PHOTOSELECTIVE DEVICES AND HARVEST INTERVALS ON BLUEBERRY PRODUCTION AND FRUIT QUALITY

by

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(Under the Direction of Zilfina Rubio Ames and Angelos Deltsidis)

ABSTRACT

This research examines cultural practices to improve the quality, yield, and establishment of young blueberry plants in Georgia. This research investigated the use of photoselective devices (Opti-Gro and ChromaGro) on ‘Meadowlark’ and ‘Keecrisp’ cultivars. These devices improved overall the growth and establishment of young blueberry plants. Asynchronous ripening in blueberries requires multiple harvests to ensure better fruit quality; however, labor shortages and increasing costs have led to mechanical and prolonged harvest intervals, resulting in compromised berry quality for the fresh market. The second part of this thesis addressed these issues by evaluating different harvest intervals on the postharvest quality of southern highbush and rabbiteye blueberries. Results showed that shorter intervals maintained higher firmness and reduced berry damage, while longer intervals increased weight loss and anthocyanin content. Together, these studies provide strategies to optimize blueberry establishment, yield, quality, and storage life through the use of photoselective technologies and optimized harvest timing.

INDEX WORDS: southern highbush, rabbiteye, fruit quality, ripening, photoselective, photosynthesis, harvesting intervals,

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PRODUCTION AND FRUIT QUALITY

by

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BS, Agriculture University Jodhpur, India, 2018

Master’s, The University of Adelaide, Australia, 2021

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2025

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May 2025

DEDICATION

To my sister and niece Richa

To the future of the blueberry industry, with the hope that our research will serve as a valuable resource.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my family for their unwavering support throughout my academic journey. I want to acknowledge my beloved parents, Vimla Devi and Satpal Godara, my aunt and uncle, Indra Devi, and the late Bhoopsingh Godara, for their unconditional love and sacrifices that have shaped my journey and given me the strength to pursue my dreams. My brother, Manish, and sister-in-law, Sonal, I am deeply grateful for your steadfast support and encouragement. Manish Bhai Ji, your guidance and belief in me have been instrumental in shaping my journey. Your constant support has strengthened my determination and given me the confidence to pursue my goals. You have been the foundation of my achievements. I would also like to heartfelt thank my sister, Pinky Choudhary, and Minku, as well as my brothers-in-law, Deepak Phogat and Pardeep Choudhary, also my nephews, Rudranash Phogat and Advait Choudhary. My dear wife, Manisha, your love, patience, and encouragement have been my greatest strength. Your belief in me, through every challenge, has given me the determination to keep going. This achievement is as much yours as it is mine, and I am deeply grateful to have you by my side.

I would like to express my sincere appreciation to my friends, Ved Prakash and Kamalpreet Dhillon, for their exceptional support and assistance throughout my thesis.

I am incredibly grateful to my advisors, Dr. Zilfina Rubio Ames, and Dr. Angelos Deltsidis, for insightful guidance, constant support, and enduring patience. Their scholarly advice and mentorship have been invaluable to the completion of this thesis. I would also like to thank my committee members, Dr. Savithri Nambeesan and Dr. Gerardo Nunez, for their insightful feedback and expertise, which have greatly improved my research.

I would like to acknowledge my lab mates, Orestis Giannopoulos, Ramsey Corn, Lilian Carcamo, and Natalia Espinoza as well as the interns and research scholars, Fabian Reyes, Vinicius Araujo, Marcos Del Masso Fairbanks, Madison Grace Booth, and Karoline Ponder, for their help in harvesting, data collection, and laboratory analysis. A special thank you to Melissa Ann Faulk for her continuous support and help throughout this research.

I would like to acknowledge OptiHarvest and the Georgia Blueberry Commission for funding my research, as well as our grower's cooperation in providing their blueberry fields for this research.

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CHAPTER 1
INTRODUCTION

Environmental factors such as temperature, quality and quantity of light, precipitation, and wind have a significant impact on plant physiology, especially for newly established plants. Severe weather conditions can negatively impact crop production and reduce the economic life of blueberry plantings. Further, fruit quality will not improve after harvest, thus fruit exposed to extreme weather patterns can have a short shelf life and poor quality.

In Georgia, blueberry plants are exposed to high levels of solar radiation during fruit development, and ripening. During the harvest season in Georgia, plants and ripening fruit are exposed to temperatures above 30°C and heavy rainfall, which could be detrimental to fruit quality. Therefore, in this thesis, we evaluated the incorporation of photoselective devices in blueberry production systems and the effect of different harvest intervals on blueberry fruit quality and storability.

It is a common practice to place grow tubes after blueberry planting to protect plants from herbicide and mechanical damage and to create a narrow canopy structure suitable for machine harvest. However, grow tubes reduce light penetration and ventilation, while increasing the temperature inside the grow tube, which can limit photosynthesis. The quantity and quality of light directly affect plant growth and development, and light quantity impacts photosynthetic rates and carbohydrate synthesis. We proposed the use of photoselective devices as an alternative to grow tubes to help alleviate environmental stress and improve plant establishment, productivity, and fruit quality. In this research project, we used two types of photoselective devices (Opti-Gro and ChromaGro) that were placed on two blueberry varieties 'Meadowlark' and 'Keecrisp.' The objective of this research was to provide alternative options to the Georgia blueberry industry to increase the sustainability of blueberry production. The photoselective devices significantly enhanced plant height, photosynthetic efficiency, yield, fruit size, and total soluble solids in both cultivars and increased anthocyanin concentration in ‘Keecrisp.’

The second component of this thesis was to assess the harvest intervals in blueberry fields. Due to a shortage of labor and a high labor cost, the use of mechanical harvesters has been adopted in the last decade. Blueberries are considered ready to pick when the skin is completely blue. However, it is possible for blueberries to be visually similar (100% blue) but have different maturity ages. The variability in the ripeness of blueberries at harvest can affect their postharvest storage potential. Berries that are overripe at harvest are more likely to soften and develop decay during storage. While some studies have shown that delaying harvest (berries remain on the plant after reaching physiological maturity) for short periods of time does not have a significant impact on fruit quality, other studies have shown that it can lead to decreased firmness, increased pulp deterioration, and reduced shelf life due to overripening. In recent years, growers have reported fruit quality issues such as leaking from the stem scar and splitting. Leaking from the stem scar can harbor pathogens, deteriorating the quality of healthy berries. Since the source of this postharvest disorder has not been fully documented, a study to investigate the disorder and its possible causes was proposed. We hypothesized that the use of machine harvest due to the high labor cost might be forcing producers to increase the harvest interval, which could result in poor berry quality. Therefore, to address the effects of harvest intervals on berry’s postharvest quality and storability, this research project laid a baseline to understand the effect of different harvest intervals on the postharvest quality of fresh-market blueberries. The goal was to educate blueberry producers on how delayed harvest impacts fruit quality and storability so that they can make informed decisions during harvest. Our results highlighted that a 7-day interval resulted in lower firmness, higher berry weight loss, and higher leaking fruit and wet sunken berries. Furthermore, intervals of three days between harvests resulted in fruit with higher firmness during storage.

CHAPTER 2
LITERATURE REVIEW

Blueberry Production

Blueberries belong to the *Ericaceae* family, are native to North America, and were domesticated in 1908 (Coville, 1937; Mainland, 2012). The main types of blueberry grown in the United States are Northern Highbush (NHB, *Vaccinium corymbosum* L.), Southern Highbush (SHB, *Vaccinium corymbosum* L. interspecific hybrids) and Rabbiteye (RE, *Vaccinium virgatum* Ait.) (Darrow, 1962). The leading blueberry-producing states in the United States are Oregon, Washington, California, New Jersey, Georgia, Michigan, Florida, and North Carolina (Brazelton, 2023). Georgia accounts for 23% of the total U.S. harvested area (U.S. Department of Agriculture, 2021). In Georgia, two types of blueberries are cultivated, Southern Highbush (SHB) and Rabbiteye. SHB blueberries are harvested from April to early June, which allows producers to obtain better prices for their fruit. Rabbiteye blueberries, are native to Georgia and are harvested from June to July, usually under temperatures over 30°C and continuous rainfall (Lyrene & Sherman, 1979; Retamales & Hancock, 2018).

Blueberry Cultivation

In Georgia, blueberry plants are established on high-raised beds. The high rise beds are amended with pine bark, especially for SHB blueberry plants (Strik, 2007). After planting, growers place grow tubes (commercially used empty milk or juice cartons) around young plants to protect them from wind, pest damage, and herbicide damage (Strik et al., 2014). The placement of grow tubes prevents plant losses after establishment but also creates a microenvironment inside the tube. Grow tubes reduce ventilation, crown and root growth during establishment years, and decrease light penetration leading to reduced photosynthesis (Tarara et al., 2013; Strik et al., 2014). Even though blueberry plants are shade adapted, light below 700 μmol/m^2/s can reduce carbohydrate accumulation leading to low yield and fruit quality (Teramura et al., 1979; Davies and Darnell, 2018).

Light and Light Quality

During photosynthesis, solar energy is converted into chemical energy, which is stored in different plant organs, including fruits. For adequate crop production, the photosynthetic rate must be maintained, and carbohydrate partitioning must be balanced among the growing organs (Taiz & Zeiger, 2010). However, when light intensity exceeds optimal levels,700-800 photosynthetic photon flux (PPF), it can leads to photooxidation and later to photoinhibition in leaf tissue (Teramura et al., 1979; Moon et al., 1987). As a result, the excess light energy can damage the photosynthetic apparatus, particularly Photosystem II (Powles, 1984; Aro et al., 1993; Anderson & Chow, 2002; Krieger-Liszkay, 2005; Roach & Krieger-Liszkay, 2014), reducing the rate of the light reaction and electron transport chain, which can ultimately lead to low CO_2 fixation (Allahverdiyeva & Aro, 2012; Shi et al., 2022). Thus, reducing the growth and productivity of the plant

The growth and development of plants depend on the quantity and quality of light. Plants have a range of photoreceptors that respond to light, such as phytotropins, cryptochromes, and phytochromes (Folta & Maruhnich, 2007). Modifying light quality by enhancing or isolating transmission at specific wavelengths has been demonstrated to influence vegetative growth (Rapparini et al., 1999), reproductive growth (Basile et al., 2008), and fruit quality (Liu et al., 2015; Zhang et al., 2015) in various crops like blueberry, citrus, kiwi, and ornamental crops (Li & Syvertsen, 2006; Retamales et al., 2006; Basile et al., 2008; Lobos et al., 2012; Lobos et al., 2013; Zoratti et al., 2015).

Light quality encompasses different wavelengths such as blue, red, and far-red light. Different light wavelengths trigger various photoreceptors that influence photosynthesis, hormone regulation, and gene expression, thus affecting plant morphology, growth patterns, and reproductive traits (Kinoshita et al., 2001; Wang & Folta, 2013; Cho et al., 2017; Figiel-Kroczyńska et al., 2022; An et al., 2023; Wei et al., 2023). For instance, blue light is known to regulate stomatal opening and leaf morphology, while red and far-red light can modulate stem elongation, flowering, and fruit development (McCree, 1971; Frechilla et al., 2000; Kinoshita et al., 2001; Lincoln Taiz et al., 2015; Son & Oh, 2015). Light quality significantly influences flowering characteristics and plant morphology in blueberries. Blue light enhanced the number of flowers in the 'Misty' cultivar (Cho et al., 2019). Blue light increased chlorophyll content, and anthocyanins concentration, and the photosynthetic rate was significantly higher under a 60% red and 40% blue light ratio (An et al., 2023). Plants grown under red (50%) and blue (50%) light-produced fruits with larger diameters and higher fruit weight (Cho et al., 2017).

Red light enhances fruit quality, fruits grown under red and blue light resulted in higher total soluble solids levels and lower titratable acidity (Cho et al., 2017). Exposure to red light significantly boosted vegetative growth, leading to increased shoot length, accelerated growth rate, and leaf area (An et al., 2023). Red light reduced the juvenile phase in southern highbush blueberries, with seeds achieving over 80% germination within 35 days (Ohishi-Yamazaki et al., 2018). Far-red light (6 $\mu mol\ m^{-2}\ s^{-1}$ and 14 $\mu mol\ m^{-2}\ s^{-1}$) significantly increased leaf area, shoot length, shoot number, and fresh and dry weight of young blueberry plants. However, these treatments reduced chlorophyll content while enhancing electron transport rates (Wang et al., 2024). Far-red light (FR) positively impacted tissue-cultured blueberry transplants acclimated indoors, promoting greater root dry mass and longer root growth, enhancing overall growth in indoor conditions (Gómez et al., 2021). Thus, emerging photoselective technologies offer the potential to optimize light environments, with the aim of manipulating plant growth and development to achieve desirable outcomes.

Photoselective Technology

The manipulation of light quality using photoselective filters or nets has been used in horticultural practices to optimize growth conditions and improve crop yield and quality across a diverse range of horticultural crops (Oren-Shamir et al., 2001; Retamales et al., 2006; Shahak et al., 2008) (Kambalapally & Rajapakse, 1998; Wilson & Rajapakse, 2001; Cerny et al., 2003; Shahak et al., 2004; Ito et al., 2006; Stamps & Chandler, 2006; Ada et al., 2008; Fallik et al., 2008). Thus, using photoselective covers or devices can significantly influence physiological responses and the quality of harvested produce.

Photoselective nets are created by adding chromatic additives and light-dispersive or reflective elements during manufacturing (Shahak et al., 2006). These nets include colored, red, yellow, green, blue, pearl, white, and grey (Shahak et al., 2006). These devices were engineered to filter various solar radiation spectral bands and disperse light (Shahak et al., 2004; Shahak et al., 2006), allowing light to penetrate the inner plant canopy, which can enhance vegetative growth, photosynthetic efficiency, yield, and fruit quality (Retamales et al., 2006; Shahak et al., 2006; Lobos et al., 2008).

Indeed, blue photoselective nets have been shown to enhance the transmission of blue light (400-500 nm) which enhanced chlorophyll levels and shading (45% PAR) improved photosystem II efficiency and the shoot-to-root ratio in citrus (Li & Syvertsen, 2006). In kiwifruit, blue nets increased fruit weight, cane length, fresh weight of pruned canes, and overall yield (Basile et al., 2008). In apples, the results obtained were not all favorable.

Red photoselective nets enhance the transmission of red light (600-700 nm)(Lobos et al., 2012). Peach trees grown under red netting experienced higher yield, flowering, and fruit diameter, and peach and apple trees also resulted in a reduction in canopy temperature (Shahak et al., 2004). Red photoselective nets delay fruit maturation in grapes and increase fruit weight and cane length in kiwifruit (Shahak et al., 2006; Basile et al., 2008). Red and yellow photoselective nets were studied in foliage crop production, these nets increased vegetative growth rates and vigor when compared to black nets (50-80% PAR) and grey nets promote branching and a more compact, bushy growth structure of *Pittosporum variegatum, Fatsia japonica, Monstera deliciosa* (Shahak et al., 2008). Similar studies were conducted on apples, peaches, and table grapes, that showed net-covering was able to reduce heat, chill, and wind stresses, moderate harsh climatic variations, and improve photosynthesis when compared to un-netted orchards (Shahak et al., 2004; Shahak et al., 2008). The different light-filtering properties of each net affected various aspects of the plants, including fruit set, harvest timing (early or late maturity), fruit yield, size, color, internal quality, and overall appearance (Shahak et al., 2008). According to the manufacturer, the photoselective devices used in our research are made of red polymers that filter sunlight. The devices have a certain degree of intrinsic light transmission, hence any light that passes through it is higher than 620nm. Furthermore, any light that is reflected off an inner surface is red-enriched (Opti-Harvest, 2024).

Use of photoselective nets in blueberry

There is no extensive literature on the use of photoselective nets or devices in blueberry production. However, the body of work previously published reported positive outcomes (Retamales et al., 2006; Lobos et al., 2012; Lobos et al., 2013; Smrke et al., 2024). In blueberry production red and white color nets enhance photosynthesis, leading to improved growth and higher yields (Retamales et al., 2006; Lobos et al., 2012; Lobos et al., 2013). The use of white and red shade nets on the highbush blueberry cultivar ‘Miraflores’ increased yield compared to the control without net (Retamales et al., 2006). A study conducted in Michigan using the cultivar ‘Elliot’ reported that the highest yields were found under white and red nets with 50% shading (Lobos et al., 2013). In addition, shading nets of different colors (white, red, and black) and shading percentages were tested in two locations and compared to full sun (control) using the variety ‘Elliot’. The use of white and red nets increased PSII photochemical efficiency (Fv/Fm), total leaf chlorophyll content, and the chlorophyll-to-leaf nitrogen ratio (Lobos et al., 2012).

The study by Smrke et al. (2024), investigated the effects of photoselective netting on the ripening, maturity, and chemical composition of highbush blueberry (*Vaccinium corymbosum* L.) fruit. The results showed that the red net led to the highest total volatile content in 2022. The sugar-to-organic acid ratio varied significantly, being lowest under the yellow net (4.62) and highest under the black net (7.74). Additionally, total phenolics and total anthocyanins levels were highest in fruit grown under the black net, and the lowest levels were observed under the white exclusion net. The use of black net increased yield in ‘Elliott’ blueberries compared to red and white nets. Additionally, fruits under red and white nets showed higher total soluble solids, while black and red nets enhanced fruit firmness compared to the white net (Lobos et al., 2013).

Photoselective nets have been extensively used in different horticulture crops but new technologies such as Opti-Gro and ChromaGro devices have not yet been investigated, thus their effect on plant growth and fruit quality is unknown.

Fruit Development and Ripening

Blueberries experience biochemical changes during ripening, such as softening of the cell walls, increase in total soluble solids, reduced acidity, water loss, and susceptibility to pathogens (Shi et al., 2023). Fruit development in blueberries occurs after pollination and exhibits a double sigmoidal pattern similar to grapes and peaches (Edwards et al., 1970; Darnell et al., 1992; Godoy et al., 2008; Lombardo et al., 2011; Letchov & Roychev, 2017; Heidelbeere et al., 2018). Berry development and ripening in northern highbush can take 42–90 days after bloom, in southern highbush, 55–60 days after bloom, and in rabbiteye, 60–135 days after bloom, depending on the cultivar and environmental factors (Darnell, 2006; Retamales & Hancock, 2018). Three growth stages can be observed in blueberry fruits. Stage I: cell number and dry weight increase. Stage II: seed development takes place; it is also called the lag phase. Stage III: cell enlargement occurs, and ripening is initiated where sugars and anthocyanins accumulate and titratable acidity (TA) decreases (Eck & Childers, 1966; Forney, 2008; Godoy et al., 2008; Retamales & Hancock, 2018). During fruit ripening blueberries experience an asynchronous pattern; thus, berries within a cluster do not ripen at the same time (Gorchov, 1985). Indeed, multiple harvests throughout the season are recommended to harvest the fruit at the optimal maturity stage (Lobos et al., 2014; Strik, 2019). This underlines the importance of adopting harvesting strategies that consider the maturity stage of berry. Berry maturity at harvest plays a significant role in determining the postharvest quality of blueberries (Beaudry et al., 1998; Lobos et al., 2014; Moggia et al., 2017). Thus, harvesting at optimum maturity is crucial to maintain postharvest quality throughout the supply chain.

