. Under the exclusion net, a higher PPFD was measured throughout the day when compared with the black net, despite a smaller mesh size. This could result from specific net properties, as the black net absorbs the same amount of light throughout the entire spectrum, while the white net absorbs only ultraviolet radiation (Shahak, 2008a).

3.2. Ripening

Fig. 3 shows the fruit yield share for each harvest date in 2022 and

2023. In the first year, fruit from all treatments began to ripen at the same time while, in the second year of the experiment, fruit under the black and red nets began to ripen earlier. Barkai-Golan (2001) has stated that, under a yellow photosensitive net, scattered light penetrates deeper into the plant canopy and delays fruit ripening. This probably lead to earlier fruit ripening under the black and red photosensitive nets. Lobos et al. (2013) and Zoratti et al. (2015) have reported that elevated shading delayed the harvest date, which differs from our results. This could be a result of higher shading levels used in their studies. In 2022, plants under the red net reached the highest yield on the fifth harvest date, while all other treatments reached it on the six harvest date. A similar satiation was observed in 2023, when plants under the yellow and white exclusion nets reached their peak on the seventh harvest date. However, plants under the black and red nets had already reached their highest yield at the beginning of the ripening period. In 2023, high variability between harvest dates occurred in yield share, which resulted from irregular weather conditions, with frequent rain and lower temperature events. In 2022, peak harvest presented between 15.3 % and 22.1 % of the total yield, while in 2023, it was between 17.9 % and 28.2 % of the total yield.

3.3. Maturity parameters

The maturity parameters of blueberry fruit were measured in both years of the experiment (Table 2). In 2022, significant differences between the nets were detected in the L^* and C^* values. However, the differences were minor and hard for a consumer to detect. The opposite was noticed in 2023, when non-significant results in peel color parameters between the fruit from different nets were obtained. Blueberries are harvested based on visual estimation of peel color; therefore, no significant difference in color parameters between treatments should be obtained during postharvest measurements. The effect of photosensitive netting on fruit coloration has mostly been examined on apple fruit, where no impact was determined (Iglesias and Alegre, 2006). However, Lobos et al. (2013) showed a significant interaction between peel color and shading intensity, rather than the peel and net color, in the highbush blueberry 'Elliot'.

In the first year of the experiment, no significant difference between treatments was observed in fruit firmness, while in 2023, significant differences between the nets were detected (Table 2). Significantly, the firmest fruit were harvested from the black and white exclusion nets. Recent studies have reported that fruit firmness is more dependent on light quantity than quality (Basile et al., 2012; Lobos et al., 2013). A significant difference was also determined between both years of the experiment in all but the black net. Some authors have stated that cultivar, crop load, planting system and plant age affect fruit internal quality (including fruit firmness) more than photosensitive nets (Stampar et al., 2002; Widmer, 2001).

In 2022, the content of TSS was significantly the highest in fruit from the control and white exclusion net, while in 2023, no significance was detected (Table 2). Total soluble solids (TSS) content has been reported to decrease in blueberry fruit simultaneously with increasing shadow (Lobos et al., 2013), which supports our findings from the first experimental year. However, the results from 2023 are in agreement with those published by Retamales et al. (2008), where no significance was determined between full sun, black, red, white and gray nets with 35 % and 50 % shading intensity. At this point, we should mention again that the netting treatments in 2023 were not compared with natural conditions, due to the hailstorm event.

