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Photoselective Devices Increased Productivity of Southern Highbush Blueberries (*Vaccinium corymbosum* Interspecific Hybrids)

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***Abstract.* Blueberry is the leading specialty crop in the state of Georgia, USA, with a farm gate value of more than 449 million US dollars. The productivity and development of southern highbush blueberry plants (SHB-*Vaccinium corymbosum* interspecific hybrids L.) were examined under photoselective devices in Georgia, USA, over two growing seasons. The photoselective devices: Opti-Gro and ChromaGro, were tested on two blueberry cultivars, Keecrisp and Meadowlark, alongside grow tubes and an untreated control group. The results revealed that relative to the control group, cultivar Meadowlark, exhibited an average yield increase of 1170% under Opti-Gro and 919% under ChromaGro. Similarly, the 'Keecrisp' exhibited yield increases of 1076% under Opti-Gro and 384% under ChromaGro. In the Opti-Gro treatment, 'Meadowlark' exhibited an increase in height of 15.8 cm, whereas 'Keecrisp' showed a more pronounced increase of 37.34 cm. Similarly, the ChromaGro treatment led to height increases of 15.49 cm for 'Meadowlark' and 39.87 cm for 'Keecrisp' in the 2 years of the study. Net photosynthesis, electron transport rate, and quantum yield of photosystem II were significantly higher in plants under photoselective treatments. In addition, berries harvested from plants under photoselective devices had a larger diameter and total soluble solids in both cultivars. Berries from the cultivar Keecrsip under the ChromaGro treatment had higher anthocyanin concentrations. Overall, this study demonstrates that photoselective devices can significantly enhance the yield, growth, and fruit quality of young blueberry plants by improving photosynthetic capacity. These findings offer a promising strategy for optimizing the establishment and productivity of young blueberry plants in Georgia, USA.**

Blueberries are cultivated worldwide to meet the consumer demand driven by their high antioxidant content and health benefits (Nile and Park 2014; Patel 2014; Schrager et al. 2015; Strik 2005). Environmental factors such as temperature, quality, and quantity of light have significant influences on the development and growth of blueberry plants (Hancock 2006; Retamales and Hancock 2018). The quantity of light measured as photosynthetically active radiation (PAR) determines the rate of photosynthesis, which ultimately affects yield and fruit quality (Lobos et al. 2013; Taiz et al. 2015). Plants have a range of photoreceptors that detect light, resulting in growth signaling and responses. For instance, phytochromes detect red and far-red light, playing a crucial role in regulating processes such as germination, vegetative growth, and photosynthesis (Liu and Van Iersel 2021; McCree 1971; Takano et al. 2009). Cryptochromes and phototropins absorb blue light and are involved in controlling circadian rhythms, flowering, and phototropism (De Wit and Pierik 2016). Light plays an important role in both plant morphogenesis and photosynthesis (Long et al. 2015; Yamori et al. 2016; Zhu et al. 2010). For instance, exposure to red light has been shown to enhance and delay flowering in strawberries (Takeda et al. 2008; Yoshida et al. 2012). Additionally, red light stimulates plant growth by enhancing aboveground biomass accumulation, whereas blue light promotes stomatal opening (Kreslavski et al. 2013). Specifically, in southern highbush blueberries, a higher ratio of red light (60%) to blue light (40%) can significantly improve the net photosynthetic rate (An et al. 2023).

To optimize the quality and quantity of light received by plants, the use of photoselective color nets has become popular across various horticulture crops (Lobos et al. 2013; Serra et al. 2020; Shahak et al. 2006; Tinyane et al. 2013). These nets serve as protective structures that help mitigate the impact of extreme weather events experienced under open-field production (Demchak 2009; Kalcsits et al. 2017; Narjesi et al. 2023). Photoselective nets also can filter solar radiation, hence boosting the efficiency of light-dependent reactions, and the spectral modifications on light quality can stimulate photomorphogenesis (Shahak et al. 2004; Stamps 2009).

The native habitat of blueberry plants is the understory of the forest; thus, the plant is adapted to shaded environments with diffuse light, which is different from open-field commercial production, in which plants are exposed to high levels of solar radiation (Hancock 2006; Retamales et al. 2006; Retamales and Hancock 2018). As a result of these growing conditions, blueberry plants can undergo physiological stress that could affect their plant growth, productivity, and fruit quality (Stamps 2009). In this sense, as an alternative to improve plant growth, Lobos et al. (2013) tested shading nets on northern highbush blueberries (*Vaccinium corymbosum* L. cv. Elliott) and found that net covers influenced growth and productivity. White photoselective nets allowed more light penetration compared with red and black nets, and as the percentage of light increased, flower bud development decreased, but the total number of flower buds and terminal shoots increased. Retamales et al. (2006) also reported that blueberry plants under white, gray, and red color nets had higher yields than plants under black color nets.

Several authors have reported the effect of photoselective nets on diffusion, reflectance, and transmittance of light reaching the plant canopy (Al-Helal and Abdel-Ghany 2010; Ganelevin 2006; Shahak 2014; Sivakumar et al. 2018). However, photoselective devices like Opti-Gro and ChromaGro, which provide a red light–enriched environment within the canopy, have never been tested in blueberry production systems. The walls of these devices are textured in such a way as to diffuse the light in many directions (Opti-Harvest 2024). Diffuse light promotes light distribution within the canopy, maximizing light absorption in the middle leaf layers, increasing radiation-use efficiency, and subsequently enhancing photosynthetic efficiency (Healey et al. 1998; Hemming et al. 2007; Sinclair et al. 1992).