Harvesting Mechanism

Blueberries have traditionally been harvested by hand to ensure good postharvest quality and shelf life for the fresh market (Gallardo et al., 2018). The high cost of labor and increasing labor shortages make hand harvesting challenging for the blueberry industry (Brown et al., 1996; Rutledge, 2024). The labor costs and shortages challenge faced by the blueberry industry led growers to use machine harvesters (Brown et al., 1996; Clark, 2017). Over the row harvesters (OTR) reduced labor requirements for blueberry operations by 85 to 98% and reduced total production cost by 65% (Brown et al., 1996; Galinato et al.,2016). Despite these advantages, machine harvesting faces challenges related to low harvest efficiency, particularly in fresh-market blueberries, due to significant fruit losses. Further, berries picked by hand consistently exhibit higher quality than berries harvested by machine (Brown et al., 1996; Takeda et al., 2008; Gallardo & Zilberman, 2016). Wei et al. (2019), also reported that machine-harvested blueberries display a reduction in firmness during cold storage compared to handpicked fruit leading to poor shelf life. Van Dalfsen and Gaye (1999) observed a 14–16% reduction in yield when comparing three different rotary machine harvesters to hand-picking 'Bluecrop' in British Columbia, Canada (Van Dalfsen & Gaye, 1999).

The percentage of green fruit loss during machine harvesting of 'Duke' and 'Draper' cultivars in Washington was 8.4% and 17.9%, respectively (DeVetter et al., 2019). In order to mitigate the removal of unripe berries, growers could extend machine harvest intervals. However, this approach can negatively lead to soft berries, and poor postharvest quality, as berries within the clusters ripen at different rates (Olmstead & Finn, 2014). In Florida, machine-harvested southern highbush cultivars averaged 5% soft sort-outs, compared to just 1.3% for hand-picked fruit, illustrating the quality loss due to overripe and soft berries in mechanical harvesting systems (Takeda et al., 2013). Therefore, extending the harvest intervals to avoid yield loss by harvesting green berries results in overmatured berries with short shelf life and poor quality (Moggia et al., 2017). Strik (2019), reported that a 12-day interval reduced fruit firmness by 5–12% compared to the 4-day interval in hand-harvested berries of the cultivars 'Aurora,' 'Bluecrop,' 'Draper,' 'Duke,' 'And Liberty' with the exception of 'Legacy' and 'Ozarkblue'.

Currently, blueberry harvest schedules are primarily determined by a subjective color assessment. This research focuses on evaluating the effect of different hand-harvest picking intervals on the quality and storability of the southern highbush blueberry cultivar ‘Meadowlark’ and rabbiteye cultivar. ‘Brightwell.’. The findings of this research will provide valuable insights into the blueberry industry and help develop more efficient harvesting strategies.

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CHAPTER 3
PHOTOSELECTIVE DEVICES INCREASED PRODUCTIVITY OF SOUTHERN HIGHBUSH BLUEBERRIES (*VACCINIUM CORYMBOSUM* INTERSPECIFIC HYBRIDS)[1]

[1] Amit Godara, Angelos Deltsidis, Zilfina Rubio Ames. 2024. Accepted by HortScience. Presenting here with permission of the authors (all articles published in this journal, copyright is retained by the authors.

Abstract

Blueberry is a leading specialty crop in the state of Georgia, with a farm gate value of more than 449 million US dollars. The productivity and development of southern highbush blueberry plants (*Vaccinium corymbosum* 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, the 'Meadowlark' cultivar exhibited an average yield increase of 1170 % with Opti-Gro and 919 % with ChromaGro. Similarly, the 'Keecrisp' cultivar showed yield increases of 1076.44% for Opti-Gro and 384.23% for ChromaGro. In the Opti-Gro treatment, 'Meadowlark' exhibited a height increase of 15.8 cm, whereas 'Keecrisp' showed a more pronounced increase of 37.34 cm. Similarly, the ChromaGro treatment led to height increases of 15.5 cm for 'Meadowlark' and 39.9 cm for 'Keecrisp' in two years. 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 'Keecrsip' cultivar 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 newly planted blueberries by improving their photosynthetic capacity. These findings offer a promising strategy for optimizing the establishment and productivity of young blueberry plants in Georgia.

KEYWORDS**:** photosynthesis, electron transport rate, photosystem II, quality, anthocyanin concentration.

Introduction

Blueberries are cultivated worldwide to meet the consumer demands driven by their high antioxidant content and health benefits (Strik, 2005; Nile & Park, 2014; Patel, 2014; Schrager et al., 2015). Environmental factors such as temperature, quality, and quantity of light have significant influences on the development and growth of blueberry plants (Hancock, 2006; Retamales & Hancock, 2018). The quantity of light measured as photosynthetically active radiation (PAR) determines the rate of photosynthesis, which ultimately impacts 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 (McCree, 1971; Takano et al., 2009; Liu & Van Iersel, 2021). Cryptochromes and phototropin absorb blue light and are involved in controlling circadian rhythms, flowering, and phototropism (De Wit & Pierik, 2016). Light plays an important role in both plant morphogenesis and photosynthesis (Zhu et al., 2010; Long et al., 2015; Yamori et al., 2016). 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: blue (60:40) light 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 (Shahak et al., 2006; Lobos et al., 2013; Tinyane et al., 2013; Serra et al., 2020). 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 where plants are exposed to high levels of solar radiation (Hancock, 2006; Retamales et al., 2006; Retamales & 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 to 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 that photoselective nets impact the light reaching plants via diffusion, reflectance, and transmittance (Ganelevin, 2006; Al-Helal & Abdel-Ghany, 2010; Shahak, 2012; 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 (Sinclair et al., 1992; Healey et al., 1998; Hemming et al., 2007).

In blueberry production systems a common practice is the use of grow tubes that are placed right after planting, Grow tubes, are used to protect young plants from herbicide damage and 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, the reduction of light penetration and photosynthetic rates, factors that limit carbohydrate resources for plant development (Tarara et al., 2013; Strik et al., 2014).

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 methods

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 and traditional methods. The experiment design used was a randomized complete block (RCBD), 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 x 101.6 cm) and ChromaGro (31.2 cm x 61.2 cm), provided by Opti-Harvest, Inc. (Los Angeles, CA), were tested on two southern highbush blueberry cultivars (*Vaccinium corymbosum* interspecific hybrids), 'Meadowlark' in Rebecca (plants were established in December 2020; treatments installed in June 2022), and 'Keecrisp' in Alma (plants were established in December 2021; treatments installed in January 2022). Fertilization for the 'Meadowlark' cultivar consisted of applying 11-52-0 fertilizer at a rate of 168.13 kg per hectare and 10-10-10 (Super Rainbow) fertilizer at 168.13 kg per hectare. For the 'Keecrisp' cultivar, 13-6-6 was applied at a rate of 448.34 kg per hectare, followed by 13-2-13, containing 2% magnesium and 21% sulfur, at 448.34 kg per hectare.

Growing degree days (GDDs)

Three HOBO data loggers (Onset HOBO MX2300, Bourne, MA) were installed per treatment to continuously monitor air temperature and humidity every five minutes 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 was used to calculate monthly growing degree days (Kovaleski et al., 2015).

$$\Sigma GDD = [(Tmax - Tmin) / 2] - Tbase\}$$

Where:

Tmax: maximum daily temperature

Tmin: minimum daily temperature

Tbase: the base temperature for blueberry (7°C)

Leaf gas exchange and chlorophyll fluorescence

A portable photosynthesis system (Licor-6800, LI-COR, Lincoln NE) was used to measure net photosynthetic rate (A_N), intercellular CO_2 concentration (C_i), and stomatal conductance (*gs*) in July 2023 and April 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 photosynthetically active radiation (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, Lincoln NE). After recording steady-state values maximum fluorescence intensity (F_m') was determined using a high-intensity multi-phase 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 [Φ_{PSII}= (F_m'−F_s)/F_m']. Furthermore, the electron transport rate (ETR) through photosystem II (PSII) was calculated using the formula [ETR = Φ_{PSII} × PAR × 0.84 × 0.5]. Here, 0.84 represents the typical fraction of incident photosynthetically active radiation (PAR) absorbed by C3 plants, and 0.5 indicates the fraction of absorbed PAR that is specifically utilized by PSII (Genty et al., 1989; Maxwell & Johnson, 2000).

Vegetative measurements and yield

Plant height was measured with a flexible tape, cane diameter using an electronic digital Vernier caliper (Jiavarry, 20-F, China), and cane numbers by counting the number of canes. The baseline measurements were recorded in September 2022, with subsequent measurements in April 2023 and April 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.

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.- 7066-D Commerce Circle. Pleasanton, CA). Total soluble solids (TSS), titratable acidity (TA), and anthocyanin concentration were analyzed using 60 g samples that were blended, homogenized, and centrifuged at 9000 RPM and

4°C (Sorvall X4R Pro-MD, Thermo Scientific, Osterode, Germany). The resulting supernatant was collected for further analysis. Total soluble solids (TSS) were determined by placing an aliquot of blueberry sample on a digital refractometer (ATAGO, PAL-1, Model 3810, Japan) with results expressed as a percentage. Titratable acidity (TA) 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, FL) and result expressed as % citric acid equivalents. Anthocyanin content was determined using a microplate spectrophotometer (BioTek, Epoch 2, 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 potassium chloride (KCl) at pH 1.0 and 0.4 M sodium acetate (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.

Total Anthocyanin content (mg·L^{-1}): $A = \frac{A*MW*DF*1000}{\varepsilon*1}$

Where: A= (A520 nm - A700 nm) pH 1.0 – (A520 nm - A700 nm) pH 4.5

MW: 449.2 (cyanidin-3-glucoside molecular weight)

DF: dilution factor

Ɛ: 26,900 (molar absorptivity)

Statistical analysis

The effect of the treatments was estimated by a one-way ANOVA. The statistical analysis of data was performed with the JMP pro 17 software (SAS Institute Inc., Cary, NC, USA) with comparisons made between treatments, and analyses conducted separately for each year. Means were separated using Tukey's HSD test ($P \leq 0.05$). Graphs were generated using SigmaPlot 15.0 (Systat Software Inc., San Jose, CA).

Results

Growing degree days (GDDs)

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 but less than the Grow tube (Table 1). For ‘Meadowlark,’ the grow tube treatment recorded the highest GDDs in August 2022 (750.95) and 2023 (780.29), while for ‘Keecrisp,’ the grow tube treatment consistently accumulated the highest GDDs, reaching 773.04 in July 2022 and 812.77 in July 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’, both Opti-Gro and ChromaGro treatments consistently resulted in significantly higher net photosynthesis compared to the control and grow tube treatments in both years (Fig. 2A). Intercellular CO_2 concentration was significantly higher in ChromaGro in 2023 compared to the grow tube treatment but showed no difference compared to 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 to the grow tube and control treatments. The grow tube treatment exhibited the lowest stomatal conductance in both years (Fig. 2C). The electron transport rate (ETR) and Quantum yield of photosystem II (ΦPSII) were also significantly higher in plants under Opti-Gro and ChromaGro treatments in both years compared to the control and grow tube (Fig. 3A, 3B).

In ‘Keecrisp’ plants under Opti-Gro and ChromaGro treatments exhibited higher net photosynthesis values compared to the control (Fig. 4A). In 2023, plants growing under Opti-Gro and ChromaGro treatment had higher Intercellular CO_2 concentration and stomatal conductance compared to 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 ΦPSII were consistently higher in the Opti-Gro and ChromaGro treatments in both years (Fig. 5A, 5B). In 2023, ETR reached 323.58 $\mu mol\ m^{-2}\ s^{-1}$ in Opti-Gro, compared to 76.69 $\mu mol\ m^{-2}\ s^{-1}$ 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' (Fig. 6B,7B). In 2022, 'Meadowlark' blueberry plants grown under Opti-Gro and ChromaGro had higher plant heights (87.71 and 82.21 cm, respectively) compared to the control (56.32 cm) as shown in Fig. 6B. In 2023 and 2024 both cultivars also had a significant increase in plant height under Opti-Gro and ChromaGro treatments compared to control. 'Meadowlark' plant under the Opti-Gro treatment exhibited an average height increase of 15.8 cm in 2024 (Fig. 6B), while '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 (Fig. 6B, 7B). Contrary, plants under the control and grow tube treatment had slower growth in the two years of the study, which was reflected in their short height (Fig. 6B, 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 to 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 to 0.037 kg/plant, respectively (Fig. 8B).

The fruit quality of the ‘Meadowlark’ and ‘Keecrisp’ blueberry cultivars was differently influenced by treatments. For ‘Meadowlark’, berries harvested from the ChromaGro treatment had significantly bigger diameters in both years evaluated, while 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 to 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 to the control and grow tube (Table 3). The largest berry diameter was obtained from bushes under Opti-Gro, ChromaGro, and grow tube treatments compared to 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, while 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 traits such as berry diameter, TSS, and anthocyanin were enhanced by the use of ChromaGro. This confirms that altered light spectra can optimize growth conditions, potentially leading to better yield and quality in blueberry cultivation, as reported for other horticultural crops

(Ganelevin, 2006; Retamales et al., 2006; Al-Helal & Abdel-Ghany, 2010; Shahak, 2012; Lobos et al., 2013; Sivakumar et al., 2018; Serra et al., 2020). McCree (1971), first demonstrated that within the 400–700 nm photosynthetically active radiation (PAR) spectrum, red light (600–700 nm) produces the highest quantum yield for photosynthesis due to the strong absorption by chlorophyll pigments. This finding is supported by subsequent studies, which indicate that a higher proportion of red light enhances plant growth and photosynthetic efficiency (Hogewoning et al., 2010; Lobos et al., 2012; Li et al., 2021). This efficient absorption optimizes light-harvesting and energy conversion, enhancing photosystem II activity and boosting overall photosynthetic performance (McCree, 1971; Taiz et al., 2015; Liu & Van Iersel, 2021). In the present work, 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 to other treatments due to the higher efficiency of red photons effectively driving photosynthesis (McCree, 1971; Inada, 1976; Lobos et al., 2012; Liu & Van Iersel, 2021). 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 (Fletcher et al., 2002; Pollet & Pieters, 2002; Jongschaap et al., 2006; Hemming et al., 2008; Shahak et al., 2008; Cabrera et al., 2009; Li et al., 2014). Retamal et al. (2015), explained that direct radiation tends to lower the quantum yield of photosystem II, which negatively impacts 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. In the present work, 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 quantum yield of photosystem II (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 et al., 2017).

Blueberry plants cultivated under red photoselective devices for two years had significantly greater 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 (Rehman et al., 2020; Liu & Van Iersel, 2021; Li et al., 2023). 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 distance, leaf area, and stem fresh and dry weight compared to 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 & Borthwick, 1963; Vince, 1964; Rehman et al., 2020). The high efficiency of red light in promoting plant growth is well understood, as its wavelengths align perfectly with the absorption peaks of chlorophylls and phytochromes. Specifically, photoselective devices increased gas exchange parameters, including net photosynthesis, intercellular CO_2 concentration, and stomatal conductance, resulting in higher carbohydrate accumulation and better plant growth.

Plants grown under photoselective devices had higher yield and larger diameter, which could be attributed to the increased net 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 as a result of red nets, fruits were 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, where white and red photoselective nets also enhanced yield (Retamales et al., 2006; Shahak et al., 2008; Lobos et al., 2013; Brkljača et al., 2016). 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 may 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 numerous studies (Miao et al., 2016; Zhang et al., 2018; Sun et al., 2024). 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 to 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. In this sense, several authors have indicated that heat and direct sunlight exposure could help mitigate anthocyanin degradation (Reshef et al., 2017; Marigliano et al., 2022). 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 (Zhang et al., 2018; Sun et al., 2024). 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 (RBL) 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 (SOD) and peroxidase (POD), supporting the enhanced pigmentation observed in this study (Wei et al., 2023).

Conclusion

In summary, Opti-Gro and ChromaGro significantly enhanced physiological, morphological, and fruit quality traits in ‘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 two 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.

Acknowledgments

We express our sincere gratitude to the growers on the commercial blueberry farms in Georgia for providing the research sites and supporting the study. Special thanks to Dr. Zhiheng Xing and Dr. Jakeline Zuluaga Acosta for reviewing and editing the manuscript.

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Table 3.1 Monthly growing degree days (GDDs) accumulated in the Opti-Gro, ChromaGro, control, and grow tube treatment during 2022 (July and August) and 2023 (March to August).

		'Meadowlark'				'Keecrisp'			
Year	Month	Opti-Gro	ChromaGro	Control	Grow tube	Opti-Gro	ChromaGro	Control	Grow tube
2022	July	699.81	719.45	684.76	729.54	750.48	791.65	740.37	773.04
2022	August	707.19	724.32	705.72	750.95	747.57	758.29	767.85	766.48
2023	March	333.69	325.60	311.93	351.78	370.45	388.50	405.66	416.67
2023	April	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	June	608.37	653.67	608.39	665.97	630.16	686.44	680.47	697.52
2023	July	708.10	749.83	723.60	768.59	746.27	807.55	803.46	812.77
2023	August	711.58	730.70	730.73	780.29	734.84	761.98	793.62	791.34

Monthly GDDs are calculated as GDDs = $[(T_{\text{daily max}} - T_{\text{daily min}}/2) - T_{\text{base}}]$. T_{base} = 7°C for southern highbush blueberries.

Table 3.2.Effect of Opti-Gro, ChromaGro, control and grow tube on fruit quality parameters, including firmness ($g \cdot mm^{-1}$), berry diameter (mm), total soluble solids (TSS, %), titratable acidity (TA, percentage of citric acid equivalents), and anthocyanins concentration ($mg\ L^{-1}$) in the 'Meadowlark' cultivar during 2023 and 2024. Values are presented as mean ± standard error (SE) for each parameter, with comparisons made between treatments within a given year. Treatments not sharing a common letter are significantly different at $p \leq 0.05$ based on Tukey's HSD test. P-values less than 0.05 are indicated with an asterisk to denote a significant treatment effect.

Year	Treatments	Firmness ($g \cdot mm^{-1}$)	Berry diameter (mm)	Total soluble solids [iii]	Titratable acidity [iv]	Anthocyanins concentration [V]
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*-values[i]**	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*-values[i]**	0.1379	0.0001*	0.0279*	0.1101	0.121

[i] *P*-value for treatment.

[ii] no data was recorded due to insufficient berries.

[iii] Total soluble solid expressed as (%).

[iv] Titratable acidity expressed as percentage citric acid equivalents.

[V] Anthocyanins concentration expressed as $mg \cdot L^{-1}$.

Table 3.3. Effect of Opti-Gro, ChromaGro, control and grow tube on fruit quality parameters, including firmness (g·mm⁻¹), berry diameter (mm), total soluble solids (TSS, %), titratable acidity (TA, percentage of citric acid equivalents), and anthocyanin concentration (mg L^{-1}) in the 'Keecrisp' cultivar during 2023 and 2024. Values are presented as mean ± standard error (SE) for each parameter, with comparisons made between treatments within a given year. Treatments not sharing a common letter are significantly different at $p \leq 0.05$ based on Tukey's HSD test. P-values less than 0.05 are indicated with an asterisk to denote a significant treatment effect.