3.4. Volatile compounds

In the present study, in 'Bluecrop' fruit, we identified 18 individual volatile compounds that were classified into six groups: alcohols, aldehydes, hydrocarbons, ketones, lactones and monoterpenes (Fig. 4). Significant differences between treatments were detected in most of the

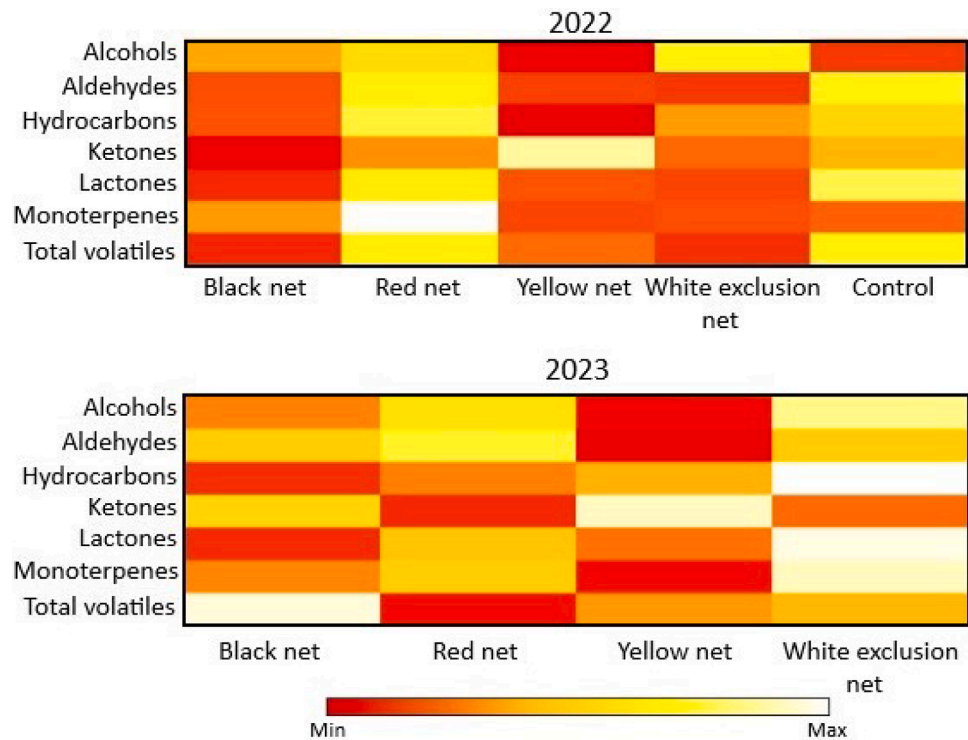


Fig. 4. Content of volatile compounds groups in blueberry fruit from the black, red, yellow and white exclusion nets and the control at harvest in 2022 and 2023.

Table 3
Sucrose, glucose, fructose and total sugar content in blueberry fruit from black, red, yellow and white exclusion nets at harvest in 2023.

Treatment	Sucrose (mg g ⁻¹)	Glucose (mg g ⁻¹)	Fructose (mg g ⁻¹)	Total quantified sugars (mg g ⁻¹)
Black net	7.34 ± 0.38 c	33.75 ± 1.74 a	32.64 ± 1.53 a	73.73 ± 3.07 a
Red net	9.46 ± 0.48 b	28.60 ± 0.99 b	27.95 ± 1.47 b	66.00 ± 2.44 b
Yellow net	10.96 ± 0.20 a	24.80 ± 0.69 c	24.18 ± 0.81 c	59.94 ± 1.40 c
White exclusion net	9.95 ± 0.34 b	27.70 ± 0.79 b	27.13 ± 1.08 b	64.87 ± 1.86 b
Sign.	***	***	***	***

Data are presented as the mean ± standard error calculated from 5 replicates per treatment. Different letters (a-c) indicate significant differences between treatments (Tukey's test, $\alpha < 0.05$). ***, $p < 0.001$.