In blueberry production systems, a common practice is the use of grow tubes that are placed right after establishment. Grow tubes are used to protect young plants from herbicide damage also to create an upright canopy structure, favorable for mechanical harvesting (Tarara et al. 2014). Nevertheless, grow tubes have several disadvantages, such as the reduction of root and crown dry weight during the first year of establishment, as well as the reduction of light penetration and photosynthetic rates, factors that limit carbohydrate resources for plant development (Strik et al. 2014; Tarara et al. 2013).

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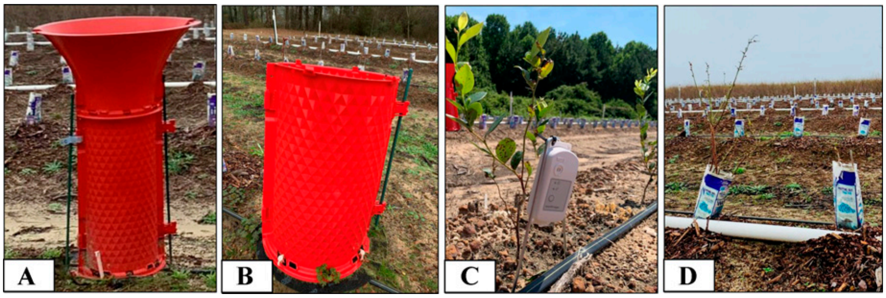

Fig. 1. Treatments applied in research trial conducted in commercial blueberry fields in Alma and Rebecca, GA, USA. (**A**) Opti-Gro. (**B**) ChromaGro. (**C**) Control. (**D**) Grow tube: commercially used cardboard.

Table 1. Monthly growing degree days accumulated in the Opti-Gro, ChromaGro, control, and grow tube treatment during 2022 (Jul and Aug) and 2023 (Mar to Aug).

		Meadowlark				Keecrisp			
Year	Month	Opti-Gro	ChromaGro	Control	Grow tube	Opti-Gro	ChromaGro	Control	Grow tube
2022	Jul	699.81	719.45	684.76	729.54	750.48	791.65	740.37	773.04
2022	Aug	707.19	724.32	705.72	750.95	747.57	758.29	767.85	766.48
2023	Mar	333.69	325.60	311.93	351.78	370.45	388.50	405.66	416.67
2023	Apr	396.39	394.50	375.47	434.03	437.76	470.51	478.65	495.38
2023	May	507.84	536.16	492.47	560.81	541.40	581.35	585.36	605.67
2023	Jun	608.37	653.67	608.39	665.97	630.16	686.44	680.47	697.52
2023	Jul	708.10	749.83	723.60	768.59	746.27	807.55	803.46	812.77
2023	Aug	711.58	730.70	730.73	780.29	734.84	761.98	793.62	791.34

Monthly growing degree days are calculated as follows: [($T_{daily\ max}$ − $T_{daily\ min}$/2) − T_{base}], where T_{base} = 7 °C for southern highbush blueberries.

We hypothesized that the use of photoselective devices in blueberry cultivation could be an alternative to commercially used grow tubes by reducing environmental stress, improving plant establishment, and leading to higher productivity and better fruit quality. Consequently, the aim of this study was to examine the effect of photoselective devices on the morphology, productivity, and fruit quality of Meadowlark and Keecrisp blueberry cultivars.

Materials and Method

Experimental site and design. The research trial was established in 2022 on two different commercial blueberry fields located in Rebecca (31°53′52″N, 83°21′58″W) and Alma (31°39′23″N, 83°35′11″W), Georgia, USA, to evaluate the effectiveness of different photoselective devices and traditional methods. The experiment design used was a randomized complete block, with four treatments: Opti-Gro, ChromaGro, control, and grow tube (commercial cardboard) (Fig. 1). Each replicated five times with five plants per replication. The photoselective devices Opti-Gro (26.7 cm × 101.6 cm) and ChromaGro (31.2 cm × 61.2 cm), provided by Opti-Harvest, Inc. (Los Angeles, CA, USA), were tested on two southern highbush blueberry cultivars (*Vaccinium corymbosum* interspecific hybrids): ‘Meadowlark’ in Rebecca (plants were established in Dec 2020; treatments installed in Jun 2022) and ‘Keecrisp’ in Alma (plants were established in Dec 2021; treatments installed in Jan 2022). Fertilization for ‘Meadowlark’ consisted of applying 168.13 kg·ha^{-1} of N and P and 168.13 kg·ha^{-1} of N–P–K. For ‘Keecrisp’, a rate of 448.34 kg·ha^{-1} of N–P–K, followed by 13N–2P–13K, containing 2% magnesium and 21% sulfur, at 448.34 kg·ha^{-1}.

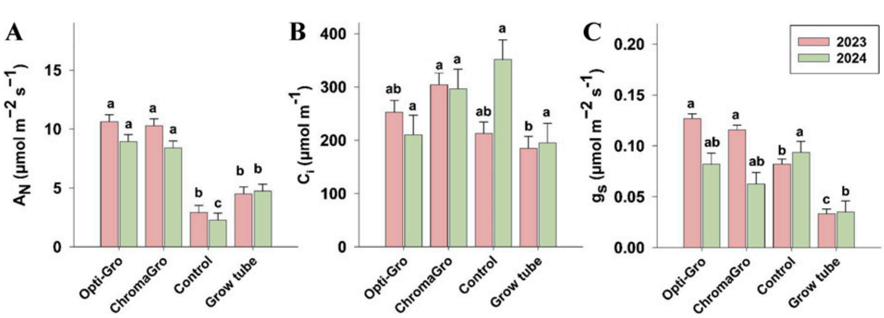

Fig. 2. Effect of Opti-Gro, ChromaGro, control, and grow tube on net photosynthetic rate (**A**), intercellular CO_2 concentration (**B**), and stomatal conductance (**C**), in the Meadowlark cultivar at the Rebecca location in 2023 (pink) and 2024 (green). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey’s honestly significant difference test.