Year	**Treatments**	**Firmness (g·mm^{-1})**	**Berry diameter (mm)**	**Total soluble solids** [ii]	**Titratable acidity** [iii]	**Anthocyanins concentration** [iv]
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**[i]	0.0123*	<.0001*	<.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**[i]	0.0017*	<.0001*	0.0005*	0.0538	0.0202*

[i] *P*-value for treatment.

[ii] Total soluble solid expressed as (%).

[iii] Titratable acidity expressed as percentage citric acid equivalents.

[iv] Anthocyanins concentration expressed as mg·L^{-1}.

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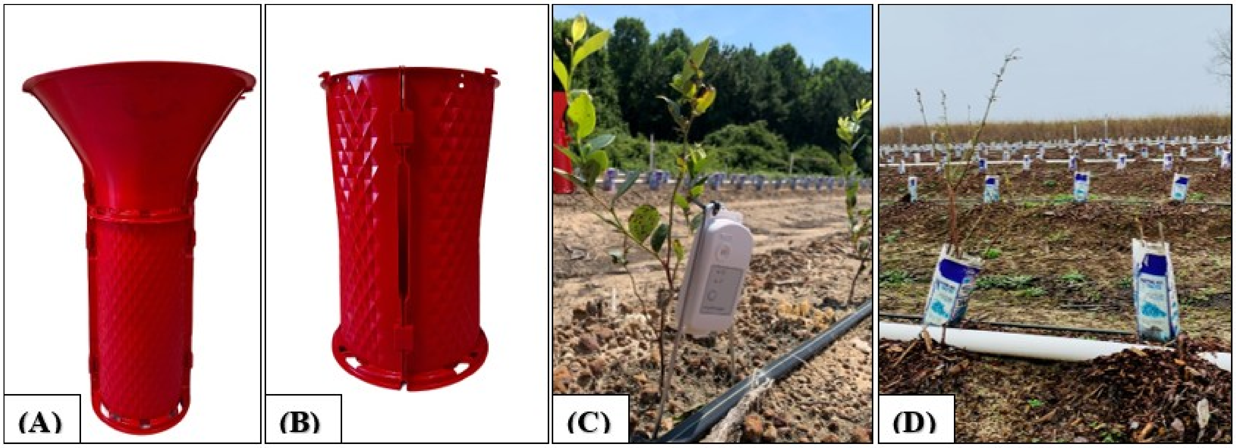

Figure 3.1. Treatments applied in research trial conducted in commercial blueberry fields in Alma and Rebecca, Georgia, USA. Opti-Gro (A), ChromaGro (B), Control (C), and Grow tube: commercially used cardboard (D).

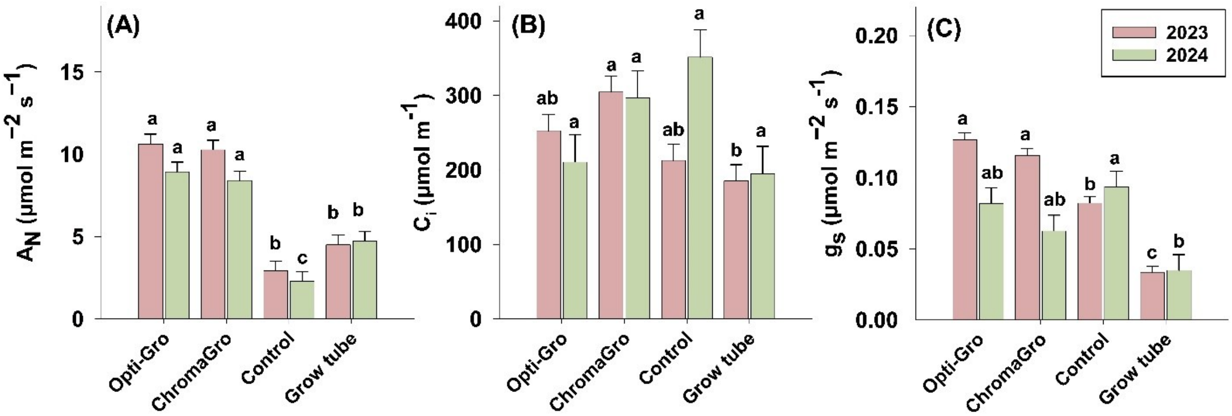

Figure 3.2. Effect of Opti-Gro, ChromaGro, control and grow tube on net photosynthetic rate (A), intercellular CO2 concentration (B), and stomatal conductance (C), in the 'Meadowlark' cultivar at the Rebecca location in 2023 (light pink) and 2024 (green). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at p ≤ 0.05 based on Tukey's HSD test.

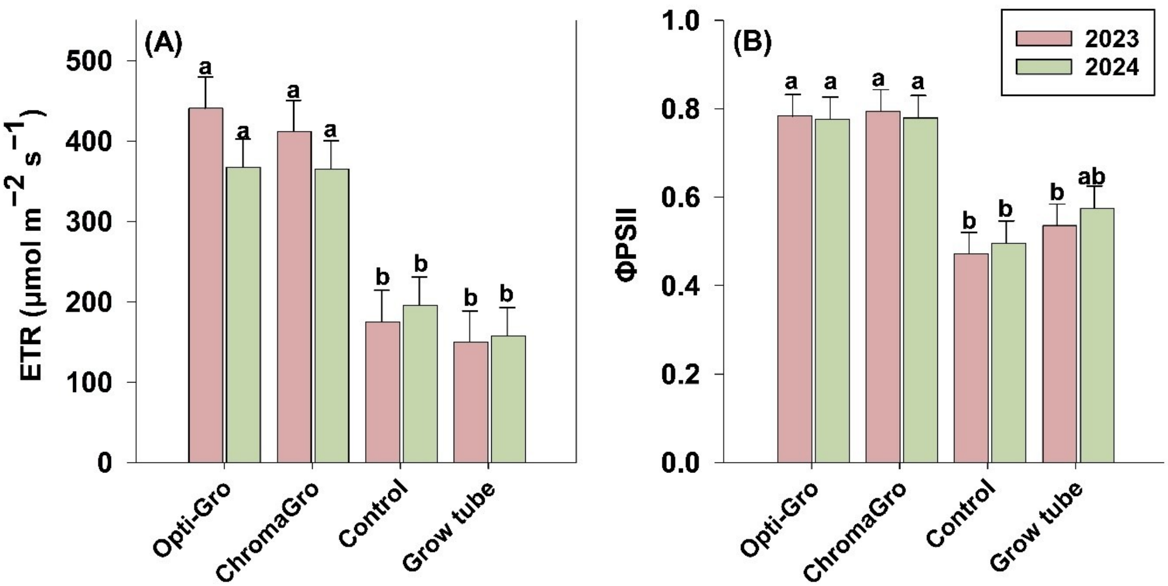

Figure 3.3. Effect of Opti-Gro, ChromaGro, control and grow tube on net electron transport rate (A), the quantum yield of photosystem II (B), in the 'Meadowlark' cultivar at the Rebecca location in 2023 (light pink) and 2024 (green). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

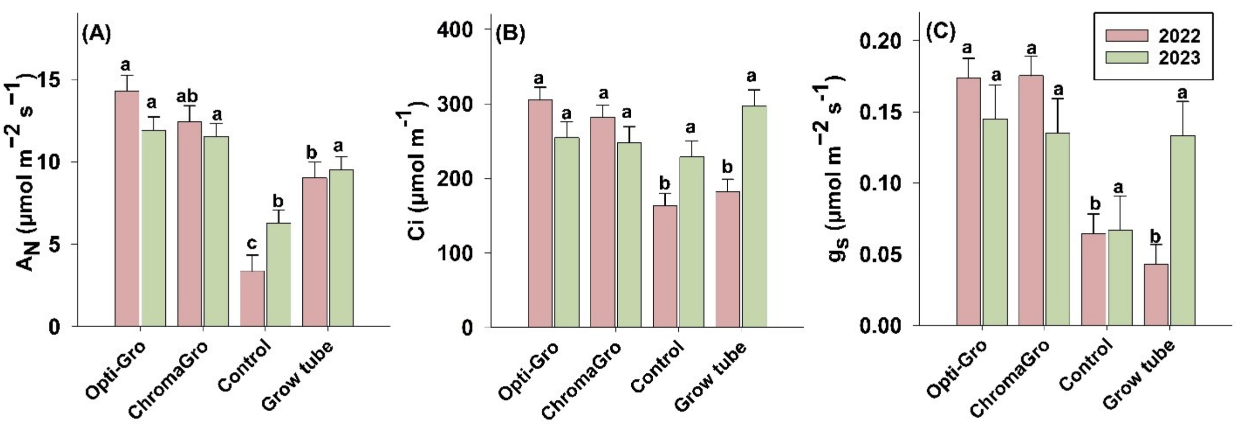

Figure 3.4. Effect of Opti-Gro, ChromaGro, control and grow tube on net photosynthetic rate (A), intercellular CO2 concentration (B), and stomatal conductance (C), in the 'Keecrisp' cultivar at the Alma location in 2023 (light pink) and 2024 (green). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

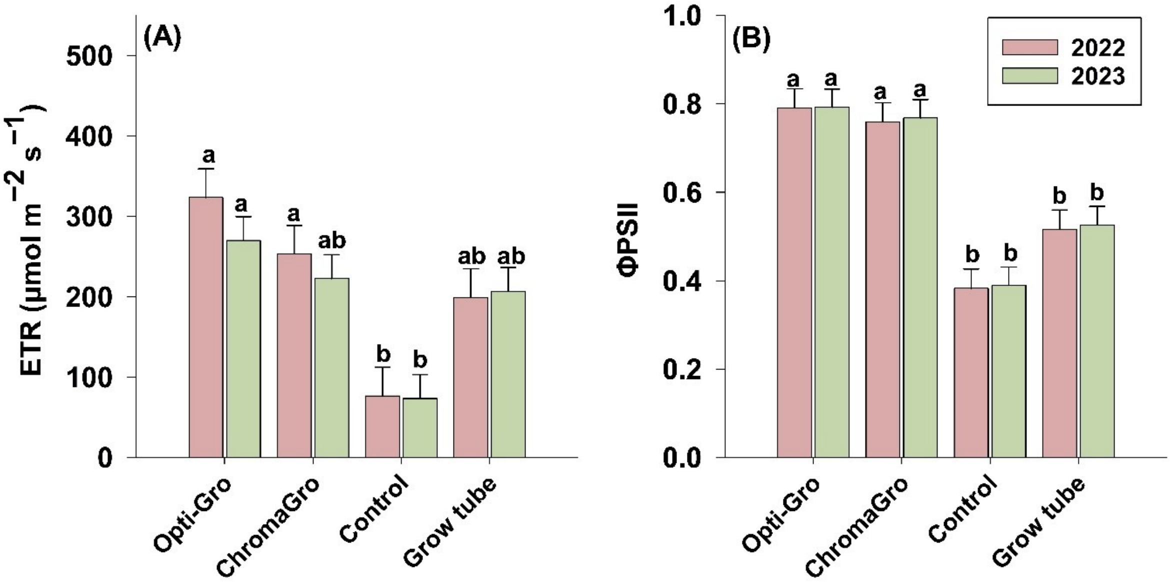

Figure 3.5. Effect of Opti-Gro, ChromaGro, control and grow tube on net electron transport rate (A), the quantum yield of photosystem II (B), in the 'Keecrisp' cultivar at the Alma location in 2023 (light pink) and 2024 (green). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

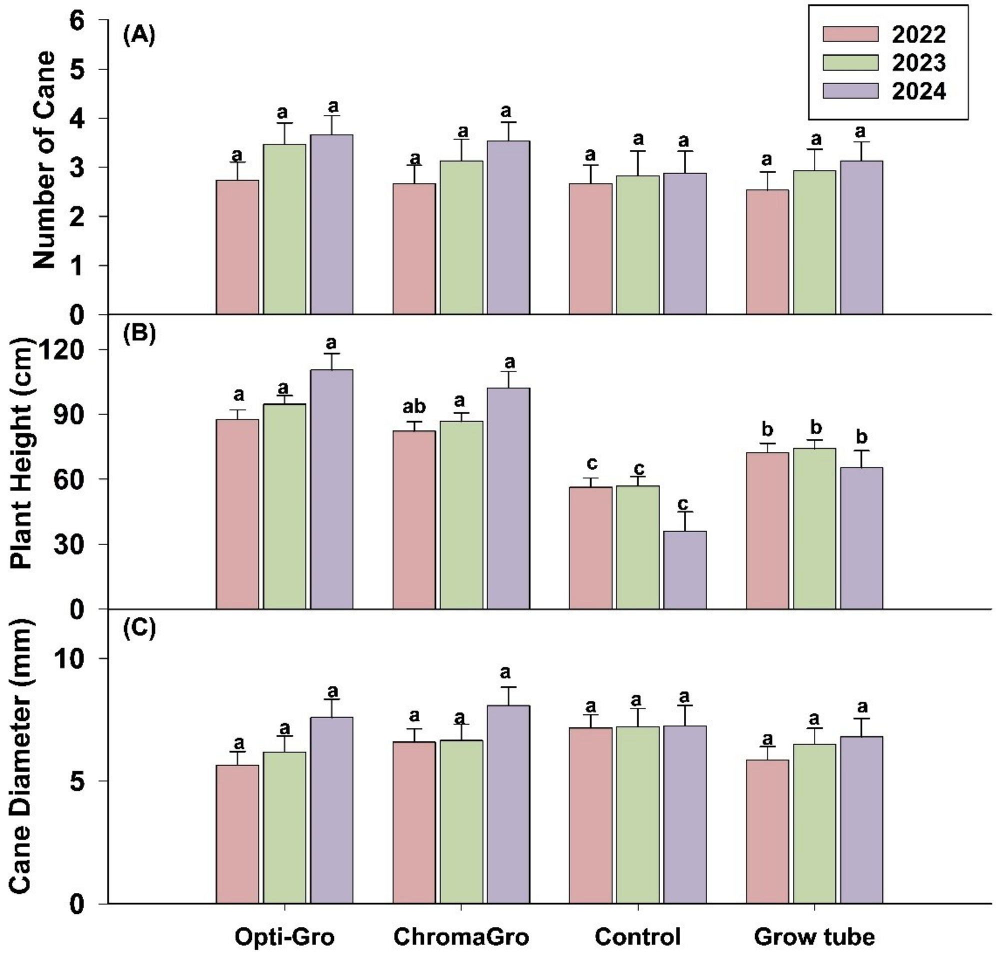

Figure 3.6. Effect of Opti-Gro, ChromaGro, control and grow tube on cane numbers (A), plant height (B), and average cane diameter (C) in the 'Meadowlark' cultivars at the Rebecca location in 2022 (light pink), 2023 (green), and 2024 (purple). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

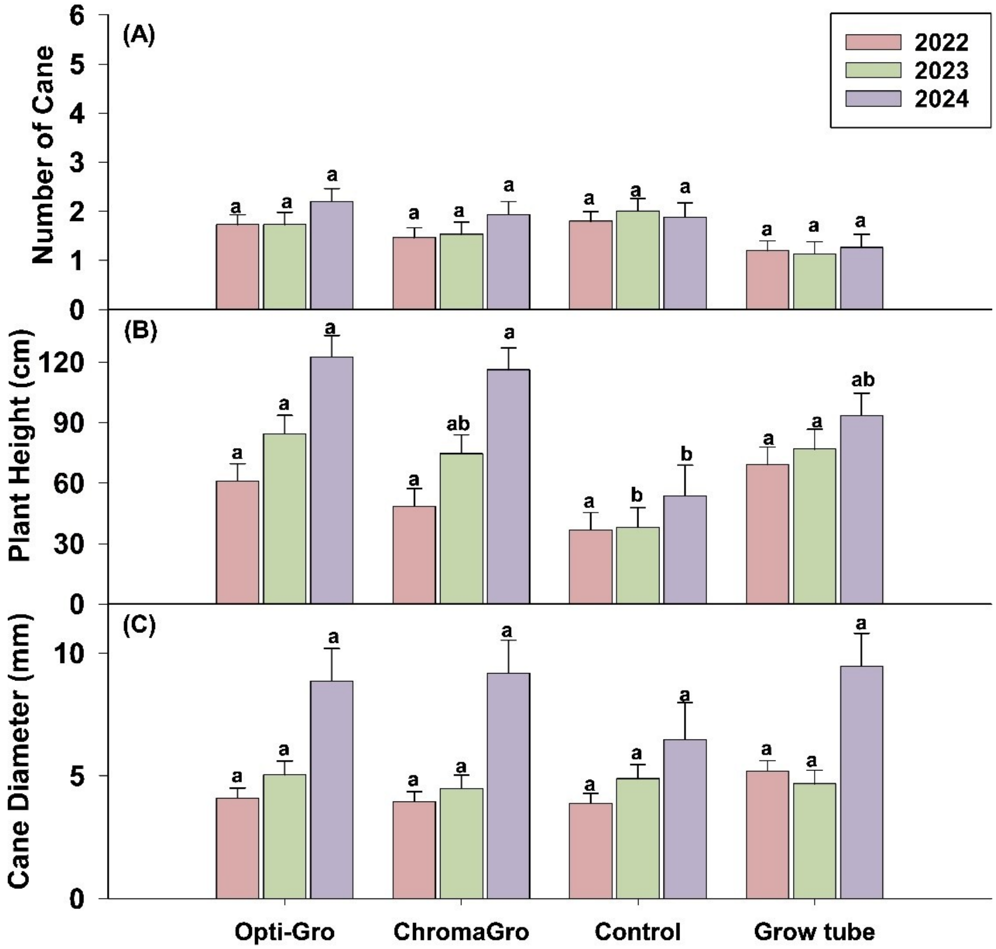

Figure 3.7. Effect of Opti-Gro, ChromaGro, control and grow tube on cane numbers (A), plant height (B), and average cane diameter (C) in the 'Keecrisp' cultivars at the Alma location in 2022 (light pink), 2023 (green), and 2024 (purple). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

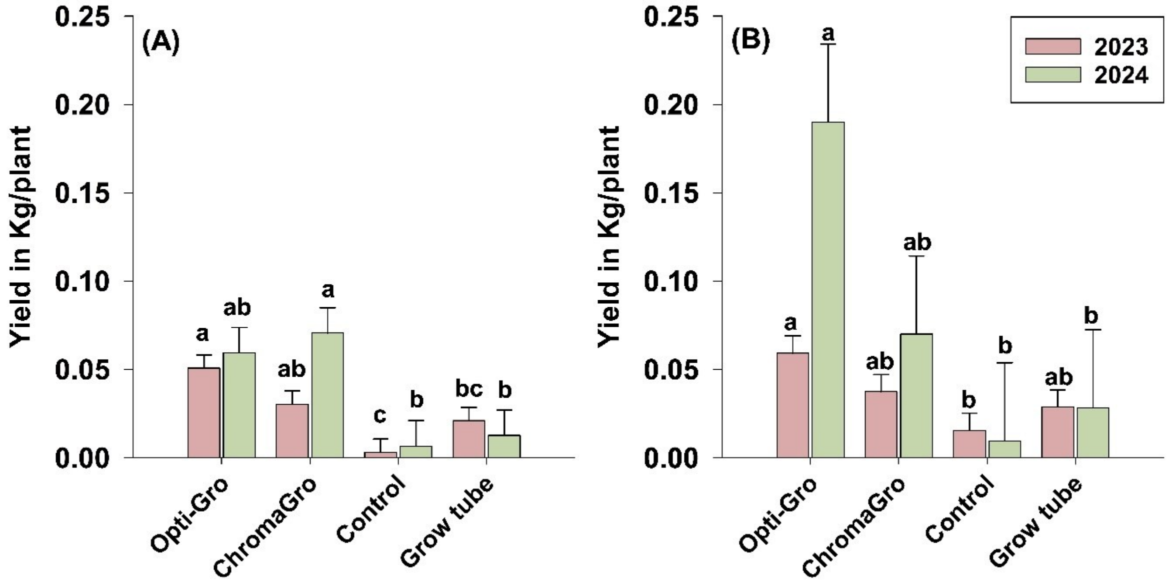

Figure 3.8. Effect of Opti-Gro, ChromaGro, control and grow tube on fruit yield (kg/plant) in 'Meadowlark' (A) and 'Keecrisp' (B) cultivars at the Rebecca and Alma locations, respectively in 2023 (light pink) and 2024 (green). Bars represent mean value and error bars represent standard error with comparisons made between treatments within a given year. Different letters indicate significance at $p \leq 0.05$ based on Tukey's HSD test.