individual volatile compounds and corresponding groups, with the exception of aldehydes, where no significance was detected in 2023. In the first year of the experiment, the highest total content of volatiles was measured in fruit from the red net and the control (Supplementary Materials, Table S2), to which the content of aldehydes, hydrocarbon and lactones contributed the most. (E)-2-Hexenal and hexanal contributed the most to the total content of aldehydes, resulting in similar statistical analysis between these two compounds, total aldehydes and total volatiles. (E)-2-Hexenal has a green, fatty and cheesy aroma, while hexanal has a fresh green, fruity and sweaty aroma (Dias et al., 2023). In the second-largest group of volatiles, ketones—and consequently in 2-Methyl-2-cyclopenten-1-one content, which is the prevailing compound among them—the highest content was detected in fruit harvested from plants under the yellow net, which is in accordance with the results from the second experimental year. These results indicate similar trends in volatile compound content between both years of the experiment, including alcohols, lactones and monoterpenes. In 2023, no significant difference was detected regarding the content of

total volatile compounds, despite significant differences between the nets in the majority of individual compounds. The ripening in 2023 was characterized by rainy weather with unusually low temperatures, which may have affected the synthesis of volatile compounds (Gndodu et al., 2021). Significant differences in individual volatile compound content between the nets result from mutual functioning of several environmental factors on plants.

3.5. Individual sugars and organic acids

Blueberry fruit primary metabolites (i.e., individual sugars and organic acids) were monitored and evaluated only in 2023, with the aim of updating current research in the second experimental year. In 2022, only TSS were monitored and based on these results we wanted to gain a more precise insight into the individual sugar content. Total sugar content differed significantly between each net (Table 3), with the

Table 4
Citric, tartaric, malic, shikimic and total organic acid content in blueberry fruit from black, red, yellow and white exclusion nets at harvest in 2023.

Treatment	Citric acid (mg g ⁻¹)	Tartaric acid (mg g ⁻¹)	Malic acid (mg g ⁻¹)	Shikimic acid (mg g ⁻¹)	Total quantified organic acids (mg g ⁻¹)
Black net	8.07 ± 0.62 c	0.65 ± 0.07	0.79 ± 0.04 c	0.04 ± 0.004	9.55 ± 0.66 c
Red net	9.32 ± 0.29 b	0.68 ± 0.07	0.87 ± 0.05 bc	0.04 ± 0.005	10.92 ± 0.40 b
Yellow net	11.36 ± 0.43 a	0.62 ± 0.17	0.96 ± 0.08 ab	0.04 ± 0.005	12.98 ± 0.55 a
White exclusion net	11.02 ± 0.79 a	0.73 ± 0.05	1.02 ± 0.10 a	0.04 ± 0.005	12.80 ± 0.92 a
Significance	***	NS	***	NS	***

Data are presented as the mean ± standard error calculated from 5 replicates per treatment. Different letters (a-c) indicate significant differences between treatments (Tukey's test, $\alpha < 0.05$). ***, $p < 0.001$; NS, not significant.

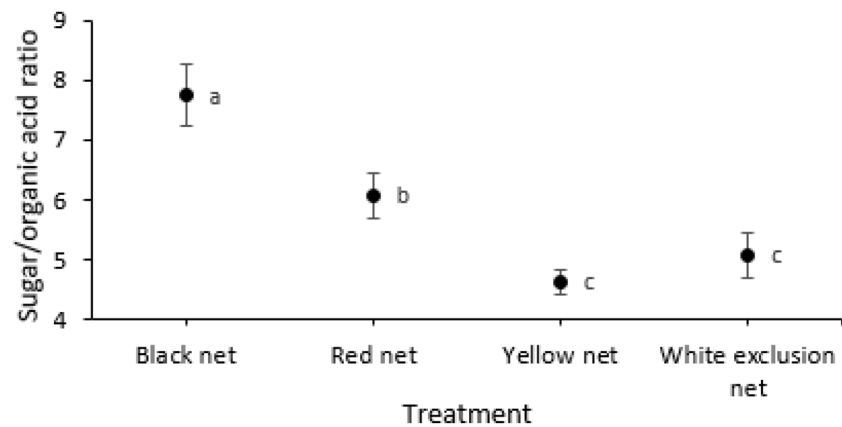


Fig. 5. Sugar/organic acid ratio in blueberry fruit from black, red, yellow and white exclusion nets at harvest in 2023.