Growing degree days. Three HOBO MX2300 sensors (Onset Computer Corporation, Bourne, MA, USA) were installed per treatment to continuously monitor air temperature and humidity every 5 min in the open field under photoselective devices and other treatments. Data loggers were positioned 10 cm above the ground to protect from rain and waterlogging. Weather data were used to calculate monthly growing degree days (GDDs) (Kovaleski et al. 2015):

$$\Sigma \text{GDD} = [(T_{\max} - T_{\min})/2] - T_{\text{base}}$$

where T_{max} is the maximum daily temperature; T_{min} is the minimum daily temperature; and T_{base} is the base temperature for blueberry (7 °C).

Leaf gas exchange and chlorophyll fluorescence. A portable photosynthesis system (LI-6800; LI-COR, Lincoln, NE, USA) was used to measure net photosynthetic rate (A_N), intercellular CO_2 concentration (C_i), and stomatal conductance (g_s) in Jul 2023 and Apr 2024 on the middle three plants of a replication (n = 15). Steady-state environmental conditions inside the leaf chamber were maintained for each midday measurement under PAR at 1200 μmol·m^{-2}·s^{-1} (average midday saturating light intensities for our location), ambient temperature (25 °C), 60 ± 10% relative humidity, 400 μmol·mol^{-1} CO_2, and 600 μmol·s^{-1} flow rate. Simultaneous chlorophyll fluorescence was measured on the same leaf using a porometer/fluorometer (LI-600N; LI-COR). After recording steady-state values, maximum fluorescence intensity ($F_m{}'$) was determined using a high-intensity multiphase flash, as outlined by Demmig-Adams et al. (1996). Using these chlorophyll fluorescence data, the actual quantum yield of photosystem II (Φ_{PSII}) was derived using the formula by LI-600N [$\Phi_{PSII} = (F_m{}' - F_s)/F_m{}'$]. Furthermore, the electron transport rate (ETR) through photosystem II (PSII) was calculated using the following formula: [ETR = Φ_{PSII} × PAR × 0.84 × 0.5]. In this study, 0.84 represents the typical fraction of incident PAR absorbed by C3 plants, and 0.5 indicates the fraction of absorbed PAR that is specifically used by PSII (Genty et al. 1989; Maxwell and Johnson 2000).

Vegetative measurements and yield. Plant height was measured with a flexible tape, cane diameter was measured using an electronic digital Vernier caliper (Jiavarry, F-20, Fujian, China), and cane numbers were determined by counting the number of canes. The first measurements were recorded in Sep 2022, with subsequent measurements in Apr 2023 and Apr 2024. These measurements were performed on three plants per replication. The same three plants were used to measure yield in the 2023 and 2024 harvest seasons.

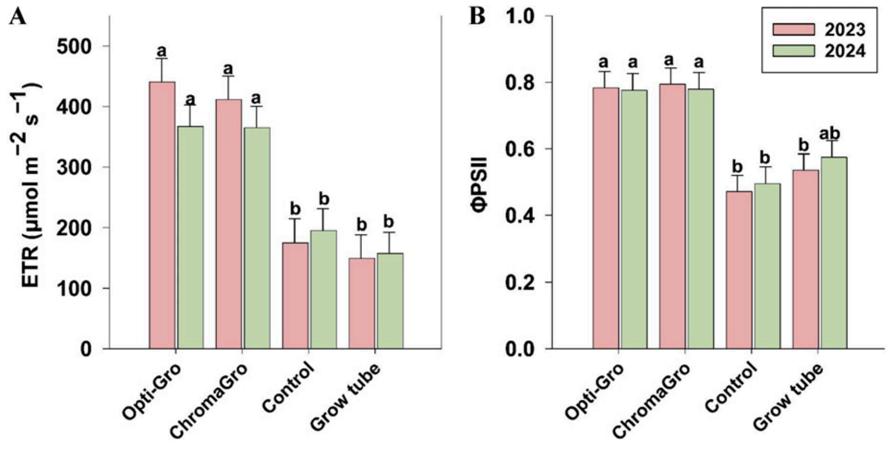

Fig. 3. Effect of Opti-Gro, ChromaGro, control, and grow tube on net electron transport rate (**A**) and the quantum yield of photosystem II (**B**) in the Meadowlark cultivar at the Rebecca location in 2023 (pink) and 2024 (green). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test. ETR = electron transport rate, ΦPSII = photosystem II.

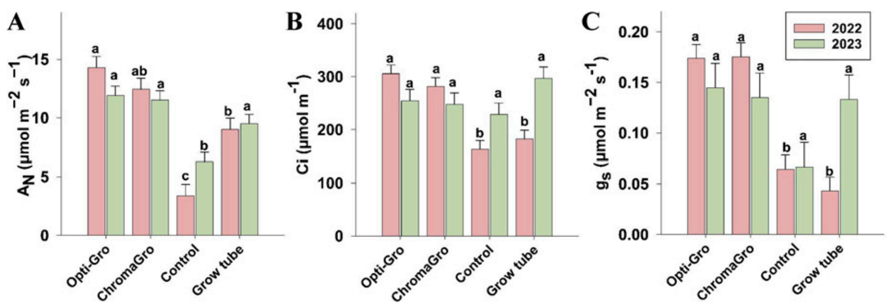

Fig. 4. Effect of Opti-Gro, ChromaGro, control, and grow tube on net photosynthetic rate (**A**), intercellular CO_2 concentration (**B**), and stomatal conductance (**C**) in the Keecrisp cultivar at the Alma location in 2023 (pink) and 2024 (green). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test.