CHAPTER 4
DELAYED HARVEST REDUCES POSTHARVEST QUALITY AND STORABILITY OF SOUTHERN HIGHBUSH CV. ‘MEADOWLARK’ AND RABBITEYE BLUEBERRY CV. ‘BRIGHTWELL’[2]

[2] Godara, A., Rubio Ames, Z., & Deltsidis, A. 2025. HortScience, 60(2), 182-190. Reprinted here with permission of the publisher.

Abstract

Blueberries are produced worldwide due to their high demand and antioxidant benefits. Berry quality, including texture, flavor, and antioxidant properties influence consumer preferences and marketability. Harvesting blueberries at shorter intervals is essential for maintaining fruit quality, including firmness and flavor, while also minimizing postharvest losses. This study investigated the effects of delayed harvests on the postharvest quality of ‘Meadowlark’, highbush blueberry (SHB), and ‘Brightwell,’ a rabbiteye blueberry, harvested from two different locations in South Georgia in 2022 and 2023. The treatments consisted of harvest dates, with two harvests in 2022 and three harvests in 2023, followed by three storage durations treatments (7, 14, and 21 days of storage) to evaluate postharvest quality. Fruit firmness, berry diameter, color, total soluble solids (TSS), titratable acidity (TA), berry damage (%), and anthocyanin concentration were assessed at harvest and following storage days. In both cultivars, harvest 1 showed higher fruit firmness and storability compared to harvest 2 and 3 in 2023. During storage, the decline in firmness was higher in harvests 2 and 3 compared to harvest 1. Fruit from the delayed harvests exhibited the highest percentage of berry damage both at harvest and after 21 days of storage. Anthocyanin concentration varied across cultivars and years, with berries from harvest 2 (H2) having a higher anthocyanin concentration at harvest in 2022 and 2023 in the ‘Brightwell’ cultivar. Overall, this study highlights the importance of optimizing harvest dates to maintain the postharvest quality and shelf-life of blueberries.

KEYWORDS**:** total soluble solids; titratable acidity; anthocyanins; firmness.

Introduction

Over the past decade, global blueberry production has more than doubled, making blueberries the second most widely cultivated berry crop in the United States (Kramer, 2020; Protzman, 2021). In 2023, Georgia produced a total of 29,900 tons of blueberries, with a farm gate value of $449.4 million, making blueberries the State's most valuable horticulture fruit commodity (The University of Georgia, 2022; U.S. Department of Agriculture, 2021). Blueberry fruit quality encompasses several parameters; color and firmness, as well as the concentrations of sugars, organic acids, aroma volatiles, and phenolic compounds (Gilbert et al., 2014; Molina et al., 2008). Firmness is a critical factor in consumer acceptance of fresh blueberries, directly affecting texture and postharvest quality (Blaker et al., 2014; Chiabrando et al. 2009; Giongo et al., 2013). Blueberry postharvest quality can be influenced by several factors such as climatic conditions, temperature, fruit maturity or ripeness, and harvest interval (Bergqvist et al., 2001; Di Vittori et al., 2018). All these parameters can impact the overall quality, thus affecting consumer acceptability and repeat purchasing of blueberries (Gilbert et al., 2014; Qu et al., 2017).

Blueberry color is a major factor influencing consumer choice (Gilbert et al., 2014; Saftner et al., 2008), cuticular wax contributes to the surface color by giving a lighter blue appearance, generally preferred by consumers (Chu et al., 2018; Yan et al., 2023). This wax layer plays a critical role in reducing water loss, delaying decay, and maintaining the sensory and nutritional quality of the fruit, which collectively extends its shelf-life (Chu et al., 2018). However, the wax layer is susceptible to damage or removal during harvesting, packaging, and transport, which can diminish the fruit's visual appeal (Mukhtar et al., 2014). Furthermore, blueberry peel color is the primary index used to indicate fruit maturity and harvestability (Kalt et al., 1995; Lobos et al. 2014). Blueberry growers determine the optimal picking date, with 100% blue color being the most widely used criterion to facilitate commercial harvesting operations (Leiva-Valenzuela et al., 2013; Ribera et al., 2016). Nevertheless, blueberries can be visually identical (100% blue) but at different degrees of physiological maturity, since surface color is no longer a reliable indicator of physiological maturity once berries reach the full blue stage (Lobos et al., 2018). Thus, it is common that some blueberries are ripe while others may be overripe within a cluster. In this sense, several harvests with short intervals are needed to optimize fruit quality (Moggia et al., 2017, Lobos et al., 2018).

A major challenge in blueberry harvesting is that individual berries within the same plant and fruit cluster ripen asynchronously (Vander Kloet and Cabilio, 2010). Variations in blueberry maturity at harvest can affect their postharvest quality and storage potential, with overripe berries being more prone to softening and decay during storage. On the contrary, berries that are underripe at harvest may not have the desired flavor or texture (Lobos et al., 2018). Therefore, to accomplish optimal blueberry quality and to maintain storage potential, it has traditionally been recommended that harvest intervals remain shorter, approximately every three to five days between successive harvests on a single plant to enhance shelf-life (Lobos et al., 2018; Strik, 2019). This strategy aims to preserve fruit quality throughout the supply chain.

Blueberry hand harvesting requires a high number of personnel, resulting in high expenditure for blueberry growers. Currently, the blueberry industry is facing labor shortages and high labor costs, leading to increased use of machine harvesters for the fresh market (Gallardo et al., 2018). The shift to mechanical harvesting has led blueberry growers to experiment with longer harvest intervals to avoid fruit yield losses. As a result, harvests are performed in less-than-optimal intervals which leads to a greater percentage of overly ripe fruit being harvested (Lobos et al., 2018; Olmstead and Finn, 2014). This can negatively impact the quality of the packed fruit especially when it is stored for extended periods (Strik, 2019). In Georgia, quality issues such as leaking, splitting, wet stem scar, and tearing have been reported by growers in recent years (Rubio personal communication, 2022). These fruit quality issues are characterized by rapid fruit softening and the subsequent leakage of juice from the stem wet scar at harvest, which increases the susceptibility of berries to postharvest decay, rendering them unfit for fresh market sales.

As a result, substantial financial losses due to rejected loads are often encountered in the local blueberry industry. The cause of these quality issues has not been previously investigated in Georgia. Therefore, this study aimed to investigate the effects of different harvest dates on the postharvest quality of southern highbush (SHB) and rabbiteye (RE) blueberry cultivars with the hypothesis that delayed harvests are responsible for reduced berry quality and storability. The findings will provide valuable insights into the effects of harvest timing on the postharvest quality of blueberries, facilitating more efficient harvesting practices. Ultimately, this research will contribute to enhancing the economic sustainability of the blueberry industry by reducing postharvest losses and improving fruit marketability.

Materials and Methods

Experimental setup

The research trial was conducted on two different commercial farms located in Georgia, USA, using the cultivars Meadowlark in Clinch County (latitude 30°57′21.5″N; longitude 82°40′50.7″W) and Brightwell in Coffee County (latitude 31°30′31.7″N; longitude 82°42′12.4″W) (Table 4.1). In 2022, two harvests (n=2) were conducted, while in 2023, three harvests (n=3) were carried out for both cultivars. The harvest dates were considered as treatments: Harvest 1 (H1) was conducted on the date determined by the commercial producer for both cultivars. Harvest 2 (H2) took place seven days after H1, using a set of plants that were left unharvested. Harvest 3 (H3), which was only conducted in 2023, occurred 14 days after H1. The experiment was conducted using a randomized complete block design (RCBD) with five blocks. Each block contained 30 plants, with 10 plants assigned to each treatment within the block. The treatments (harvest dates) were randomly assigned within each block to minimize variability and ensure robust statistical analysis. Fruit were hand-harvested in the morning and stored at 19°C during transportation to the Vidalia Onion Research Laboratory (Postharvest lab) in Tifton, Georgia. Upon arrival at the lab after 1 pm, fruit were hand-sorted and packed into vented 170.1 grams clamshells (one dry pint, TerraBox, FL) and stored at 1 °C and 85% relative humidity for up to 21 days. Fruit evaluations were done at harvest and subsequently after 7, 14, and 21 days (n=3) following harvest (storage). Three clamshells per replication were evaluated at harvested, after 7, 14, and 21 days of cold storage, resulting in a total of 12 clamshells per replication per harvest. Overall, we had five replications in total resulting in 60 clamshells per harvest.

Postharvest laboratory analysis

The external color of the berry was measured using 25 berries per replication from the equatorial side perched with a colorimeter (Minolta CR-400 Chroma Meter, Tokyo, Japan) calibrated with a white tile. The results were expressed as CIE (L**C***h*) color space. The values of L* (lightness), *C**(Chroma) and *h* (hue angle) were used to report the color. A digital fruit firmness machine (FruitFirm® 500, CVM Inc. Pleasanton, CA) was used to assess firmness and berry diameter using the same 25 berries used for color measurements.

Berries with symptoms of splitting and juice efflux from the wet stem scar (pedicel scar) and splitting/peel tearing were visually assessed using 100 fruit samples per replicate. The collective damage from these symptoms was determined as a percentage and was calculated as follows:

Berry damage (%): $\frac{\text{Number of oozing and splitting fruit}}{\text{Total number of tested fruit}} \cdot 100$

Total soluble solids (TSS) concentration, titratable acidity (TA), and total anthocyanins concentration were measured using an aliquot of 100 g of berries blended with a tissue homogenizer (PowerGen 500, Fisher Scientific, Schwerte, Germany). The slurry was then centrifuged at 4 °C and 9,000 rpm (Sorvall X4R Pro-MD, Thermo Scientific, Osterode, Germany). Subsequently, the supernatant was filtered using cheesecloth, stored in plastic vials, and frozen at -20 °C until analysis. Titratable acidity (TA) was measured by titrating 6 mL of blueberry juice mixed in 50 ml of deionized water to pH 8.2 with 0.1 mol L−1 NaOH using a titrator (916 Ti-Touch, Metrohm AG, Herisau, Switzerland). TA results were expressed as % citric acid equivalents. TSS was determined by placing an aliquot of blueberry juice on a digital refractometer (ATAGO, PAL-1, Model 3810, Japan) while expressing results as a percentage.

Anthocyanins concentration were measured using the pH differential method as described by Giusti and Wrolstad (2001). Blueberry juice was mixed separately with two buffers: potassium chloride (KCl) at a concentration of 0.025 M and a pH of 1.0, and sodium acetate (CH_3COONa) at a concentration of 0.4 M and a pH of 4.5. A microplate spectrophotometer (BioTek, Epoch 2, Winooski, VT) was used to measure the absorbance of anthocyanins at 520 and 700 nm wavelengths using a blank cell filled with deionized water as a reference. The concentration of the total monomeric anthocyanins was calculated as follows:

Total anthocyanin concentration ($mg \cdot L^{-1}$): $\frac{A \cdot MW \cdot DF \cdot 1000}{\varepsilon \cdot 1}$

Where: $A = (A_{520\ nm} - A_{700\ nm})_{pH\ 1.0} - (A_{520\ nm} - A_{700\ nm})_{pH\ 4.5}$

MW: 449.2 (cyanidin-3-glucoside molecular weight)

DF: dilution factor (10)

Ɛ: 26,900 (molar absorptivity)

l: path length (1 cm)

Statistical analyses

All statistical analyses were conducted using JMP Pro 17 software (SAS Institute, Cary, NC, USA). Two harvests were conducted in 2022 and three harvests in 2023 for both cultivars. For the comparative analysis, harvest dates (H1, H2, and H3) were treated as treatments, and a one-way ANOVA was conducted, where harvest date was modeled as a fixed effect and replications as random effects. Analyses were conducted separately by year for measurements recorded at harvest and for each storage duration (7, 14, and 21 days) to assess the effect of harvest dates at each evaluated period. In 2022, only two harvest dates (H1 and H2) were analyzed, while in 2023, three harvest dates (H1, H2, and H3) were analyzed. The Fisher's least significant difference (LSD) test was used for mean separation at a significance level of $\alpha = 0.05$.

A full factorial model (harvest date × storage duration) was used to analyze the interactions between harvest dates and storage periods. For post hoc comparisons, Tukey's Honest Significant Difference (HSD) test was used. Statistical differences were indicated by different letters, with significance set at $\alpha = 0.05$, and the data from this analysis are presented in the additional tables 4.4 and 4.5 as supplementary material. Graphical representations of the results were generated using SigmaPlot 15.0 (Systat Software Inc., San Jose, CA).

Results

Weather data from both locations

Average maximum air temperatures in Clinch County from early April to late May were higher in 2022 (26.7°C and 31°C, respectively) compared to 2023 (26.5°C and 28.3°C, respectively), indicating a warmer season (Fig. 4.1A). Precipitation was higher in April 2023 (4 mm) compared to April 2022 (1 mm), while May rainfall was similar in both years at 4 mm. (Fig. 4.1B). In Coffee County, the maximum and minimum air temperature in June was also higher in 2022 (34.5°C and

21.1°C, respectively) compared to 2023 (31.4°C and 20°C, respectively) (Fig. 4.1C). Similarly, the precipitation data indicates that 2023 experienced more rainfall compared to 2022 (2.3 mm and 4 mm, respectively) (Fig. 4.1D). These observations highlight significant year-to-year variations in temperature and rainfall, which are crucial for understanding regional climate patterns.

Changes in Meadowlark Berries with Delayed Harvest

Berry firmness, diameter, and color

Meadowlark berries show a strong change in firmness with the harvest date and generally, all decrease in firmness with storage (Table 4.4). In 2022, the firmness of berries harvested at H1 was not significantly different compared to H2. In 2023, berries from H1 were significantly firmer at harvest compared to H2 and H3 (Fig. 4.2A). A similar result was obtained across all storage durations (7, 14, and 21 days), in which berries from H2 and H3 had significantly lower firmness (Table 4.2). The decline in berry firmness was more pronounced in H2 and H3 after 21 of storage (Table 4.4). Berry diameter at harvest was not significantly affected by harvest dates in 2022 and 2023. However, during storage in 2022, H2 berries had a larger diameter compared to H1 berries after 21 days of storage (Fig. 4.2B). In 2023, H2 berries had a larger diameter compared to H1 berries after seven days of storage, while no significant differences were found between harvest dates after 21 days of storage (Table 4.2).

In 2022, H1 berries had higher L* values compared to H2 berries at harvest (Fig. 4.3A). A significant difference in L* values was found during the storage duration (7, 14, and 21 days) (Table 4.2). In 2023, H1 berries had the highest L* values at harvest and during storage (after 7 and 14 days) compared to H2 and H3 (Fig. 4.3A and Table 4.2). Chroma (C*) was significantly affected by harvest date in which berries from H2 in 2022 and H3 in 2023 had significantly lower chroma values at harvest (Fig. 4.3B). During storage (after 7 and 14 days) berries from H1 had higher chroma values in 2022 and 2023 and chroma was not significantly different after 21 days of storage (Table 4.2). Hue angle (h°) was not significantly affected by the harvest date in 2022 but after 14 days of storage, H1 berries had a lower hue value (Fig. 4.3C and Table 4.2). In 2023, the hue was significantly higher in berries from H3 at harvest and after 21 days of storage (Fig. 4.3C and Table 4.2).

Fruit Composition

Total Soluble Solids (%) were not significantly affected at harvest in 2022. In 2023, berries from H2 and H3 had significantly higher TSS values of 11.5 % and 12% compared to 10.4% for H1 (Fig. 4.4A). During storage in 2022, H2 berries had higher total soluble solids after seven and 21 days of storage, while there was no difference after 14 days of storage (Table 4.2). In 2023, H3 berries had higher TSS compared to H1 after 21 days of storage (Table 4.2). Titratable acidity (TA) was not significantly affected by the harvest date in 2022. In 2023, berries harvested at H1 exhibited the highest titratable acidity (TA) value of 1.3% at harvest, compared to 0.57% for H2 and 0.41% for H3 (Fig. 4.4B). During storage, H1 berries had higher titratable acidity compared to H2 after seven and 14 days in 2022 (Table 4.2). In 2023, H1 berries also had higher TA compared to H2 and H3 throughout the storage duration (Table 4.2).

In 2022, the percentage of berry damage at harvest was significantly higher in H2 compared to H1 (Fig. 4.4C). In 2023, H3 berries had the highest percentage of damage, followed by H2 at harvest (Fig. 4.4C). The percentage of berry damage was consistently higher in H2 compared to H1 across all storage durations in 2022 (Table 4.2). In 2023, berries from the H3 had the highest percentage of damage throughout the storage duration (Table 4.2). The berry damage significantly increased to 48.2% for H2 in 2022 and 23.1 and 74.4% for H2 and H3 in 2023 after 21 days of storage (Table 4.4)

Total anthocyanin varied with harvest date and year. Anthocyanin concentration at harvest was significantly increased from 280 to 450 mg·L^{-1} between H1 and H2. In 2023, total anthocyanin was lower, at 180, and increased slightly by H3 to 280 mg·L^{-1} (Fig. 4.4D). In 2022, H2 berries had higher anthocyanin concentrations compared to H1 after 14 days of storage. In 2023, berries from H1 had a significantly lower anthocyanin concentration compared to H2 after 21 days of storage (Table 4.2).