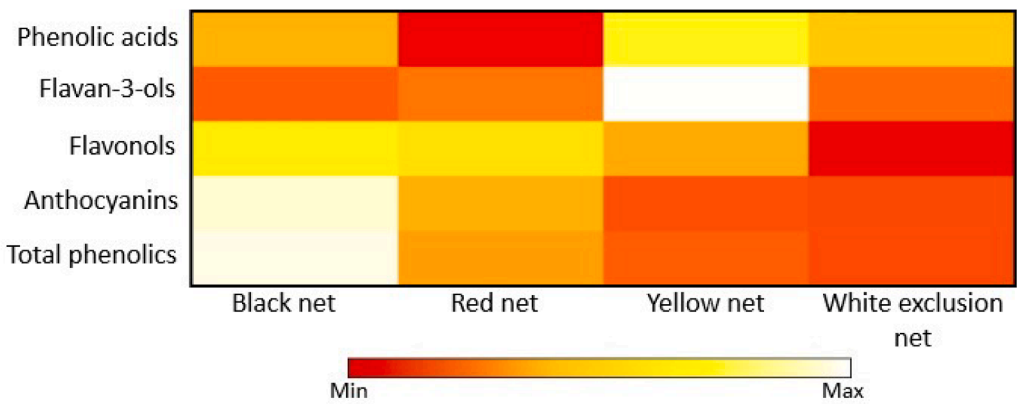


Fig. 6. Heatmap for the content of phenolic acids, flavan-3-ols, flavonols, anthocyanins and total phenolics in blueberry fruit from the black, red, yellow and white exclusion nets at harvest in 2023.

highest values in fruit from the black net (Fig. 7). These results are determined mainly according to the content of glucose and fructose, which are the main sugars in blueberry fruit. Their content is strongly associated with TSS, as they are water-soluble sugars (Li et al., 2016). Our results regarding the glucose and fructose content under different nets contradict the fact that sugar content increases linearly with

increasing PPFD. However, minor differences in PPFD between the nets could explain the above-mentioned discrepancy. According to the results of one study, the response of highbush blueberry plants to modified radiation at the level of individual sugars is strongly cultivar-dependent (Smrke et al., 2021). Photosensitive nets may also affect individual sugars through interfering with the source–sink relationship, resulting

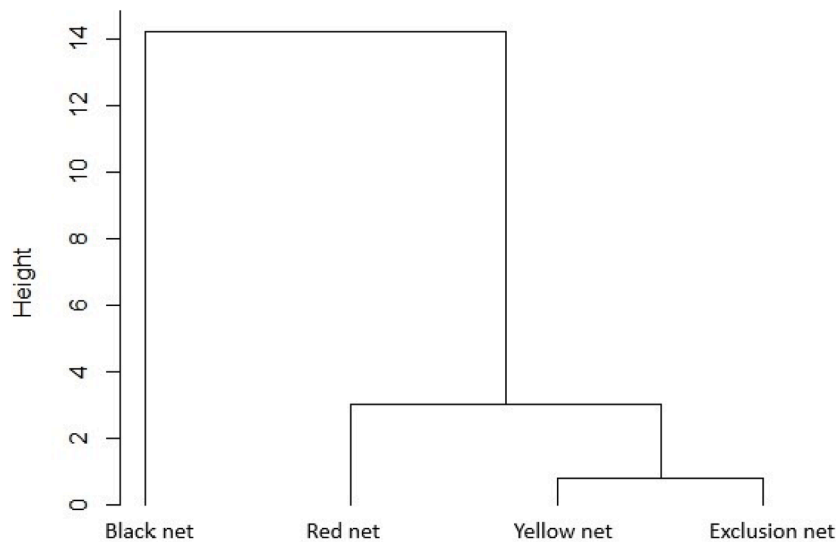


Fig. 7. Dendrogram for total sugars, organic acids and phenolic compounds in blueberry fruit from black, red, yellow and white exclusion nets at harvest 2023, using Ward's method based on Euclidian distances.

from direct (microclimatic conditions, etc.) and indirect (yield, leaf area, canopy density, etc.) effects of nets on plants (Basile et al., 2012).