Fruit quality traits. Fruit firmness and diameter were measured on ten berries per treatment per replication using a digital firmness machine (FruitFirm 1000; CVM Inc., Pleasanton, CA, USA). Total soluble solids (TSSs), titratable acidity, and anthocyanin concentration were analyzed using 60-g samples that were blended, homogenized, and centrifuged at 13,855 g_n and 4 °C (Sorvall X4R Pro-MD; Thermo Scientific, Osterode, Germany). The resulting supernatant was collected for further analysis. TSSs were determined by placing an aliquot of blueberry sample on a digital refractometer (model 3810, PAL-1; ATAGO, Tokyo, Japan) with results expressed as a percentage. Titratable acidity was determined by titrating 6 mL of blueberry juice, diluted in 50 mL of deionized water, to a pH of 8.2 using 0.1 mol·L^{-1} NaOH with a titrator (916 Ti-Touch, 915 KF Ti-Touch, and 917 Coulometer with 810 Sample Processor; Metrohm AG, Riverview, FL, USA) with the results expressed as the percentage of citric acid equivalents. Anthocyanin content was determined using a microplate spectrophotometer (Epoch 2; BioTek, Winooski, VT, USA) by the pH differential method outlined by Giusti and Wrolstad (2001). Blueberry juice was mixed with two separate buffers: 0.025 M KCl at pH 1.0 and 0.4 M CH_3COONa at pH 4.5. Absorbance readings were taken at 520 nm and 700 nm, using a blank cell with deionized water as the reference. Anthocyanin concentration (A) was then calculated as outlined below:

$$\text{Total anthocyanin content } (\text{mg}\cdot\text{L}^{-1}): \quad A = \frac{A^{*}\text{MW}^{*}\text{DF}^{*}1000}{\varepsilon^{*}1}$$

where A is ($A_{520\ nm} - A_{700\ nm}$) pH 1.0 − ($A_{520\ nm} - A_{700\ nm}$) pH 4.5, MW is 449.2 (cyanidin-3-glucoside molecular weight), DF is the dilution factor, and ε is 26,900 (molar absorptivity).

Statistical analysis. The data from each trial were analyzed independently using JMP Pro 17 software (SAS Institute Inc., Cary, NC, USA). A one-way analysis of variance was performed to assess the effects of the treatments, with analyses conducted separately for each year. Replications were treated as random effects, whereas treatments were treated as fixed effects. Differences between treatment means were determined using Tukey's honestly significant difference test ($P \leq 0.05$). Graphs were created using SigmaPlot 15.0 (Systat Software Inc., San Jose, CA, USA).

Results

Growing degree days. The GDDs calculated using a base temperature of 7 °C indicated that the ChromaGro and grow tube treatments generally accumulated more GDDs than the control (Table 1). For 'Meadowlark', the grow tube treatment recorded the highest GDDs in Aug 2022 (750.95) and 2023 (780.29), whereas for 'Keecrisp', the grow tube treatment consistently accumulated the highest GDDs, reaching 773.04 in Jul 2022 and 812.77 in Jul 2023 (Table 1).

Gas exchange and chlorophyll fluorescence. The physiological parameters of the two cultivars evaluated in both 2023 and 2024 were significantly influenced by the treatments applied. Specifically, in 'Meadowlark',

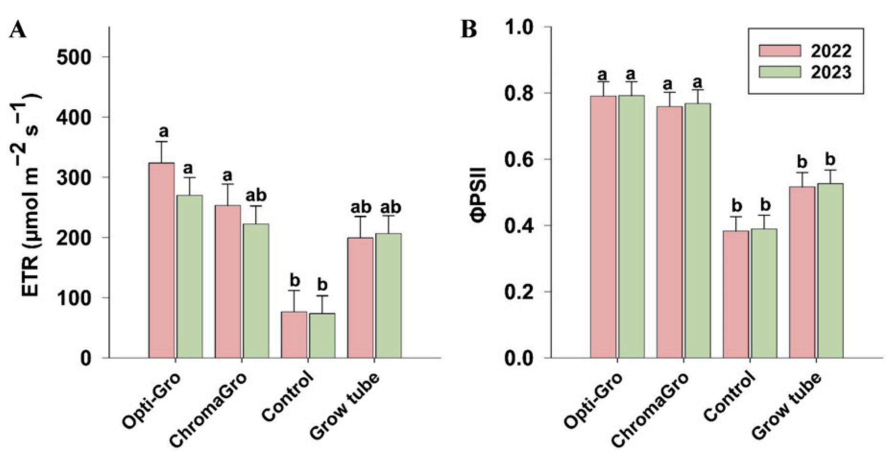

Fig. 5. Effect of Opti-Gro, ChromaGro, control, and grow tube on net electron transport rate (**A**), the quantum yield of photosystem II (**B**) in the Keecrisp cultivar at the Alma location in 2023 (pink) and 2024 (green). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test. ETR = electron transport rate, ΦPSII = photosystem II.