Changes in Brightwell Berries with Delayed Harvest

Berry firmness, diameter, and color

In 2022 and 2023, berries harvested from H1 had significantly higher firmness at harvest compared to H2 and H3 (Fig. 4.5A). In 2022, H1 berries had significantly higher firmness compared to H2 throughout the storage duration. In 2023, berries from H3 had the lowest firmness throughout storage compared to H1 (Table 4.3). The firmness decline was more pronounced in H3 after 21 days of storage in 2023 (Table 4.5). Berry diameter at harvest was not significantly affected in 2022. In 2023, H2 berries had a smaller diameter compared to H1 and H3 (Fig. 4.5B). In 2022, berries from H2 had a larger diameter throughout the storage duration. In 2023, berries from H3 showed a significant decline in diameter after 14 days of storage, while there were mixed results for the rest of the harvests during storage (Table 4.3).

In 2022, H2 berries had a higher L* value compared to H1 at harvest and after seven days of storage (Fig. 4.6A and Table 4.3). In 2023, H3 berries had the highest L* values at harvest, compared to H2 and H1 (Fig. 4.6A). In 2023, H3 berries had the highest L* values compared to H1 and H2 throughout storage (Table 4.3). In 2022, the Chroma value at harvest was not significantly different. In 2023, chroma value was significantly lower for berries from H1 compared to H2 and H3 at harvest and after 14 and 21 days of storage (Fig. 4.6B and Table 4.3).

In 2022, hue was significantly higher at harvest and after 14 days of storage in berries from H1 (Fig. 4.6C and Table 4.3). In 2023, berries from H1 had a higher hue value compared to H2 and H3 after 14 and 21 days of storage (Table 4.3).

Fruit Composition

Total Soluble Solids (%) was significantly higher at harvest with 15.2% in berries from H1 in 2022. In 2023, TSS was not significantly affected by the harvest date (Fig 4.7A). In 2022, H1 berries had higher TSS after seven days of storage while TSS did not change after 14 and 21 days of storage (Table 4.2). In 2023, H2 berries had higher TSS throughout the storage duration (Table 4.3). In 2022, titratable acidity (TA) declined from 1.5 to 1.2% at H2 (Fig. 4.7B). TA in 2023 was not significantly affected by the harvest date. In 2022, H1 berries had higher titratable acidity compared to H2 throughout storage. In 2023, H3 berries had higher TA after seven days of storage, while H2 berries had higher TA compared to H3 after 14 days of storage (Table 4.3).

The berry damage was 7.2% higher in H2 compared to H1 at harvest in 2022 (Fig. 4.7C). In 2023, berries from H3 and H2 had a significantly higher percentage of damage with 21 and 25% berry damage, at harvest, compared to H1 (Fig. 4.7C). In 2023, berries from H3 and berries from H2 in 2022 showed the highest percentage of damage after 21 days of storage compared to H1 (Table 4.3).

In 2022 and 2023, anthocyanins concentration was significantly higher in berries from H2 (248 and 379 $mg \cdot L^{-1}$) compared to H1 and H3 (Fig 4.7D). Anthocyanins concentration did not show any change during storage and was not significant in 2022. In 2023, H2 berries had significantly higher anthocyanins concentrations after seven days of storage and no significant difference was found after 14 and 21 days of storage (Table 4.3).

Discussion

In the present study, three harvests were performed at one-week intervals to evaluate the berry quality at harvest and the storage potential of blueberries collected at each harvest date. The findings improve preharvest decision-making as well as general postharvest handling recommendations for southern highbush cv. ‘Meadowlark’ and rabbiteye cv. ‘Brightwell’ blueberry growers in the southeastern United States. The importance of harvest timing and optimal maturity in blueberries relies on the rapid changes in fruit cell wall components due to increased enzymatic activity during ripening leading to changes in fruit texture (Chen et al., 2015; Giongo et al., 2013: Vicente et al., 2007). Higher berry firmness has been associated with denser harvest intervals, suggesting that overmature berries are softer both at harvest and during storage. This means that harvesting berries 3 to 6 days after reaching the 100% blue stage results in lower firmness (Sargent et al., 2006; Lobos et al., 2018; Strik 2019; Moggia et al., 2022). Delaying harvests reduced firmness in ‘Meadowlark’ and ‘Brightwell,’ negatively impacting shelf-life, as fruit firmness is an essential economic trait for long-distance shipping and extended shelf-life. Strik (2019), reported a similar result in which a delayed harvest of 8 and 12 days resulted in a firmness decline in ‘Aurora’, ‘Bluecorp’, and ‘Duke’ cultivars of blueberry. Harvesting blueberries at the appropriate maturity stage ensures fruit of higher quality with a longer shelf-life (Rivera et al., 2022; Varaldo et al., 2022). The firmness of blueberries may vary significantly depending on the cultivar, as different genetic characteristics influence the texture and structural integrity of the fruit (Lobos et al., 2014). For instance, the storage life of the ‘Elliott’ cultivar was negatively impacted by berry maturity, whereas the 'Aurora' and 'Liberty' cultivars were not significantly affected by crop ripeness (Lobos et al., 2014). Harvesting blueberries at the appropriate maturity stage ensures fruit of higher quality with a longer shelf-life (Rivera et al., 2022; Varaldo et al., 2022). Berry diameter results were inconsistent at harvest in 2023, likely due to high rainfall. However, during storage berries from H2 in 2022 and berries from H3 in 2023 showed a larger diameter compared to H1 in the 'Brightwell' cultivar. This observation aligns with Stage III of the double sigmoid growth model, where significant fruit volume expansion occurs, resulting in berries that were not only larger at harvest but also maintained a greater size after 21 days of storage (Godoy et al., 2008).

The color of blueberry fruit transitions from green to dark blue due to the accumulation of anthocyanins in the skin and pulp (Chung et al., 2016; Lin et al., 2018). In the CIE color space, L* represents the lightness of the color, with values ranging from 0 (black) to 100 (white), indicating how light or dark the color appears. Chroma (C*) describes the intensity or saturation of the color, where higher values denote more vivid and saturated colors. Hue (h°) refers to the type of color on the color wheel, such as red, yellow, green, or blue, and is measured as an angle. The ripening and harvesting periods of southern highbush ('Meadowlark') and rabbiteye ('Brightwell') blueberries differ significantly in Georgia reflecting variations in their genetic makeup and environmental requirements, with 'Meadowlark' typically harvested in April and May, and 'Brightwell' in June. Brightwell berries exhibited higher lightness and chroma in delayed harvests (H2 and H3). On the other hand, higher hue values were observed in H1 berries, this indicates a shift towards a more vivid and bluish tone in the delayed harvests (H2 and H3). This change can likely be attributed to an increased wax deposition at maturity and the gradual wearing of the wax in over-mature fruits giving the different color values. Yan et al. (2023) reported that wax removed treatment had lower lightness (L*) and higher glossiness compared to berries with wax covered. On the other hand, berries from the cultivar 'Meadowlark' showed a gradual decline in chroma values observed during delayed harvests (H2 and H3) which may be attributed to the increased deposition of epicuticular waxes, as indicated by previous studies (Saftner et al., 2008; Konarska, 2015; Chu et al., 2018). The accumulation of cuticular wax (or fruit bloom) in blueberries increases throughout fruit development, resulting in a thicker cuticle at maturity, contributing to a less vibrant skin color (Chu et al., 2018; Trivedi et al., 2019). The decrease in L* values observed during this period likely reflects anthocyanin accumulation, aligning with findings reported in other blueberry cultivars (Chung et al., 2016; Matiacevich et al., 2013; Spinardi et al., 2019; Smrke et al., 2023). These findings underscore the importance of considering postharvest storage conditions and harvest timing to maintain the desired color qualities of blueberries, which are crucial for consumer acceptance and market value.

Blueberries undergo significant changes during maturation and ripening, biochemical changes occur as total soluble solids increase and titratable acidity decreases (Hassan et al., 2022; Li et al., 2020; Liu et al. 2019; Moggia et al., 2018). Additionally, harvesting blueberries five to seven days after reaching 100% blue resulted in a higher accumulation of total soluble solids (TSS), with levels reaching 16.5% compared to 13.8% at the 100% blue stage (Moggia et al., 2016). This aligned with present work, for 'Meadowlark' and 'Brightwell' in 2022 and 2023, the TSS content was highest in berries from H2 and H3 at harvest and during storage. Similar results were reported by Strik (2019) who found that harvest intervals longer than 12 days resulted in 12% increased TSS content and 46% decreased TA content. In the present work, TA was higher in H1 berries and declined with delayed harvests (H2 and H3) consistent with results reported by other authors (Lobos et al., 2014; Moggia et al., 2018; Strik, 2019). The inverse trajectories of sugars and organic acids in ripening fruit are a general phenomenon across fruit crops (Fawole and Opara, 2013; Strik, 2019; Teka, 2013). Overall, our study confirmed that the physicochemical properties of blueberry fruit vary significantly between commercial harvest stages and overripe berries.

The percentage of berry damage was also significantly higher in delayed harvests of H2 and H3 in 'Brightwell' and 'Meadowlark' cultivars in both years. This increase is likely attributed to the accumulation of overripe fruit resulting from the extended harvest dates, as overripe berries typically exhibit lower firmness at harvest and throughout storage, making them more susceptible to damage compared to those harvested at optimal maturity. (Lobos et al., 2018). This is supported by another study which states that fruit from the advanced maturity stage (delayed harvests) have higher decay incidence (Miller et al., 1988). Furthermore, the variation in anthocyanin concentration based on harvest time and storage duration observed in our study was aligned with findings by Mallik and Hamilton (2017), who investigated the effect of harvest date and storage conditions on the quality and health-related chemistry of wild blueberries native to NW Ontario, Canada and found that late harvest and low-temperature storage significantly increased total phenol and anthocyanin contents for most genotypes. This observation is consistent with the present work, in which berries from H2 in 2022 and 2023 and H3 berries from the 'Meadowlark' cultivar had higher anthocyanin concentrations. Kalt et al. (2003) found that total anthocyanin concentration was substantially higher in the fruit of advanced maturity stages, whereas the phenolic content and antioxidant capacity were lower in over-mature fruit. The blueberry cultivars 'Brigitta and 'Nelson; resulted in decreased anthocyanin from the 100% blue stage to the fully ripe stage. This suggests that anthocyanin concentration along with other beneficial compounds, might increase during fruit maturation. However, they can subsequently decrease when the fruit is overmature (Kalt et al., 2003).

Conclusion

Based on our two-year study, delayed harvests influenced the postharvest quality of southern highbush cv. ‘Meadowlark’ and rabbiteye cv ‘Brightwell’ blueberries. Delayed harvests resulted in greater TSS accumulation in ‘Meadowlark’ berries in 2023, which may be beneficial for flavor. However, delayed harvests decreased fruit initial firmness and during storage for both cultivars. In particular, firmness declined more significantly in delayed harvests after a 21-day storage period. Additionally, the percentage of berry damage was significantly higher in delayed harvests (H2 and H3). Maintaining shorter harvest intervals for blueberries cultivated in warm and humid environments, in conjunction with optimized storage conditions, is essential for preserving the postharvest quality and extending the shelf life. Future studies should focus on implementing harvest intervals shorter than seven days to better preserve the postharvest quality of fresh-market blueberries.

Acknowledgments

We are grateful to the blueberry growers, Mr. Goodman, Mr. Anderson, and Mr. Aron for providing access to their fields and for their valuable help. Our special gratitude to Dr. Joshua Vander Weide, Dr. Ye (Juliet) Chu, Dr. Zhiheng Xing, and Dr. Jakeline Zuluaga Acosta for reviewing, and editing the manuscript.

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Table 4.1. Harvest Schedule and Frequency for Meadowlark and Brightwell Blueberries in 2022 and 2023.

No.	Cultivar	Year	Harvest dates		
			Harvest 1[a]	**Harvest 2[b]**	**Harvest 3[c]**
1	Meadowlark	2022	May 17	May 24	No harvest
3	Brightwell	2022	June 2	June 9	No harvest
4	Meadowlark	2023	April 18	April 25	May 1
6	Brightwell	2023	June 2	June 9	June 16

[a] Commercial Harvest (Harvest 1; H1): This represents the initial harvest, conducted when the blueberries reach their peak commercial readiness.

[b] 7-Day Delayed Harvest (Harvest 2; H2): Occurring one week after the commercial harvest.

[c] 14-Day Delayed Harvest (Harvest 3; H3): Conducted two weeks after the commercial harvest.

Table 4.2. Effects of harvest date on fruit quality of 'Meadowlark' southern highbush blueberry at each storage duration (7, 14, and 21 days) in 2022 and 2023. Fruit were stored at 1°C and 85% RH. Parameters measured include firmness ($g \cdot mm^{-1}$), berry diameter (mm), color (L*, C*, h°), berry damage (%), titratable acidity (%), total soluble solids (%), and anthocyanin concentration ($mg\ L^{-1}$). Values are presented as mean ± standard error (SE) for each parameter. Comparisons are made between harvest dates in 2022 (H1 and H2) and 2023 (H1, H2, and H3) within each storage duration, and means followed by different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

Year	Harvest date [1]	Storage days	Firmness ($g \cdot mm^{-1}$)	Berry diameter (mm)	Color (L*) [2]	Chroma (C*)	Hue (h°)	Total soluble solids (%)	Titratable acidity (%) [3]	Berry damage (%) [4]	Anthocyanin concentration ($mg \cdot L^{-1}$)
2022	H1	7	191 ± 2.9 a	24.9 ± 0.2 b	29.4 ± 0.3 a	3 ± 0.2 a	280.2 ± 2.4 a	13.4 ± 0.3 b	0.4 ± 0.1 a	18.6 ± 1.9 b	325.2 ± 25.5 a
	H2	7	147.1 ± 2.9 b	25.9 ± 0.2 a	29.9 ± 0.3 a	2.5 ± 0.2 b	279.7 ± 2.4 a	14.5 ± 0.3 a	0.3 ± 0.1 b	35.8 ± 1.9 a	401 ± 25.5 a
	H1	14	180.4 ± 2.8 a	27 ± 0.2 a	30.1 ± 0.3 a	3.4 ± 0.2 a	276.8 ± 0.8 b	14.2 ± 0.3 a	0.4 ± 0.1 a	14.6 ± 1.6 b	279.9 ± 23.6 b
	H2	14	141.4 ± 2.8 b	26.2 ± 0.2 b	30 ± 0.3 a	3 ± 0.2 b	281.4 ± 0.8 a	15 ± 0.3 a	0.3 ± 0.1 b	31.4 ± 1.6 a	383 ± 23.6 a
	H1	21	167.2 ± 2.9 a	25.4 ± 0.2 b	29.8 ± 0.3 a	3.2 ± 0.2 a	277.4 ± 1.1 a	14 ± 0.3 b	0.5 ± 0.1 a	40.4 ± 1.9 b	296.3 ± 23.5 a
	H2	21	136.1 ± 2.9 b	25.8 ± 0.2 a	30.1 ± 0.3 a	3.1 ± 0.2 a	279.9 ± 1.1 a	15.1 ± 0.3 a	0.4 ± 0.1 a	48.2 ± 1.9 a	328.1 ± 23.5 a
2023	H1	7	210.1 ± 2.9 a	28.6 ± 0.2 b	33.2 ± 0.3 a	5.3 ± 0.2 a	275.7 ± 0.9 a	10.5 ± 0.2 c	1.2 ± 0.1 a	4 ± 2 c	211.7 ± 20.8 a
	H2	7	183.9 ± 2.9 b	29.3 ± 0.2 a	32.4 ± 0.3 b	5 ± 0.2 ab	275.6 ± 0.9 a	11.2 ± 0.2 b	0.5 ± 0.1 b	18.6 ± 2 b	191.4 ± 20.8 a
	H3	7	176.2 ± 2.9 b	28.7 ± 0.2 b	32.3 ± 0.3 b	4.9 ± 0.2 b	277.7 ± 0.9 a	12.3 ± 0.2 a	0.4 ± 0.1 b	57.6 ± 2 a	218 ± 20.8 a
	H1	14	197.2 ± 3 a	28.9 ± 0.2 ab	33.1 ± 0.3 a	5.3 ± 0.2 a	274.2 ± 0.6 b	10.6 ± 0.2 b	0.9 ± 0.1 a	6.4 ± 1.9 c	215.3 ± 17.9 a

H2	14	185.2 ± 3 b	29 ± 0.2 a	32 ± 0.3 b	4.8 ± 0.2 b	275.6 ± 0.6 ab	12 ± 0.2 a	0.5 ± 0.1 b	19.2 ± 1.9 b	226.3 ± 17.9 a
H3	14	175.8 ± 3 c	28.5 ± 0.2 b	33 ± 0.3 a	5.2 ± 0.2 a	276.5 ± 0.6 a	12 ± 0.2 a	0.4 ± 0.1 b	72.2 ± 1.9 a	176 ± 17.9 a
H1	21	193 ± 2.8 a	28.8 ± 0.2 a	32.4 ± 0.3 a	5 ± 0.2 a	275.3 ± 0.8 b	10.4 ± 0.2 b	0.8 ± 0.1 a	5.8 ± 0.7 c	184.4 ± 38.4 b
H2	21	173.1 ± 2.8 b	28.5 ± 0.2 a	32.8 ± 0.3 a	5.2 ± 0.2 a	273.9 ± 0.8 b	12.2 ± 0.2 a	0.5 ± 0.1 b	23.4 ± 0.7 b	304.9 ± 38.4 a
H3	21	156.9 ± 2.8 c	28.7 ± 0.2 a	32.6 ± 0.3 a	5 ± 0.2 a	278.7 ± 0.8 a	12.2 ± 0.2 a	0.5 ± 0.1 b	74.4 ± 0.7 a	205.1 ± 38.4 ab

[1]The first harvest (H1) was conducted as the scheduled first harvest of the season by the grower, followed by two delayed harvests, after 7 days (H2) and another after 14 days (H3).

[2] Lightness: This parameter represents the brightness of a color, with 0 being black and 100 being white.

[3] Titratable acidity (TA) is expressed as percent citric acid equivalent.

[4]100 berries from each replication were evaluated.