At harvest, blueberry fruit also differed in the content of organic acids (Table 4). The highest total organic acids were measured in fruit under yellow and white exclusion nets (Fig. 7). The same applies to citric acid, while no significant differences between the nets were measured in tartaric and shikimic acid content. Based on previous reports, it is clear that organic acid content is negatively correlated with the content of sugars (Smrke et al., 2023), which supports the findings of the current study. Our results differ from Nilsson and Gustavsson (2007), who state that an increased amount of light leads to sugar accumulation and organic acid degradation.

Significantly, the highest sugar/organic acid ratio was detected in fruit harvested from plants under the black net and the lowest from the yellow and white exclusion nets (Fig. 5). The ratio between sugars and organic acids determines internal fruit quality, which is crucial for consumer satisfaction. The high sugar/organic acid ratio is determined with high sugar and/or low organic acids and vice versa.

Data are presented as the mean $\pm$ standard error calculated from 5 replicates per treatment. Different letters indicate significant differences between treatments (Tukey's test, $\alpha < 0.05$).

3.6. Phenolic compounds

The content of individual phenolic compounds from each photo-selective net is presented in Supplementary Materials, Table S1, while the totals for each group of phenolics are presented in Fig. 6. The highest content of total phenolics, anthocyanins and all eight identified individual anthocyanins was detected in fruit from the black net. Black nets transmit a higher level of blue light compared to other nets (Ilić et al., 2018), which lead to higher accumulation of phenolic compounds (Buthelezi et al., 2016), especially anthocyanins (Johkan et al., 2010). Individual flavonols were not deemed favorable for specific treatment, due to great variability in their content. Consequently, no significance was determined between different nets in total flavonol content. Among flavan-3-ols, three compounds were identified: procyanidin dimer 1 and 2 and epicatechin. The highest amounts of all three compounds were measured in fruit from the yellow net. The prevailing compound among phenolic acids is chlorogenic acid, followed by neochlorogenic and cryptochlorogenic acids. The other nine compounds present a smaller share of the total content. Maximal content of chlorogenic acid was measured in fruit from yellow and white exclusion nets, while total content was also measured under the black net, where increased neochlorogenic acid was detected. Chlorogenic acid is at the same time found in blueberry wine, meaning that vinification is an appropriate processing approach for blueberry fruit to preserve phenolic compounds (Čakar et al., 2016).

4. Conclusions

This research is the first to examine the effect of photosensitive nets on blueberry 'Bluecrop' fruit ripening, maturity parameters and fruit chemical composition in detail. Regarding the maturity parameter measurements, minor differences between the fruit that were detected at harvest are hard to detect with the naked eye. Therefore, none of the nets was found to be superior based on the fruit's visual appearance. On the other hand, in 2023, the microclimatic conditions under the black net had the most considerable effect on the sugar/organic acid ratio and total phenolics. Regarding the content of total volatiles, fruit harvested from the red net and the control had the highest values in 2022, while no significant difference was detected in 2023. From our results, we can conclude that the black net proved to be the most effective in boosting primary metabolites and phenolics. At the same time, black nets are the most economic among all photosensitive nets, with the longest durability. On the other hand, the results of the volatile compound analysis were inconclusive and not in favor of any specific treatment. The content

of volatile compounds is highly influenced by the environment, which leads to a great inter-annual variability. In this study, we obtained some promising results, together with some ambiguities relating to the effect of each photosensitive net on the content of volatile compounds. Further research is therefore required.

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CRediT authorship contribution statement

Tina Smrke: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Mariana Cecilia Grohar:** Writing – review & editing, Data curation. **Eva Indihar:** Writing – review & editing, Data curation. **Robert Veberic:** Writing – review & editing, Methodology, Conceptualization. **Jerneja Jakopic:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Data Availability Statement

Data sharing is not applicable to this article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scienta.2024.113555](https://doi.org/10.1016/j.scienta.2024.113555).

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