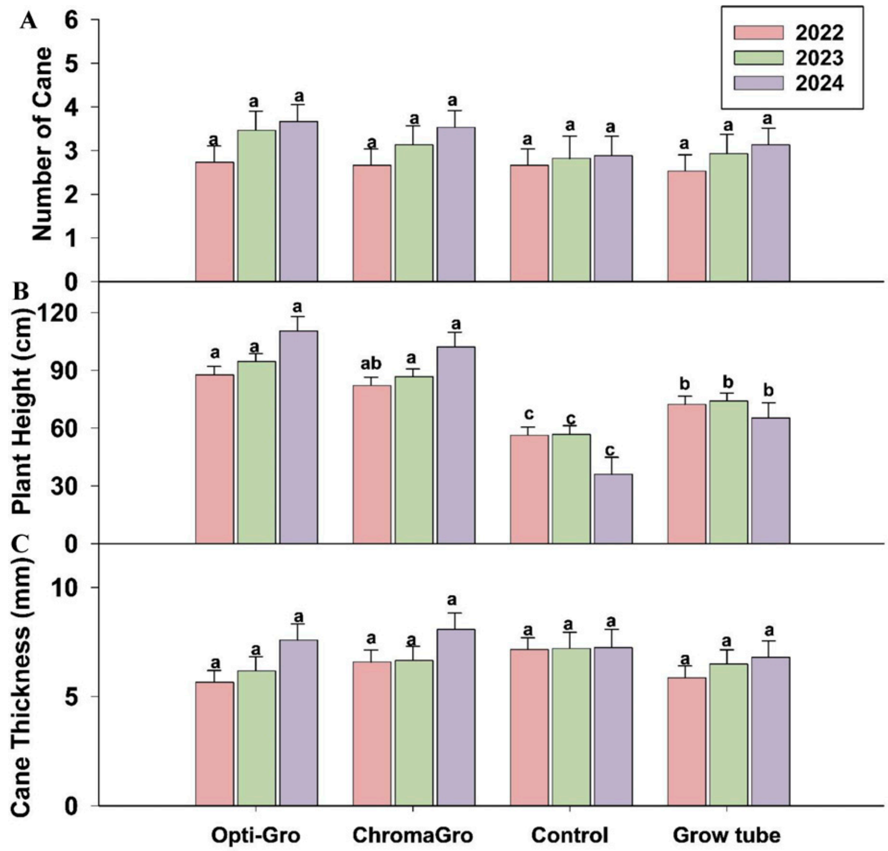

Fig. 6. Effect of Opti-Gro, ChromaGro, control, and grow tube on cane numbers (**A**), plant height (**B**), and average cane diameter (**C**) in the Meadowlark cultivars at the Rebecca location in 2022 (pink), 2023 (green), and 2024 (purple). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test.

both Opti-Gro and ChromaGro treatments consistently resulted in significantly higher net photosynthesis compared with the control and grow tube treatments in both years (Fig. 2A). Intercellular CO_2 concentration was significantly higher in ChromaGro in 2023 compared with the grow tube treatment but showed no difference compared with the control. Additionally, in 2024, no significant differences were found among treatments (Fig. 2B). In 2023, stomatal conductance was significantly higher under Opti-Gro and ChromaGro compared with the grow tube and control treatments. The grow tube treatment exhibited the lowest stomatal conductance in both years (Fig. 2C). The ETR and Φ_{PSII} were also significantly higher in plants under Opti-Gro and ChromaGro treatments in both years compared with the control and grow tube (Fig. 3A, 3B).

'Keecrisp' plants under Opti-Gro and ChromaGro treatments exhibited higher net photosynthesis values compared with the control plants (Fig. 4A). In 2023, plants growing under Opti-Gro and ChromaGro treatment had higher intercellular CO_2 concentration and stomatal conductance compared with control and grow tubes. No differences in intercellular CO_2 concentration and stomatal conductance were obtained in the second year (Fig. 4B, 4C). ETR and Φ_{PSII} were consistently higher in the Opti-Gro and ChromaGro treatments in both years (Fig. 5A, 5B). In 2023, ETR reached 323.58 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in Opti-Gro, compared with 76.69 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in the control.

Vegetative traits. In 2022, no significant differences in cane number and diameter were found for the Meadowlark (Fig. 6A, 6C) and Keecrisp cultivars (Fig. 7A, 7C). In contrast, plant height was significantly affected in both cultivars in 2023 and 2024. However, in 2022, there were significant differences in plant height for the 'Meadowlark' but not for 'Keecrisp' (Figs. 6B and 7B). In 2022, 'Meadowlark' blueberry plants grown under Opti-Gro and ChromaGro had higher plant heights (87.71 and 82.21 cm, respectively) compared with the control (56.32 cm) as shown in Fig. 6B. In 2023 and 2024, both cultivars also had a significant increases in plant height under Opti-Gro and ChromaGro treatments compared with control. 'Meadowlark' plants under the Opti-Gro treatment exhibited an average height increase of 15.8 cm in 2024 (Fig. 6B), whereas 'Keecrisp' plants had a substantial increase of 37.34 cm (Fig. 7B). Similarly, plants under the ChromaGro treatment had an increase in height of 15.49 cm for 'Meadowlark' and by 39.87 cm for 'Keecrisp' in 2024 (Figs. 6B and 7B). In contrast, plants under the control and grow tube treatments had slower growth in the 2 years of the study, which was reflected in their short height (Figs. 6B and 7B).

Productivity and fruit quality traits. In 2023 and 2024, yield was significantly different among the treatments. For the Meadowlark and Keecrisp cultivars, the Opti-Gro and ChromaGro treatments resulted in higher yields compared with the control and the grow tubes treatments in both of the years evaluated (Fig. 8A). In 2024, plants from the Keecrisp cultivar under Opti-Gro treatment outperformed the ChromaGro treatment with 0.059 kg/plant compared with 0.037 kg/plant, respectively (Fig. 8B).

The fruit quality of 'Meadowlark' and 'Keecrisp' was affected differently by treatments. For 'Meadowlark', berries harvested from the ChromaGro treatment had significantly bigger diameters in both years evaluated, whereas the smallest berries were from the grow tube treatment (Table 2). In 2023, total soluble solids were significantly higher in berries collected from Opti-Gro and ChromaGro treatments compared with the grow tube, with ChromaGro yielding the highest value in 2024. Firmness, titratable acidity, and anthocyanin concentration were not significantly affected by treatment in either year for this cultivar (Table 2).