Table 4.3. Effects of harvest date on fruit quality of 'Brightwell' rabbiteye blueberry at each storage duration (7, 14, and 21 days) in 2022 and 2023. Fruit were stored at 1°C and 85% RH. Parameters measured include firmness ($g \cdot mm^{-1}$), berry diameter (mm), color (L*, C*, h°), berry damage (%), titratable acidity (%), total soluble solids (%), and anthocyanin concentration ($mg\ L^{-1}$). Values are presented as mean ± standard error (SE) for each parameter. Comparisons are made between harvest dates in 2022 (H1 and H2) and 2023 (H1, H2, and H3) within each storage duration, and means followed by different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

Year	Harvest date [1]	Storage days	Firmness ($g \cdot mm^{-1}$)	Berry diameter (mm)	Color (L*) [2]	Chroma (C*)	Hue (h°)	Total soluble solids (%)	Titratable acidity (%) [3]	Berry damage (%) [4]	Anthocyanin concentration ($mg \cdot L^{-1}$)
2022	H1	7	176.7 ± 3.9 a	23.9 ± 0.2 b	28.1 ± 0.3 b	2.7 ± 0.2 a	264.8 ± 5.8 a	15.2 ± 0.3 a	1.4 ± 0.1 a	29.4 ± 1.3 a	287.4 ± 19.8 a
	H2	7	143.7 ± 3.9 b	24.9 ± 0.2 a	29.9 ± 0.3 a	2.9 ± 0.2 a	279.7 ± 5.8 a	14.4 ± 0.3 b	1.2 ± 0.1 b	28 ± 1.3 a	303.5 ± 19.8 a
	H1	14	180.2 ± 3.6 a	23.9 ± 0.2 b	29.1 ± 0.3 a	2.6 ± 0.2 a	295.8 ± 2 a	14.5 ± 0.4 a	1.3 ± 0.1 a	26.4 ± 2.2 a	233.5 ± 16.1 a
	H2	14	128.6 ± 3.6 b	24.7 ± 0.2 a	29.1 ± 0.3 a	2.4 ± 0.2 a	283.6 ± 2 b	14.4 ± 0.4 a	0.9 ± 0.1 b	27.4 ± 2.2 a	267.6 ± 16.1 a
	H1	21	185.9 ± 3.4 a	23.8 ± 0.2 b	29.1 ± 0.3 a	2.4 ± 0.1 a	278 ± 4.2 a	14.4 ± 0.3 a	1.2 ± 0.1 a	35.2 ± 2.1 b	230.6 ± 27.2 a
	H2	21	125.4 ± 3.4 b	24.5 ± 0.2 a	28.7 ± 0.3 a	2.4 ± 0.1 a	282.4 ± 4.2 a	14.2 ± 0.3 a	0.9 ± 0.1 b	45.6 ± 2.1 a	239.9 ± 27.2 a
2023	H1	7	159.9 ± 3.6 a	26.7 ± 0.2 b	28.3 ± 0.3 b	2.8 ± 0.2 a	283.4 ± 2.6 a	12.9 ± 0.3 b	1.2 ± 0.2 b	24.4 ± 2.5 a	198.7 ± 26.7 b
	H2	7	151.6 ± 3.6 a	28 ± 0.2 a	28.3 ± 0.3 b	2.9 ± 0.2 a	284.7 ± 2.6 a	14.3 ± 0.3 a	1 ± 0.2 b	22.8 ± 2.5 a	293.7 ± 26.7 a
	H3	7	135.8 ± 3.6 b	9.9 ± 0.2 c	30.6 ± 0.3 a	3 ± 0.2 a	269.9 ± 2.6 b	13.1 ± 0.3 b	1.7 ± 0.2 a	17.8 ± 2.5 a	181.6 ± 26.7 b
	H1	14	158.2 ± 3.6 a	27.3 ± 0.2 a	27.2 ± 0.3 c	2.5 ± 0.2 b	283.7 ± 3.2 a	13 ± 0.3 b	1.2 ± 0.2 ab	24 ± 2.7 a	287 ± 42 a

H2	14	143.3 ± 3.6 b	9.9 ± 0.2 c	30.5 ± 0.3 b	3.8 ± 0.2 a	272.1 ± 3.2 b	14.7 ± 0.3 a	1.7 ± 0.2 a	18.2 ± 2.7 a	203 ± 42 a
H3	14	120.99 ± 3.6 c	14.1 ± 0.2 b	32.5 ± 0.3 a	3.8 ± 0.2 a	271.3 ± 3.2 b	13.1 ± 0.3 b	1.1 ± 0.2 b	24.8 ± 2.7 a	198.9 ± 42 a
H1	21	150.4 ± 3.6 a	9.9 ± 0.2 c	28.7 ± 0.3 c	2.9 ± 0.2 b	278 ± 1 a	13.1 ± 0.3 b	1.2 ± 0.3 a	19.2 ± 2.1 b	213.2 ± 34.5 a
H2	21	160 ± 3.6 a	12.6 ± 0.2 b	30.8 ± 0.3 b	4.2 ± 0.2 a	275 ± 1 b	14.7 ± 0.3 a	1.7 ± 0.3 a	21 ± 2.1 ab	196.7 ± 34.5 a
H3	21	127 ± 3.6 b	14.6 ± 0.2 a	31.6 ± 0.3 a	3.9 ± 0.2 a	274.7 ± 1 b	13.7 ± 0.3 b	1.2 ± 0.3 a	25.8 ± 2.1 a	281.3 ± 34.5 a

[1]The first harvest (H1) was conducted as the scheduled first harvest of the season by the grower, followed by two delayed harvests, after 7 days (H2) and another after 14 days (H3).

[2] Lightness: This parameter represents the brightness of a color, with 0 being black and 100 being white.[3]

[3]Titratable acidity (TA) is expressed as percent citric acid equivalent.

[4]100 berries from each replication were evaluated.

Table 4.4. Effects of harvest date and storage duration on fruit quality of 'Meadowlark' southern highbush blueberry in 2022 and 2023 under a factorial design. The experiment includes a 2 × 3 factorial design in 2022 (two harvest dates and three storage durations) and a 3 × 3 factorial design in 2023 (three harvest dates and three storage durations). Fruit were stored at 1°C and 85% RH for 7, 14, and 21 days. Parameters measured include firmness (g·mm⁻¹), berry diameter (mm), color (L*, C*, h°), berry damage (%), titratable acidity (%), total soluble solids (%), and anthocyanin concentration (mg L⁻¹). Values are presented as mean ± standard error (SE) for each parameter. Interaction effects between harvest dates and storage durations are analyzed and means followed by different letters are significantly different at $p \leq 0.05$ based on Tukey's honest significant difference test.

Year	Harvest date [1]	Storage days	Firmness (g·mm⁻¹)	Berry diameter (mm)	Color (L*) [2]	Chroma (C*)	Hue (h°)	Total soluble solids (%)	Titratable acidity (%) [3]	Berry damage (%) [4]	Anthocyanin concentration (mg L⁻¹)
2022	H1	7	191 ± 2.9 a	24.9 ± 0.2 c	29.4 ± 0.3 a	3 ± 0.2 ab	280.2 ± 2.4 a	13.4 ± 0.3 b	0.4 ± 0.1 ab	18.6 ± 1.9 d	325.2 ± 25.5 a
	H2	7	147.1 ± 2.9 c	25.9 ± 0.2 b	29.9 ± 0.3 a	2.5 ± 0.2 b	279.7 ± 2.4 a	14.5 ± 0.3 ab	0.3 ± 0.1 c	35.8 ± 1.9 bc	401 ± 25.5 a
	H1	14	180.4 ± 2.8 ab	27 ± 0.2 a	30.1 ± 0.3 a	3.4 ± 0.2 a	276.8 ± 0.8 a	14.2 ± 0.3 ab	0.4 ± 0.1 ab	14.6 ± 1.6 d	279.9 ± 23.6 a
	H2	14	141.4 ± 2.8 c	26.2 ± 0.2 ab	30 ± 0.3 a	3 ± 0.2 ab	281.4 ± 0.8 a	15 ± 0.3 a	0.3 ± 0.1 abc	31.4 ± 1.6 c	383 ± 23.6 a
	H1	21	167.2 ± 2.9 b	25.4 ± 0.2 bc	29.8 ± 0.3 a	3.2 ± 0.2 a	277.4 ± 1.1 a	14 ± 0.3 ab	0.5 ± 0.1 a	40.4 ± 1.9 b	296.3 ± 23.5 a
	H2	21	136.1 ± 2.9 c	25.8 ± 0.2 b	30.1 ± 0.3 a	3.1 ± 0.2 ab	279.9 ± 1.1 a	15.1 ± 0.3 a	0.4 ± 0.1 bc	48.2 ± 1.9 a	328.1 ± 23.5 a
2023	H1	7	210.1 ± 2.9 a	28.6 ± 0.2 ab	33.2 ± 0.3 a	5.3 ± 0.2 a	275.7 ± 0.9 ab	10.5 ± 0.2 c	1.2 ± 0.1 c	4 ± 2 d	211.7 ± 20.8 a
	H2	7	183.9 ± 2.9 bcd	29.3 ± 0.2 a	32.4 ± 0.3 a	5 ± 0.2 ab	275.6 ± 0.9 a	11.2 ± 0.2 b	0.5 ± 0.1 d	18.6 ± 2 c	191.4 ± 20.8 a

H3	7	176.2 ± 2.9 cd	28.7 ± 0.2 ab	32.3 ± 0.3 a	4.9 ± 0.2 ab	277.7 ± 0.9 a	12.3 ± 0.2 a	0.4 ± 0.1 d	57.6 ± 2 b	218 ± 20.8 a
H1	14	197.2 ± 3 ab	28.9 ± 0.2 ab	33.1 ± 0.3 a	5.3 ± 0.2 a	274.2 ± 0.6 b	10.6 ± 0.2 bc	0.9 ± 0.1 b	6.4 ± 1.9 d	215.3 ± 17.9 a
H2	14	185.2 ± 3 bcd	29 ± 0.2 ab	32 ± 0.3 a	4.8 ± 0.2 ab	275.6 ± 0.6 ab	12 ± 0.2 a	0.5 ± 0.1 cd	19.2 ± 1.9 c	226.3 ± 17.9 a
H3	14	175.8 ± 3 d	28.5 ± 0.2 ab	33 ± 0.3 a	5.2 ± 0.2 ab	276.5 ± 0.6 a	12 ± 0.2 a	0.4 ± 0.1 d	72.2 ± 1.9 a	176 ± 17.9 a
H1	21	193 ± 2.8 bc	28.8 ± 0.2 ab	32.4 ± 0.3 a	5 ± 0.2 a	275.3 ± 0.8 ab	10.4 ± 0.2 c	0.8 ± 0.1 b	5.8 ± 0.7 d	184.4 ± 38.4 a
H2	21	173.1 ± 2.8 de	28.5 ± 0.2 b	32.8 ± 0.3 a	5.2 ± 0.2 b	273.9 ± 0.8 b	12.2 ± 0.2 a	0.5 ± 0.1 cd	23.4 ± 0.7 c	304.9 ± 38.4 a
H3	21	156.9 ± 2.8 e	28.7 ± 0.2 ab	32.6 ± 0.3 a	5 ± 0.2 a	278.7 ± 0.8 a	12.2 ± 0.2 a	0.5 ± 0.1 cd	74.4 ± 0.7 a	205.1 ± 38.4 a

[1]The first harvest (H1) was conducted as the scheduled first harvest of the season by the grower, followed by two delayed harvests, after 7 days (H2) and another after 14 days (H3).

[2] Lightness: This parameter represents the brightness of a color, with 0 being black and 100 being white.

[3] Titratable acidity (TA) is expressed as percent citric acid equivalent.

[4]100 berries from each replication were evaluated.

Table 4.5. Effects of harvest date and storage duration on fruit quality of 'Brightwell' rabbiteye blueberry in 2022 and 2023 under a factorial design. The experiment includes a 2 × 3 factorial design in 2022 (two harvest dates and three storage durations) and a 3 × 3 factorial design in 2023 (three harvest dates and three storage durations). Fruit were stored at 1°C and 85% RH for 7, 14, and 21 days. Parameters measured include firmness (g·mm⁻¹), berry diameter (mm), color (L*, C*, h°), berry damage (%), titratable acidity (%), total soluble solids (%), and anthocyanin concentration (mg L⁻¹). Values are presented as mean ± standard error (SE) for each parameter. Interaction effects between harvest dates and storage durations are analyzed and means followed by different letters are significantly different at $p \leq 0.05$ based on Tukey's honest significant difference test.

Year	Harvest date [1]	Storage days	Firmness ($g \cdot mm^{-1}$)	Berry diameter (mm)	Color (L*) [2]	Chroma (C*)	Hue (h°)	Total soluble solids (%)	Titratable acidity (%) [3]	Berry damage (%) [4]	Anthocyanin concentration ($mg\ L^{-1}$)
2022	H1	7	176.7 ± 3.9 ab	23.9 ± 0.2 bc	28.1 ± 0.3 a	2.7 ± 0.2 a	264.8 ± 5.8 b	15.2 ± 0.3 a	1.4 ± 0.1 a	29.4 ± 1.3 b	287.4 ± 19.8 a
	H2	7	143.7 ± 3.9 bc	24.9 ± 0.2 a	29.9 ± 0.3 a	2.9 ± 0.2 a	279.7 ± 5.8 ab	14.4 ± 0.3 a	1.2 ± 0.1 ab	28 ± 1.3 b	303.5 ± 19.8 a
	H1	14	180.2 ± 3.6 ab	23.9 ± 0.2 bc	29.1 ± 0.3 a	2.6 ± 0.2 a	295.8 ± 2 a	14.5 ± 0.4 a	1.3 ± 0.1 a	26.4 ± 2.2 b	233.5 ± 16.1 a
	H2	14	128.6 ± 3.6 c	24.7 ± 0.2 ab	29.1 ± 0.3 a	2.4 ± 0.2 a	283.6 ± 2 ab	14.4 ± 0.4 a	0.9 ± 0.1 bc	27.4 ± 2.2 b	267.6 ± 16.1 a
	H1	21	185.9 ± 3.4 a	23.8 ± 0.2 c	29.1 ± 0.3 a	2.4 ± 0.1 a	278 ± 4.2 ab	14.4 ± 0.3 a	1.2 ± 0.1 a	35.2 ± 2.1 ab	230.6 ± 27.2 a
	H2	21	125.4 ± 3.4 c	24.5 ± 0.2 abc	28.7 ± 0.3 a	2.4 ± 0.1 a	282.4 ± 4.2 ab	14.2 ± 0.3 a	0.9 ± 0.1 c	45.6 ± 2.1 a	239.9 ± 27.2 a
2023	H1	7	159.9 ± 3.6 a	26.7 ± 0.2 a	28.3 ± 0.3 bcd	2.8 ± 0.2 abcd	283.4 ± 2.6 ab	12.9 ± 0.3 b	1.2 ± 0.2 a	24.4 ± 2.5 a	198.7 ± 26.7 a

H2	7	151.6 ± 3.6 ab	28 ± 0.2 a	28.3 ± 0.3 cd	2.9 ± 0.2 bd	284.7 ± 2.6 a	14.3 ± 0.3 a	1 ± 0.2 a	22.8 ± 2.5 a	293.7 ± 26.7 a
H3	7	135.8 ± 3.6 cd	9.9 ± 0.2 cd	30.6 ± 0.3 abc	3 ± 0.2 abcd	269.9 ± 2.6 b	13.1 ± 0.3 b	1.7 ± 0.2 a	17.8 ± 2.5 a	181.6 ± 26.7 a
H1	14	158.2 ± 3.6 a	27.3 ± 0.2 d	27.2 ± 0.3 d	2.5 ± 0.2 cd	283.7 ± 3.2 ab	13 ± 0.3 b	1.2 ± 0.2 a	24 ± 2.7 a	287 ± 42 a
H2	14	143.3 ± 3.6 abc	9.9 ± 0.2 c	30.5 ± 0.3 ab	3.8 ± 0.2 ac	272.1 ± 3.2 ab	14.7 ± 0.3 a	1.7 ± 0.2 a	18.2 ± 2.7 a	203 ± 42 a
H3	14	120.99 ± 3.6 d	14.1 ± 0.2 b	32.5 ± 0.3 a	3.8 ± 0.2 abcd	271.3 ± 3.2 ab	13.1 ± 0.3 b	1.1 ± 0.2 a	24.8 ± 2.7 a	198.9 ± 42 a
H1	21	150.4 ± 3.6 abc	9.9 ± 0.2 cd	28.7 ± 0.3 bcd	2.9 ± 0.2 abcd	278 ± 1 ab	13.1 ± 0.3 b	1.2 ± 0.3 a	19.2 ± 2.1 a	213.2 ± 34.5 a
H2	21	160 ± 3.6 a	12.6 ± 0.2 bc	30.8 ± 0.3 ab	4.2 ± 0.2 a	275 ± 1 ab	14.7 ± 0.3 a	1.7 ± 0.3 a	21 ± 2.1 a	196.7 ± 34.5 a
H3	21	127 ± 3.6 bcd	14.6 ± 0.2 b	31.6 ± 0.3 a	3.9 ± 0.2 ab	274.7 ± 1 ab	13.7 ± 0.3 ab	1.2 ± 0.3 a	25.8 ± 2.1 a	281.3 ± 34.5 a

[1]The first harvest (H1) was conducted as the scheduled first harvest of the season by the grower, followed by two delayed harvests, after 7 days (H2) and another after 14 days (H3).

[2] Lightness: This parameter represents the brightness of a color, with 0 being black and 100 being white.

[3]Titratable acidity (TA) is expressed as percent citric acid equivalent.

[4]100 berries from each replication were evaluated.

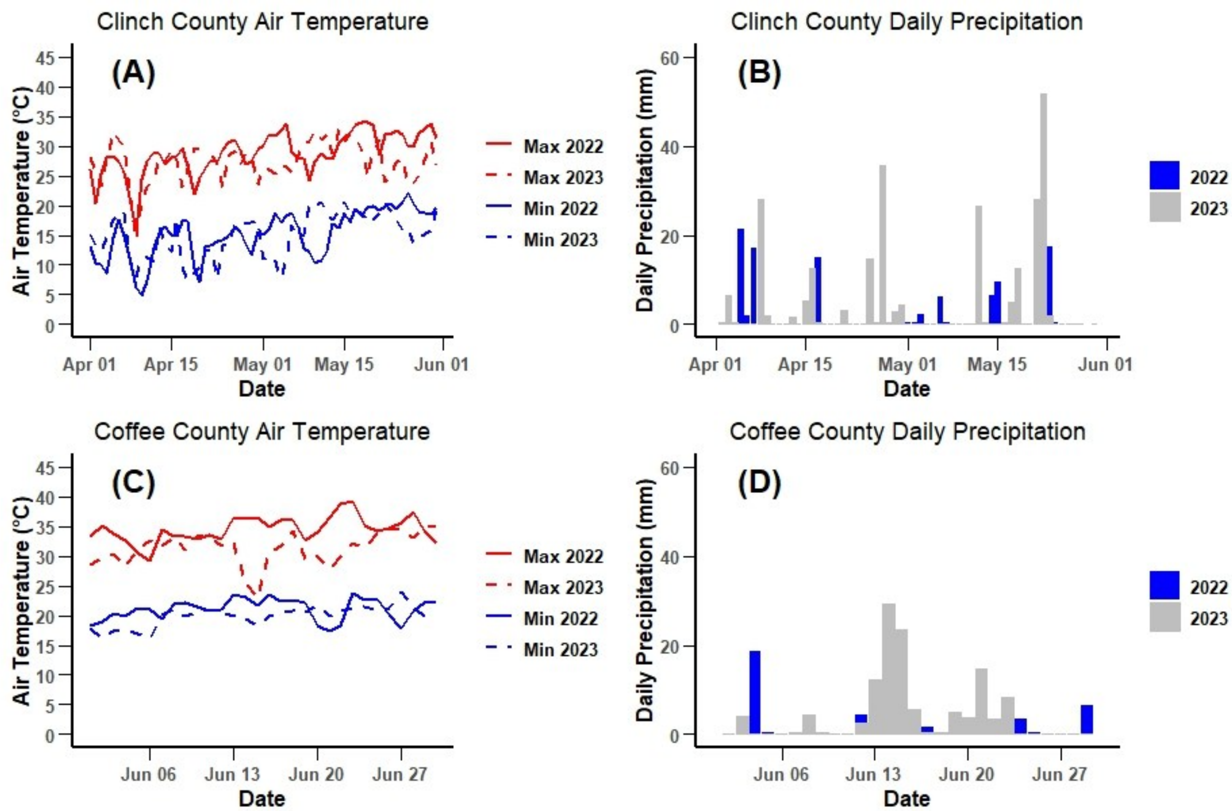

Figure 4.1. Maximum and minimum daily air temperature (A) and daily precipitation (B) in 2022 and 2023 from April 1 to May 31 at Clinch County ('Meadowlark' cultivar), and Maximum and minimum daily air temperature (C) and daily precipitation (D) from June 1 to June 30 at Coffee County ('Brightwell' cultivar). Weather data from the UGA Weather Network.

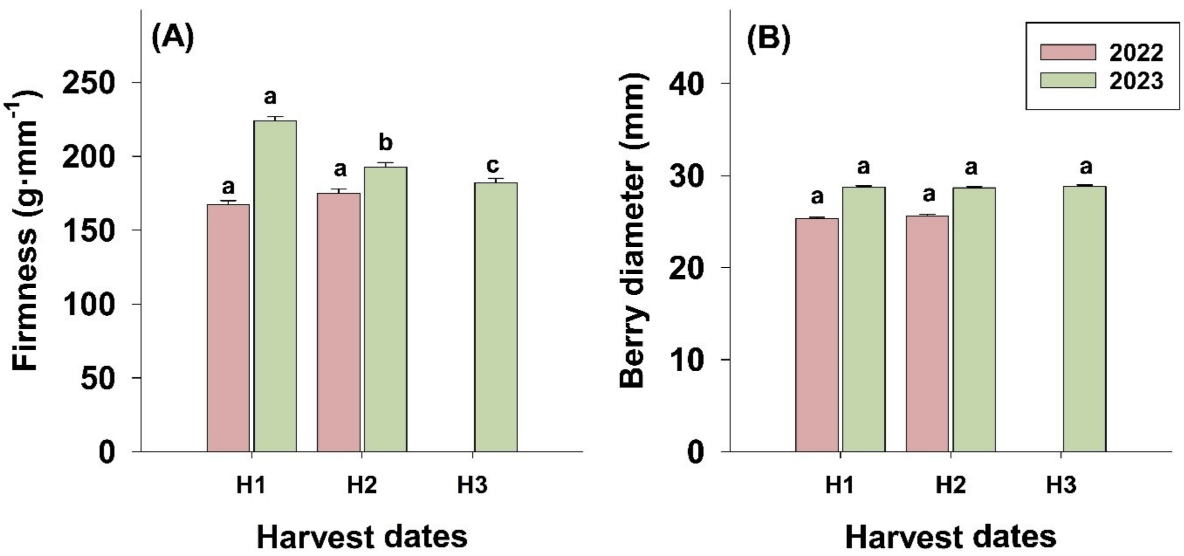

Figure 4.2. Effect of different harvest dates on fruit Firmness (A) and Berry diameter (B) of 'Meadowlark' southern highbush blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

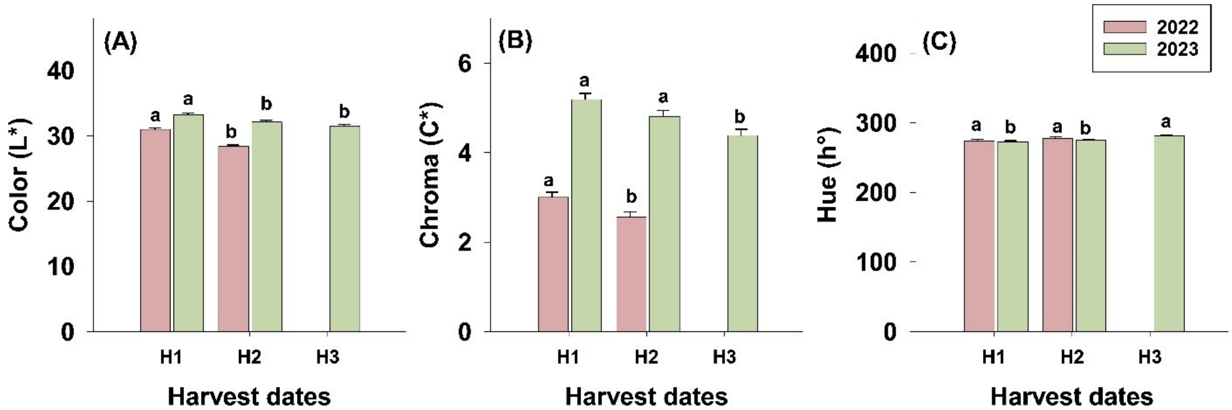

Figure 4.3. Effect of different harvest dates on color parameters, L* (A), Chroma (C*) (B), and Hue (h°) (C) of 'Meadowlark' southern highbush blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

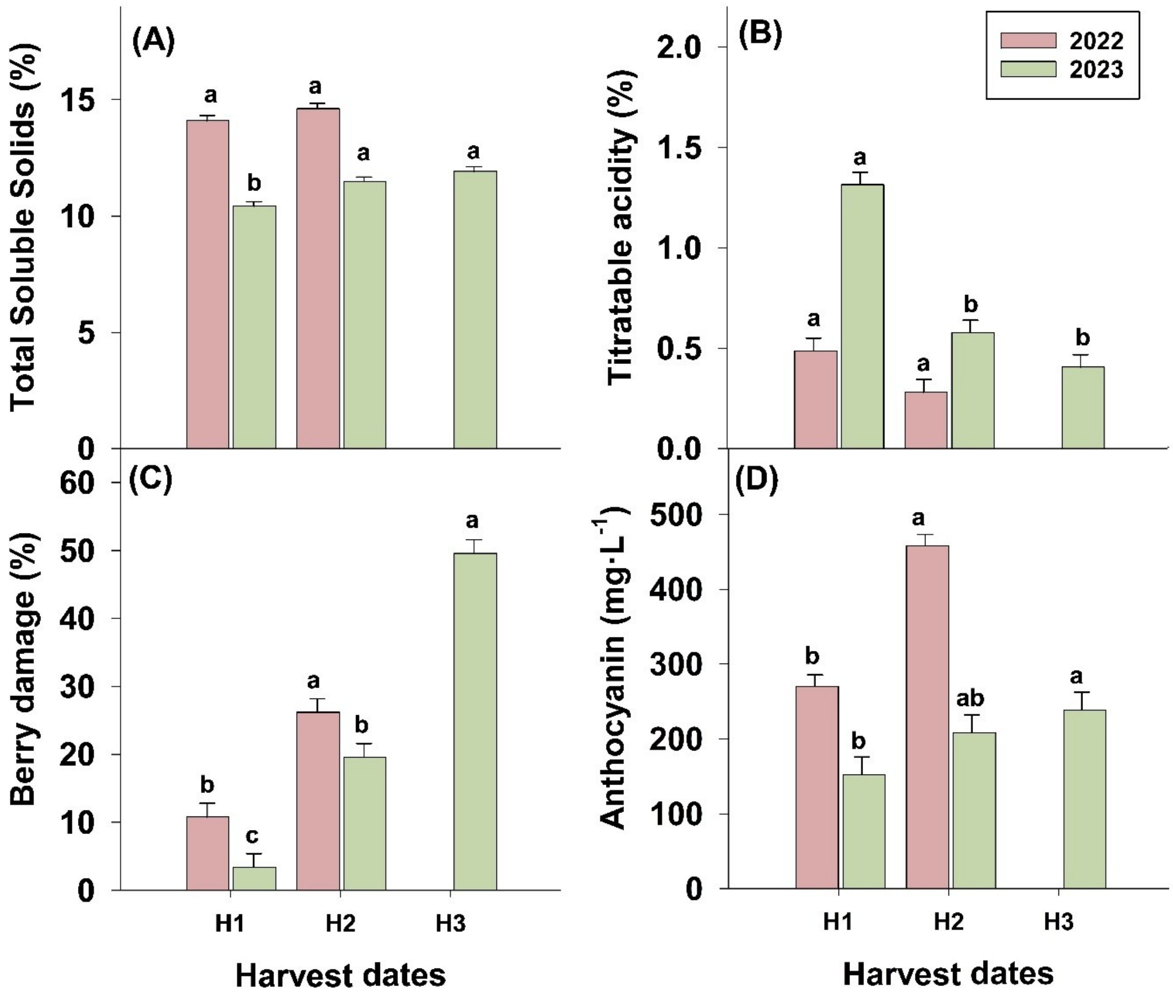

Figure 4.4. Effect of different harvest dates on fruit quality parameters, Total soluble solids (A), Titratable acidity (B), Berry damage (C), and Anthocyanin concentration (D) of 'Meadowlark' southern highbush blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

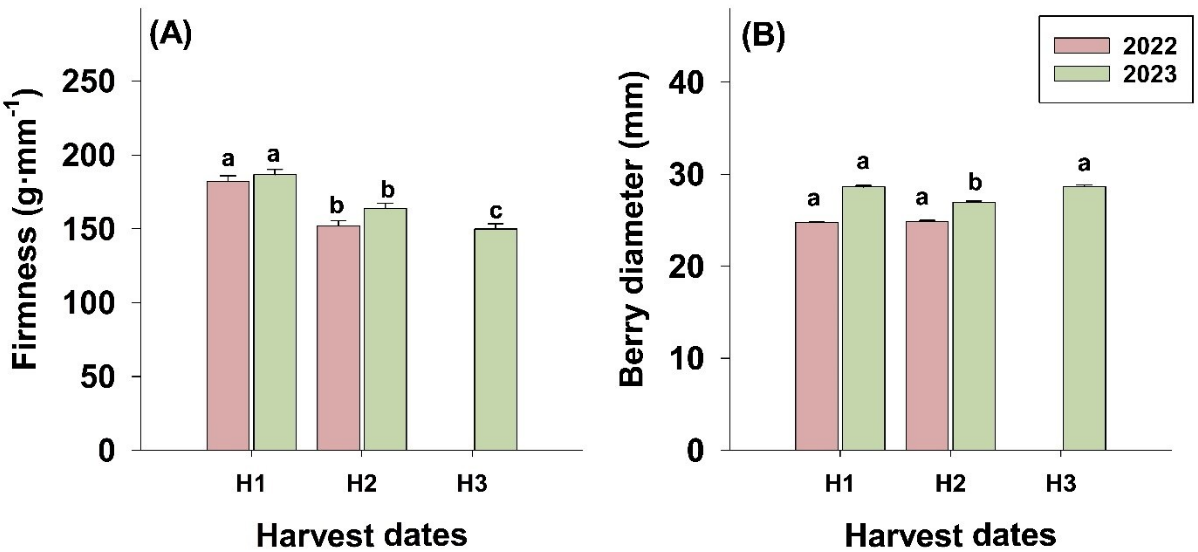

Figure 4.5. Effect of different harvest dates on fruit firmness (A) and Berry diameter (B) of 'Brightwell' rabbiteye blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

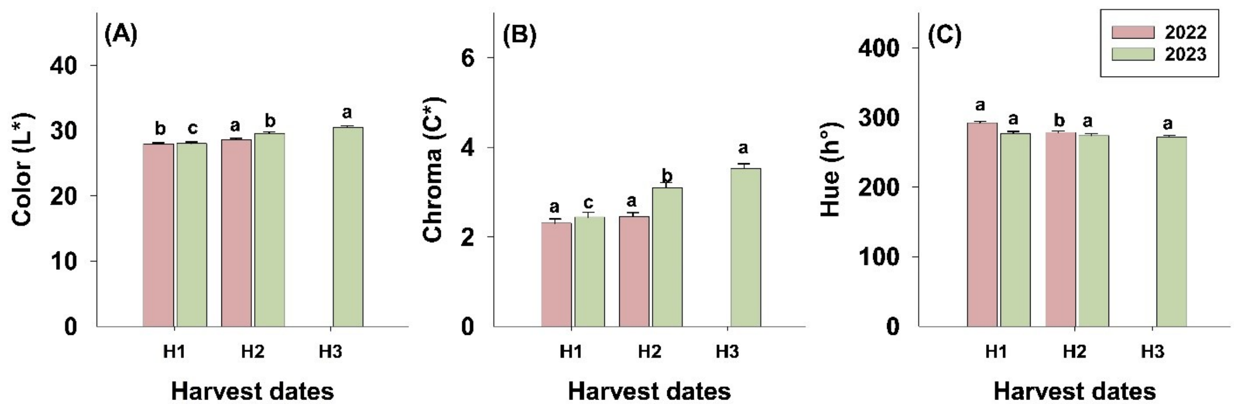

Figure 4.6. Effect of different harvest intervals on color parameters, L* (A), Chroma (C*) (B), and Hue (h°) (C) of 'Brightwell' rabbiteye blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

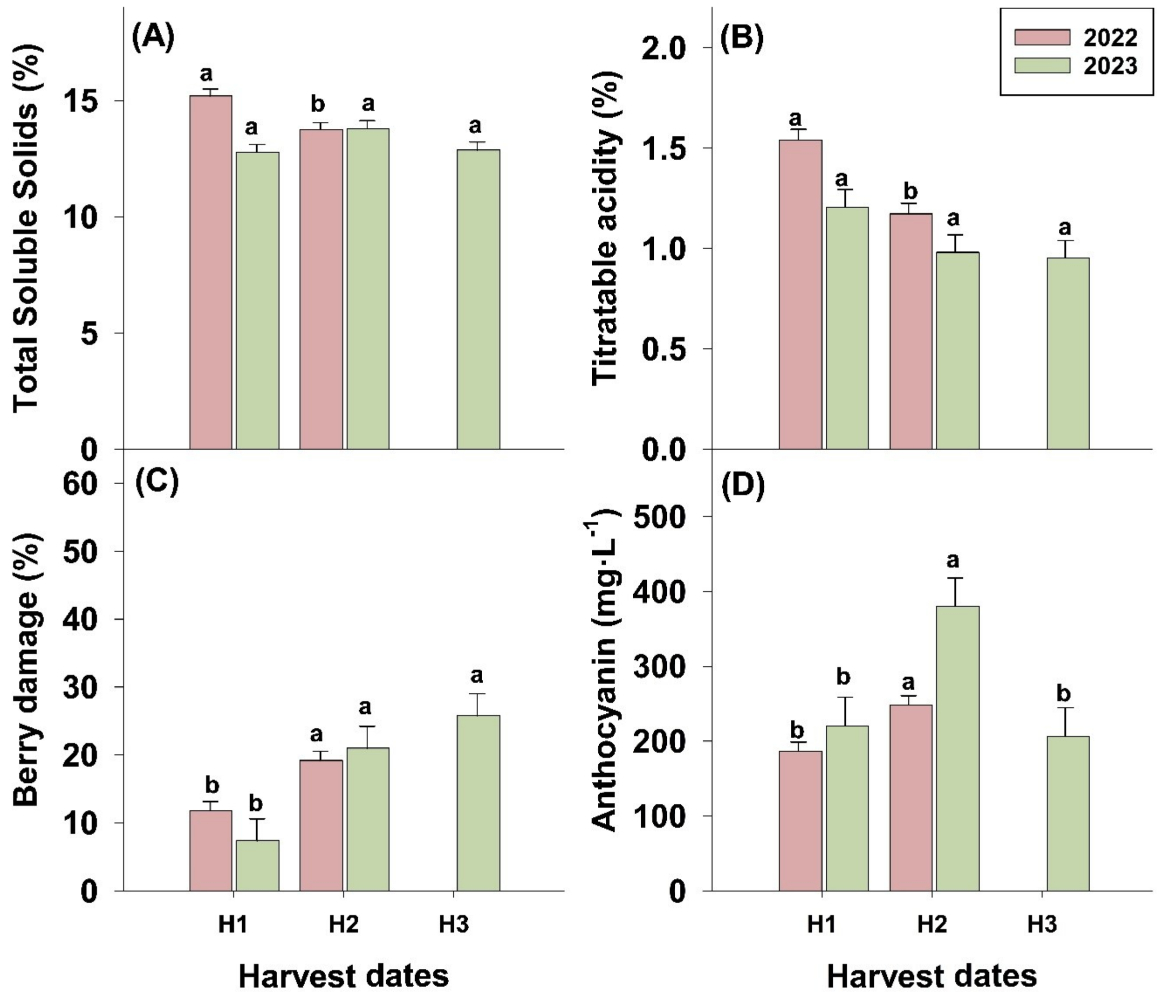

Figure 4.7. Effect of different harvest dates on fruit quality parameters, Total soluble solids (A), Titratable acidity (B), Berry damage (C), and Anthocyanin concentration (D) of 'Brightwell' rabbiteye blueberry in 2022 (pink) and 2023 (green) at harvest. The fruit were harvested at different dates (first commercial harvest: H1, two delayed harvest treatments H2 and H3). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Fisher's least significant difference (LSD) test.

CHAPTER 5
IMPACT OF SHORTER PICKING INTERVALS ON THE STORABILITY AND POSTHARVEST QUALITY OF RABBITEYE BLUEBERRY (*VACCINIUM VIRGATUM*) CV. 'BRIGHTWELL'[3]

[3]Amit Godara, Zilfina Rubio Ames, Angelos Deltsidis. 2024. Submitted in *Frontiers in Plant Science*.

Abstract

The quality and shelf-life of fresh-market blueberries are crucial aspects for both growers and consumers. Different harvesting intervals could be affecting these factors, and understanding changes associated with these issues is essential to optimize postharvest fruit performance. This study evaluated the impacts of different harvest intervals on the postharvest quality and storability of rabbiteye blueberries (*Vaccinium virgatum*) cv. 'Brightwell' in Georgia, USA, during the 2023 and 2024 seasons. Harvesting was carried out at intervals of two days (Trt A), three days (Trt B), and seven days (Trt C). The main quality parameters assessed included berry damage (%), berry diameter, weight loss, firmness, total soluble solids, titratable acidity, and total anthocyanin concentration, measured over 21 days of storage at 1°C and 85% relative humidity. Results demonstrated that fruit harvested with the longest time interval (seven days) exhibited significantly higher weight loss, higher berry damage, and lower firmness, but higher anthocyanin concentrations compared to fruit harvested with two- and three-days intervals. Frequent harvesting (Trt A and B) helped maintain higher fruit firmness, reduced weight loss and minimized postharvest berry damage while maintaining optimal sugars and acid levels. These findings highlight the importance of optimizing harvest intervals, indicating that a three-day harvest interval (Trt B) is an effective option for maintaining postharvest fruit quality and storage potential. This study provides valuable insights for blueberry growers aiming to improve the postharvest life of rabbiteye blueberries under warm climate conditions.