In 2023 and 2024, berries from the Keecrisp cultivar had the highest firmness under the Opti-Gro treatment compared with the control and grow tube (Table 3). The largest berry diameter was obtained from bushes under Opti-Gro, ChromaGro, and grow tube treatments compared with the control in 2023 and 2024. Berries harvested from plants grown with the ChromaGro treatment had significantly higher TSS than the other treatments. Titratable acidity was not significantly different in any of the treatments in both years of the study, whereas the highest anthocyanin concentration was obtained in berries from the ChromaGro treatment in 2023 and 2024 (Table 3).

Discussion

Modulating the light environment is an effective method to control plant architecture and is widely used in horticulture. In the present experiment, the morphological and physiological characteristics of blueberry plants were affected by red light filtered and scattered through photoselective devices. Fruit quality such as berry diameter, TSS, and anthocyanin was enhanced by the use of photoselective devices. Altered light spectra can optimize growth conditions, potentially leading to better yield and quality in blueberry cultivation, as reported for other horticultural crops (Al-Helal and Abdel-Ghany 2010; Ganelevin 2006; Lobos et al. 2013; Retamales et al. 2006; Serra et al. 2020; Shahak 2014; Sivakumar et al. 2018). McCree (1971) first demonstrated that within the 400- to 700-nm PAR spectrum, red light (600 to 700 nm) produces the highest quantum yield for photosynthesis due to the strong

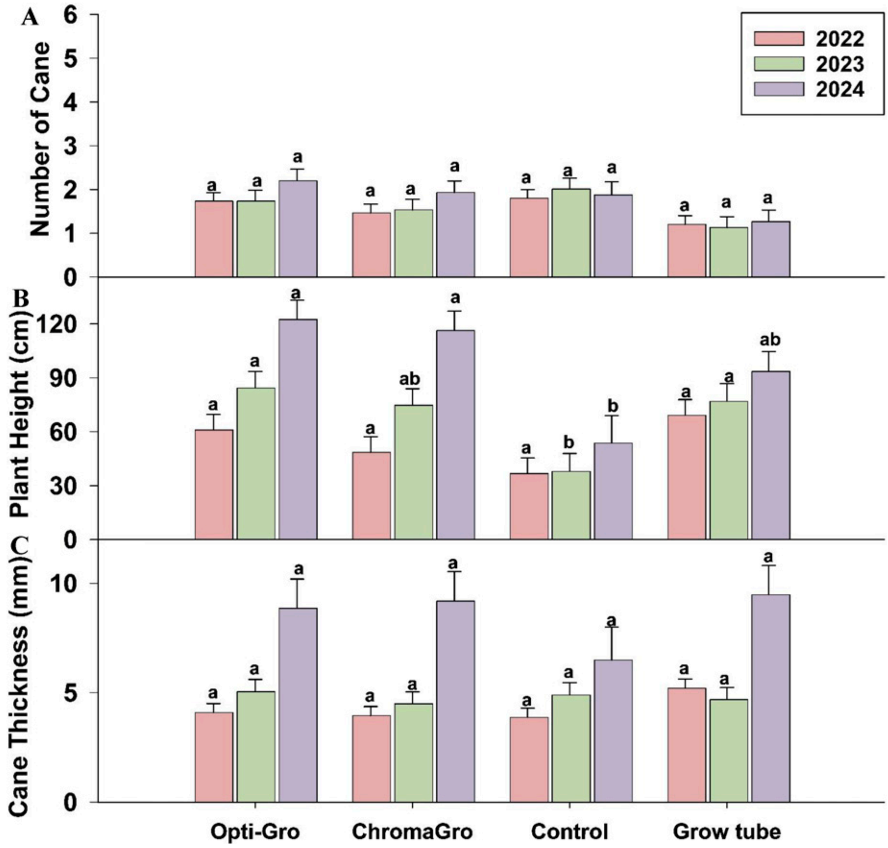

Fig. 7. Effect of Opti-Gro, ChromaGro, control, and grow tube on cane numbers (**A**), plant height (**B**), and average cane diameter (**C**) in the Keecrisp cultivars at the Alma location in 2022 (pink), 2023 (green), and 2024 (purple). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test.

absorption by chlorophyll pigments. Our findings are supported by previous studies indicating that a higher proportion of red light enhances plant growth and photosynthetic efficiency (Hogewoning et al. 2010; Li et al. 2021; Lobos et al. 2012). Efficient absorption optimizes light-harvesting and energy conversion, enhancing photosystem II activity and boosting overall photosynthetic performance (Liu and Van Iersel 2021; McCree 1971; Taiz et al. 2015). Opti-Gro and ChromaGro photoselective devices (red and scattered light) resulted in a higher net photosynthesis rate, electron transport rate, and quantum yield of PSII compared with other treatments due to the higher efficiency of red photons

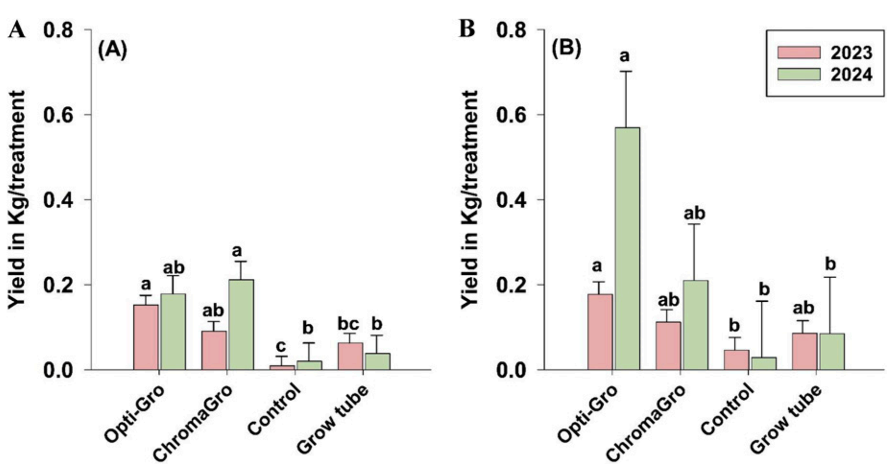

Fig. 8. Effect of Opti-Gro, ChromaGro, control, and grow tube on fruit yield (kg per plant) in Meadowlark (**A**) and Keecrisp (**B**) cultivars at the Rebecca and Alma locations, respectively, in 2023 (pink) and 2024 (green). Bars represent mean value, and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $P \leq 0.05$ based on Tukey's honestly significant difference test.

effectively driving photosynthesis (Inada 1976; Liu and Van Iersel 2021; Lobos et al. 2012; McCree 1971). The red-enriched environment increased the photosynthetic rate of blueberry plants, consistent with Lobos et al. (2012), who reported higher photosynthetic performance of blueberries under low PAR and white and red nets. The combination of red and diffuse light by photoselective devices improved the physiological performance of blueberry plants. Studies have shown that increased light diffusion in greenhouses or tunnels, facilitated by polyethylene materials, enhances photosynthesis and productivity in horticultural crops by converting direct light into diffuse light (Cabrera et al. 2009; Fletcher et al. 2002; Hemming et al. 2008; Jongschaap et al. 2006; Li et al. 2014; Pollet and Pieters 2002; Shahak et al. 2008). Retamal-Salgado et al. (2015), explained that direct radiation tends to lower the quantum yield of photosystem II, which negatively affects photosynthetic efficiency, a trend observed in the present work. Similarly, Kim et al. (2011), found that Φ_{PSII} values fluctuated between 0.2 and 0.7 at different radiation intensities. Φ_{PSII} values were significantly higher in plants subjected to photoselective treatments, demonstrating that these devices effectively mitigate stress caused by excessive radiation. In contrast, the Φ_{PSII} decreased in the control (full sun) and grow tube treatments, which could be a result of a higher degree of photoinhibition (Losciale et al. 2011; Retamal-Salgado et al. 2017).

Blueberry plants cultivated under red photoselective devices for 2 years had significantly higher heights and faster growth rates, indicating that increased red light promotes physiological growth. These morphological changes were consistent with previous findings in which a higher ratio of red light with low light intensity increased plant growth (Li et al. 2023; Liu and Van Iersel 2021; Rehman et al. 2020). Exposure to red light has been shown to significantly promote hypocotyl elongation, cotyledon expansion, and overall height in tomato seedlings (Darko et al. 2014; Thwe et al. 2020). Additionally, red light treatment increases internodal length, leaf area, and stem fresh and dry weight compared with blue and white light treatments (Izzo et al. 2020). It has been reported that red light accelerates internode elongation by inactivating phyB, which induces stem elongation and plant growth due to the activation of pigment proteins and the transduction pathway (Hendricks and Borthwick, 1963; Rehman et al. 2020; Vince 1964). The high efficiency of red light in promoting plant growth is well understood, because its wavelengths align perfectly with the absorption peaks of chlorophylls and phytochromes. Specifically, photoselective devices increased gas exchange parameters, including net photosynthesis and stomatal conductance, resulting in higher carbohydrate accumulation and better plant growth.

Plants grown under photoselective devices had higher yields and larger berry diameters, which could be attributed to the increased net

Table 2. Effect of Opti-Gro, ChromaGro, control, and grow tube on fruit quality parameters, including firmness, berry diameter, total soluble solids, titratable acidity, and anthocyanin concentration in the Meadowlark cultivar during 2023 and 2024.

Year	Treatments	Firmness ($g \cdot mm^{-1}$)	Berry diam (mm)	Total soluble solids (%)	Titratable acidity (%)[i]	Anthocyanin concns ($mg \cdot L^{-1}$)
2023	Opti-Gro	228.6 ± 10 a	16.8 ± 0.2 b	11.3 ± 0.06 a	1.6 ± 0.4 a	321.8 ± 47.9 a
	ChromaGro	262.7 ± 10 a	18.3 ± 0.2 a	11.3 ± 0.06 a	0.8 ± 0.4 a	174.1 ± 47.9 a
	Control	NA[ii]	NA[ii]	NA[ii]	NA[ii]	NA[ii]
	Grow tube	242 ± 10 a	14.8 ± 0.2 c	10.9 ± 0.06 b	2.2 ± 0.4 a	191.3 ± 47.9 a
	P value[iii]	0.1401	0.0001*	0.0038*	0.1104	0.1534
2024	Opti-Gro	245.8 ± 6.5 a	17.1 ± 0.2 b	11.3 ± 0.1 ab	1.6 ± 0.3 a	345.1 ± 38.3 a
	ChromaGro	267.1 ± 6.5 a	18.6 ± 0.2 a	11.5 ± 0.1 a	0.8 ± 0.3 a	320.9 ± 38.3 a
	Control	NA[ii]	NA[ii]	NA[ii]	NA[ii]	NA[ii]
	Grow tube	246 ± 6.5 a	15 ± 0.2 c	11 ± 0.1 b	2.2 ± 0.3 a	200.3 ± 38.3 a
	P value[iii]	0.1379	0.0001*	0.0279*	0.1101	0.121

[i] Titratable acidity is expressed as a percentage of citric acid equivalents.
[ii] NA = no data were recorded due to insufficient berries.
[iii] *P* value for treatment.
The values are presented as the mean ± standard error for each parameter, with comparisons made between treatments. Treatments not sharing a common letter are significantly different at $P \leq 0.05$ based on Tukey's honestly significant difference test. *P* values less than 0.05 are indicated with an asterisk to denote a significant treatment effect.

photosynthesis and growth rate observed. An enhanced photosynthetic activity likely led to greater carbohydrate accumulation, providing the necessary energy and resources to support higher productivity. Consequently, improved carbon assimilation may be a plausible explanation for the yield increase. Thwe et al. (2020) reported that because of red nets, tomato fruit was significantly larger and had greater fresh and dry mass, contributing to a 13% increase in fruit yield. The increased fruit yield observed under photoselective treatments aligns with other studies on apples and blueberries in which white and red photoselective nets also enhanced yield (Brkljača et al. 2016; Lobos et al. 2013; Retamales et al. 2006; Shahak et al. 2008). Fruits from plants grown under photoselective devices had higher TSS content, likely due to enhanced physiological activities under red light and high temperatures. In this sense, Thwe et al. (2020) reported that fruits grown under the red net exhibited higher levels of glucose and fructose and lower acid content, leading to an improved sugar/acid ratio. Results from the current study suggest that red light from photoselective devices promoted fruit size and quality, which also could be attributed to the effect of the light spectrum on carbon assimilation and partitioning.

Anthocyanin biosynthesis is a critical light-dependent process, as highlighted in previous studies (Miao et al. 2016; Sun et al. 2024; Zhang et al. 2018). For instance, light quality affects the skin coloration of apples and pears, with longer wavelengths enhancing red intensity (Feng et al. 2013). Additionally, fruits grown in raised beds with red plastic mulch exhibited 31.32% higher total anthocyanin content compared with those grown on white plastic mulch (Shiukhy et al. 2015). It has also been suggested that anthocyanin accumulation is influenced by ambient air temperature (Zoratti et al. 2015). In the present work, both ChromaGro and grow tubes led to increased growing degree days, indicating higher temperatures, which could be related to the enhanced anthocyanin accumulation. Similarly, other studies have reported that heat and direct sunlight exposure could help mitigate anthocyanin degradation (Marigliano et al. 2022; Reshef et al. 2017). In grapes and strawberries, red light enhances anthocyanin synthesis by activating genes such as PAL and DFR, which are crucial for the flavonoid and anthocyanin biosynthesis pathways (Sun et al. 2024; Zhang et al. 2018). For example, in grapes, supplemental red light significantly increases anthocyanin concentration by modulating gene expression, thereby improving fruit color and antioxidant properties (Sun et al. 2024). Another study on strawberries found that flavonoid and anthocyanin content were significantly increased by red–blue mixed light treatment (Chen et al. 2024). Similarly, in blueberries, red light treatments have been found to increase anthocyanin content through the upregulation of anthocyanin biosynthesis genes and increasing the activities of superoxide dismutase and peroxidase, supporting the enhanced pigmentation observed in this study (Wei et al. 2023).

Table 3. Effect of Opti-Gro, ChromaGro, control, and grow tube on fruit quality parameters, including firmness, berry diameter, total soluble solids, titratable acidity, and anthocyanin concentration in the Keecrisp cultivar during 2023 and 2024.

Year	Treatments	Firmness ($g \cdot mm^{-1}$)	Berry diam (mm)	Total soluble solids (%)	Titratable acidity (%)[i]	Anthocyanin concns ($mg \cdot L^{-1}$)
2023	Opti-Gro	298.4 ± 10 a	17.3 ± 0.3 a	13.7 ± 0.1 c	0.9 ± 0.2 a	488.5 ± 79.8 ab
	ChromaGro	265.6 ± 10 ab	16.1 ± 0.3 a	14.5 ± 0.1 a	0.8 ± 0.2 a	570.6 ± 79.8 a
	Control	243.7 ± 10 b	12.1 ± 0.3 b	14 ± 0.1 b	0.8 ± 0.2 a	271.2 ± 79.8 b
	Grow tube	243.6 ± 10 b	17.3 ± 0.3 a	14.1 ± 0.1 b	0.8 ± 0.2 a	341.2 ± 79.8 ab
	P values[ii]	0.0123*	<0.0001*	<0.0001*	0.0523	0.0284*
2024	Opti-Gro	323.4 ± 10.3 a	17.3 ± 0.4 a	13.8 ± 0.1 b	0.6 ± 0.2 a	427.7 ± 66.5 ab
	ChromaGro	306.9 ± 10.4 ab	15.7 ± 0.4 a	14.68 ± 0.1 a	0.8 ± 0.2 a	569 ± 66.5 a
	Control	230.7 ± 10.4 c	11.3 ± 0.4 b	14.1 ± 0.1 b	1.1 ± 0.2 a	289.5 ± 66.5 b
	Grow tube	268.5 ± 10.3 bc	17 ± 0.4 a	14.1 ± 0.1 b	1.4 ± 0.2 a	335.7 ± 66.5 b
	P values[ii]	0.0017*	<0.0001*	0.0005*	0.0538	0.0202*

[i] Titratable acidity is expressed as a percentage of citric acid equivalents.
[ii] *P* value for treatment.
The values are presented as the mean ± standard error for each parameter, with comparisons made between treatments. Treatments not sharing a common letter are significantly different at $P \leq 0.05$ based on Tukey's honestly significant difference test. *P* values less than 0.05 are indicated with an asterisk to denote a significant treatment effect.

Conclusions

Opti-Gro and ChromaGro significantly enhanced physiological, morphological, and fruit quality traits in the Meadowlark and Keecrisp blueberry cultivars. The installation of photoselective devices during blueberry field establishment can enhance early development and promote significant growth within the first 2 years, thereby supporting subsequent growth and improving blueberry production. However, future research should explore the long-term benefits and economic viability of these devices under different growth conditions.

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