KEYWORDS**:** firmness, weight loss, total soluble solids, anthocyanin, titratable acidity, shelf-life

Introduction

Blueberries (*Vaccinium* spp.), native to North America, are now cultivated in approximately 27 countries worldwide. The United States is considered the largest blueberry global producer, yielding around 648 million pounds from 103,000 harvested acres in 2023 (US Department of Agriculture, 2024; USHBC, 2024). In recent years, consumer demand and scientific interest in this fruit has grown, particularly due to its nutritional value and antioxidant properties. Maintaining fruit quality from harvest to the consumer is essential for ensuring marketability and reducing postharvest losses (Evans & Ballen, 2014; Chen et al., 2015; Edger et al., 2022). In blueberries, visible changes that occur during the later stages of ripening are minimal (Giacalone et al., 2000). However, in this period there are shifts in color, berry size, and internal fruit quality parameters such as total soluble solids (TSS), and titratable acidity (TA). For instance, as the fruit transitions from blue to fully ripe, TSS increases while TA decreases (Sargent et al., 2006; Eichholz et al., 2015). Additionally, the cuticular wax ("bloom"), which is present on the surface of the fruit, varies by cultivar and increases during ripening, playing a vital role in color appearance and postharvest quality (Chu et al., 2018; Yang, 2018). On the other hand, glucose and fructose are the primary sugars present in blueberries, and citric acid is the predominant organic acid, both of which contribute to the flavor profile of the fruit (Forney et al., 2010).

Blueberries exhibit ripening asynchrony, meaning fruit within the same cluster or on the same plant ripen at different times (Vander Kloet & Cabilio, 2010; Daviet et al., 2023). Additionally, the sensory profile remains stable after harvest, which poses challenges for optimizing harvest intervals and postharvest quality management (Vander Kloet & Cabilio, 2010; Heidelbeere et al., 2018). For Georgia growers, the primary sign of blueberry maturity is their color, with the berries generally deemed ready for harvest when they turn completely blue (Rubio personal communication, 2022). However, despite their uniform appearance, blueberries at 100% blue stage within a cluster can vary in maturity stages and physiological age, with some being ripe and others overripe (Moggia et al., 2017b; Lobos et al., 2018). Therefore, surface color alone may no longer be a reliable indicator of physiological maturity (Lobos et al., 2018). The maturity stages of berry at harvest significantly affect the storage potential as berries with advanced maturity stage can result in softening and decay during storage (Lobos et al., 2018; Moggia et al., 2018). Blueberry growers are shifting to machine harvesting due to high labor demands and costs. This change, driven by labor shortages, has led to longer harvest intervals to reduce yield loss, often resulting in a higher percentage of overripe fruit being harvested (Olmstead & Finn, 2014; Gallardo et al., 2018; Lobos et al., 2018). Reducing the number of harvests by increasing the interval between successive picks can help reduce labor costs but may also negatively impact fruit quality, leading to higher postharvest losses (Lyrene, 2006; Takeda et al., 2008; Galinato et al., 2016). Early harvesting, particularly in hand-picked operations, may lead to firmer fruit with better shelf-life (Bremer et al., 2008). Additionally, mechanical harvesting tends to be performed at a more advanced maturity stage to maximize yield efficiency, which can result in greater postharvest losses due to reduced firmness and subsequent fruit damage (Olmstead & Finn, 2014). In regions like Georgia, where climatic conditions such as high temperatures and rainfall occur during harvesting season, extending the harvest interval can result in a higher percentage of overripe berries, leading to increased weight loss and fruit softening during storage. Furthermore, it can increase issues such as fruit splitting, wet stem scar, sunburn, and loss of firmness, ultimately reducing the storage life and marketability of the fruit (Lyrene, 2006; Marshall et al., 2006; Lobos et al., 2014; Yang, 2018).

This study aims to evaluate the effects of different harvest intervals on the postharvest quality of rabbiteye blueberries in Georgia, USA, focusing on key quality attributes such as berry diameter, firmness, weight loss, TSS, and TA over multiple storage durations. We hypothesize that longer harvest intervals will result in postharvest losses due to the accumulation of overripe fruit, particularly in terms of firmness and weight loss. This research seeks to provide insights into optimizing harvest intervals to minimize spoilage and enhance the overall quality and marketability of rabbiteye blueberries cv. 'Brightwell.'

Materials and Methods

Experimental site

The field experiment on 'Brightwell' rabbiteye blueberries (*Vaccinium virgatum*) was conducted over the 2023 and 2024 seasons at the University of Georgia blueberry research farm in Alma, GA (lat. 31°32′05″N; long. 82°30′35″W). The research site experiences a humid subtropical climate characterized by warm summers and frequent rainfall during harvest (Fig. 5.1. A&B). All agronomic practices, including fertilization, were conducted in accordance with the blueberry commercial guidelines established by the University of Georgia for blueberry production (Kissel & Sonon, 2018b, 2018a).

Experimental design

The experiment was established using a randomized complete block design. The study conducted in this experiment involved three treatments, each treatment with a specific harvest interval such as, two days (Trt A), three days (Trt B), and seven days (Trt C). Treatments were replicated four times, with 10 plants per replication, and three harvests were carried out from each designated interval. Harvest 1 in 2023 (June 5) and 2024 (June 3) was conducted on the same day across all treatments. This date was based on the first commercial harvest of the season to simulate typical commercial harvesting conditions. Fruit were hand harvested and stored at 19°C during transportation to the Vidalia Onion Research Laboratory (Postharvest lab) in Tifton, Georgia. Upon arrival, fruit were hand sorted, filled into vented six-ounce clamshells, and stored at 1°C and 85% relative humidity (RH) for up to 21 days. Fruit parameters were assessed at harvest and subsequently after 7, 14, and 21 days of cold storage. For each evaluation at harvest and after cold storage (7, 14, and 21 days), three clamshells were used per replication, resulting in a total of 12 clamshells per evaluation (three clamshells x four replications). Since each harvest and treatment were evaluated four times during the study, a total of 48 clamshells (3 x 4 x 4) were used for quality assessments. Additionally, a separate set of clamshells was designated specifically for monitoring weight loss, following the same storage arrangement.

Postharvest laboratory analysis

The postharvest quality traits were analyzed at harvest and subsequently weekly from the day of harvest (evaluation times of fruit were 7, 14, and 21 days after harvest, as indicated above). Weight loss was measured with a digital balance and calculated by subtracting the initial weight of the clamshell from the final weight of the clamshell containing fruit. The difference between the initial and final weights was then divided by the initial weight and multiplied by 100 to express the weight loss as a percentage.

Percentage (%) weight loss was calculated according to the following equation:

Weight Loss (%): $(W_i - W_f)/Wi \cdot 100$

Where, W_i is the initial weight (Day 1), and W_f is the final weight after 21 days of storage.

Berry damage was evaluated on 100 fruit samples per replicate. Symptoms of splitting and juice leakage from the pedicel, wet scar, and skin tearing were visually assessed. The percentage (%) of oozing and splitting incidence was calculated as follows:

Berry damage (%): $\frac{\text{Number of oozing and splitting fruit}}{\text{Total number of tested fruit}} \cdot 100$

Berry diameter and firmness were measured in 25 fruit per replication using a digital fruit firmness machine (FruitFirm® 500, CVM Inc. Pleasanton, CA). Total soluble solids (TSS), titratable acidity (TA), and anthocyanin concentration was evaluated in samples from 100 g of berries, which were processed using a tissue homogenizer (PowerGen 500, Fisher Scientific, Schwerte, Germany) and then centrifuged at 4 °C and 9,000 rpm using a centrifuge (Sorvall X4R Pro-MD, Thermo Scientific, Osterode, Germany). The supernatant was filtered through cheesecloth, stored in plastic vials, and frozen at -20°C for further analysis. TSS was measured using a digital refractometer (Atago 3810 PAL-1, Tokyo, Japan), and the results were expressed as a percentage. TA was quantified by diluting six milliliter of blueberry sample in 50 mL deionized water and titrated with a 0.1 mol L^{-1} NaOH solution using a titrator (916 Ti-Touch titrator equipped with an 810 Sample Processor, Metrohm AG, Herisau, Switzerland), and the results were reported as percent citric acid. Anthocyanin concentrations were measured according to the protocol described by Giusti and Wrolstad (2001). Briefly, blueberry juice was diluted separately with two different buffer solutions, a 0.025 M potassium chloride (KCl) buffer at pH 1.0, followed by 0.4 M sodium acetate (CH_3COONa) buffer at pH 4.5. Absorbance was measured using a microplate spectrophotometer, (BioTek, Epoch 2, Winooski, Vermont, USA) at two different wavelengths, 520 and 700 nm. A blank cell filled with deionized water was used as the reference. The monomeric anthocyanin concentration in the sample was calculated using the following formula:

Total Anthocyanin concentration ($mg \cdot L^{-1}$): $\frac{A * MW * DF * 1000}{\varepsilon * 1}$

Where: A = Absorbance at a given wavelength

$A = (A_{520\,nm} - A_{700\,nm})_{pH\,1.0} - (A_{520\,nm} - A_{700\,nm})_{pH\,4.5}$

$(A_{520\,nm} - A_{700\,nm})_{pH\,1.0}$: Measures anthocyanin absorbance at pH 1.0

$(A_{520\ nm} - A_{700\ nm})_{pH\ 4.5}$: Measures anthocyanin absorbance at pH 4.5

MW: 449.2 (cyanidin-3-glucoside molecular weight)

DF: dilution factor

Ɛ: 26,900 (molar absorptivity)

Statistical analyses

Data were subjected to analysis of variance (ANOVA) and one-way analysis of variance was conducted using JMP pro 17 software (SAS Institute, Cary, NC) on variables measured at harvest and during postharvest storage. Analyses were conducted separately by year and harvests. Comparisons were made between harvest intervals at storage and within each storage duration. The Tukey's honestly significant difference (HSD) was used for mean separation at a significance level of $\alpha = 0.05$. Graphs were generated using SigmaPlot 15.0 (Systat Software Inc., San Jose, CA) and RStudio software (RStudio, PBC, Vienna, Austria).

Results

Air temperatures in June of 2024 were elevated compared to June 2023, as shown in Fig. 5.1A, pointing to a warmer harvesting season. In contrast, precipitation levels throughout the month of June were greater in 2023 than in 2024, as shown in Fig. 5.2B. These findings highlight notable interannual fluctuations in both temperature and rainfall, which are essential for interpreting regional climate patterns.

Berry weight loss (%)

Berry weight was not significantly different between treatments after 21 days of cold storage in harvest 1 in 2023 and 2024. In 2023 and 2024, berries from Trt C (seven-day interval) consistently exhibited the highest weight loss compared to Trt A and B (two- and three-day intervals respectively) in harvests 2 and 3 (Fig. 5.2A and 5.2B). Specifically, in 2024, after 21 days of storage, weight loss for Trt C berries reached 15.5%, significantly higher than Trt A and B in harvest 3 (Fig. 5.2B).

Berry damage (%)

The percentage of berry damage at harvest 1 showed no significant differences between treatments during the 2023 and 2024 seasons (Fig 5.3A and 5.3C). In 2023, Trt A and B had the lowest number of damaged berries at harvests 2 and 3, whereas Trt C exhibited the highest damage rates, with 27% and 41.5% of berries damaged at harvests 2 and 3, respectively (Fig. 5.3A). In 2024, Trt C had a significantly higher percentage of damaged berries (30.5%) compared to Trt A at harvest 3 (Fig. 5.3C). During storage, harvest 1 did not show significant differences in berry damage throughout storage duration (Table 5.1). In 2023, the damage percentage after 21 days of storage was 37.5% for harvest 2 and 44.5% for harvest 3. In 2024, these percentages were lower, at 20% for harvest 2 and 31% for harvest 3 (Table 5.1).

Berry diameter

Berry diameter evaluated at harvest 1 and 2 was not significantly affected by treatments in both years (Fig. 5.3B and 5.3D). However, at harvest 3 of 2023 and 2024, Trt A berries had significantly lower berry diameters compared to Trt B and C (Fig. 5.3B and 5.3D). Berry diameter produced mixed results during storage in 2023 and 2024 and harvest 1 did not show significant differences (Table 5.1). After seven days of cold storage, in both years evaluated, Trt A and B berries in harvest 2 and 3, were significantly larger compared to Trt C (Table 5.1). After 14 days of storage, berry diameter was significantly bigger in Trt C compared to Trt A in harvest 2 while in harvest 3, Trt B berries had a bigger diameter compared to Trt A and C in 2023 and 2024 (Table 5.1). It should be noted that after 21 days of storage, there were no significant differences in berry diameter for harvests 2 and 3 in both years.

Firmness

Firmness at harvest 1 was not significantly influenced by treatments in 2023 and 2024 (Fig. 5.4A and 5.5A). However, in both years analyzed, berries from Trt B collected at harvest 2 exhibited the highest firmness, while Trt C recorded the lowest firmness of 181.39 $g \cdot mm^{-1}$ in 2023 and 185.92 $g \cdot mm^{-1}$ in 2024. At harvest 3, berries of Trt A and B resulted in the highest firmness, whereas Trt C consistently showed the lowest firmness of 151.63 $g \cdot mm^{-1}$ in 2023 and 155.01 $g \cdot mm^{-1}$ in 2024 (Fig. 5.4A and 5.5A). After seven days of storage, berry firmness was significantly higher in Trt B berries compared to Trt C in the harvests 2 and 3, in both years analyzed (Table 5.2). Additionally, at the same harvest, firmness evaluated after 14 days of storage was significantly higher for Trt B compared to Trt A and C. In 2023 and 2024, after 21 days of storage, berry firmness in harvest 2 was significantly higher for Trt B compared to Trt C. Besides, in harvest 3, blueberries of Trt A and B had higher firmness compared to Trt C (Table 5.2).

Total Soluble Solids (%)

The total soluble solids (TSS) assessed at harvest 1 did not exhibit significant differences among the treatments in 2023 and 2024. However, in 2023, Trt A and B berries showed higher TSS levels of 14.52% and 15.30% at harvest 2 compared to Trt C, whereas no significant differences in TSS were observed at harvest 2 in 2024 (Fig. 5.4B and 5.5B). It should be noted that at harvest 3, berries from Trt C showed significantly higher TSS levels. Specifically, in 2023, TSS levels were 14.20% for Trt C, compared to 12.45% and 13.00% for Trt A and B, respectively. A similar trend was observed in 2024, with Trt C recording a TSS of 14.36%, while Trt A and B had TSS levels of 12.61% and 13.16%, respectively. (Fig. 5.4B and 5.5B).

Berries from harvest 1 did not show significant differences in TSS levels during storage (Table 5.2). In 2023 and 2024, TSS after seven days of storage was not significantly affected by treatments in berries from harvest 2, however, in harvest 3, Trt A berries had significantly higher TSS compared to Trt C berries (Table 5.2). After 14 days of storage in both years evaluated, Trt B berries exhibited the highest TSS compared to Trt C in harvest 2 while for harvest 3, Trt A berries had higher TSS compared to Trt B and C (Table 5.2). After 21 days of storage in 2023 and 2024, no significant differences in TSS in harvest 2 were observed among the treatments, but in harvest 3, Trt C berries showed significantly lower TSS compared to Trt A and B in both years (Table 5.2).

Titratable Acidity

Titratable acidity (TA) at harvests 1 and 2 was not significantly affected by treatments in 2023 and 2024. However, at harvest 3 berries of Trt A showed significantly higher TA of 1.53% and 1.51% compared to Trt B and C (Fig. 5.4C and 5.5C). During the storage period, the TA of blueberries remained relatively stable across the harvests but between treatments, significant differences were observed. For instance, the TA of berries from harvest 2 after seven days of storage was not significantly different but in harvest 3, Trt A berries had significantly higher TA compared to Trt C during both years (Table 5.2). After 14 days of storage, the TA of berries was significantly higher for Trt A and B compared to Trt C in harvests 2 and 3 in 2024. After 21 days of storage, no significant differences in TA were observed in harvest 2 between 2023 and 2024. However, in harvest 3, Trt A and B maintained higher TA levels than Trt C in both years (Table 5.2).

Anthocyanins Concentration

In both 2023 and 2024, anthocyanins concentration was significantly higher in blueberries in Trt C compared to Trt A and B at harvests 2 and 3 (Fig. 5.4D & 5.5D). This trend continued through storage days 7, 14, and 21 with the berries from Trt C consistently showing the highest anthocyanin concentration across harvests 2 and 3 in both years (Table 5.2).

Discussion

The results of this study demonstrated that harvest intervals have a significant impact on the postharvest quality and storability of rabbiteye blueberries cv. ‘Brightwell’, particularly in terms of weight loss, berry damage, firmness, total soluble solids (TSS), titratable acidity (TA), and anthocyanin concentration. The significant weight loss observed in Trt C, with longer harvest intervals, across both 2023 and 2024, suggests that extended periods between harvests contributed to greater weight loss during the 21-day storage period. Furthermore, the advanced ripeness stage in Trt C likely makes these berries more susceptible to dehydration. In this sense, more frequent harvests, as seen in Trt A and B, helped mitigate the weight loss issue by ensuring berries were collected at an optimal ripeness stage, thus reducing postharvest weight loss. As fruits ripen, their internal structure changes, since they undergo a softening process driven by the enzymatic breakdown of cell wall components, including pectin, cellulose, and hemicellulose (Proctor & Miesle, 1991; Silva et al., 2005; Chen et al., 2015). Weakening cell walls can make fruits more prone to softening and weight loss (Silva et al., 2005; Chen et al., 2015). Thus, accumulation of overripe and soft fruit could lead to increased softening incidence, higher weight loss, damage, and decay during storage, resulting in lower firmness and poor overall quality (Moggia et al., 2017b; Lobos et al., 2018; Strik, 2019).

In the present study, a high percentage of berry damage was found in fruit harvested with longer intervals (Trt C), which may also contribute to high weight loss during storage. Specifically, the fruit of those treatments exhibited a weight loss of 15%, which was related to a significant decrease in firmness in the second and third harvests. Moggia et al. (2017a), reported that factors such as stem scar or berry damage can also increase water loss and reduce firmness in blueberries during storage. Maintaining weight loss below 8% helps to preserve firmness, whereas exceeding this threshold can significantly affect the texture and firmness of the fruit (Paniagua et al., 2013). Firmness is crucial for marketability, as firmer berries are less prone to mechanical damage and decay during postharvest handling (Vicente et al., 2007). Our research shows that lower berry damage rates in blueberries from Trt A and B highlight how frequent harvesting helps maintain postharvest fruit quality and reduce damage. These outcomes emphasize the importance of minimizing weight loss by shorter picking intervals to maintain postharvest fruit quality. This is consistent with the findings of Miller et al. (1988), Chen (2006), Lobos et al. (2018), and Moggia et al. (2022), that reported higher postharvest damage susceptibility in blueberries harvested at weekly intervals to due to the presence of overripe berries, which are more prone to decay compared to ripe or immature berries. Recent work from our group in southern highbush and rabbiteye blueberries in Georgia confirmed that delaying harvests by one or two weeks, negatively impacts quality at harvest and during storage (Godara et al., 2025).

The ripening process along with the accumulation of overripe fruit significantly affects fruit firmness at harvest and during storage (Strik, 2019; Moggia et al., 2022). Therefore, frequent harvesting, (Trt A and B), could contribute to maintaining higher firmness levels both at harvest and during storage. Lobos et al. (2018), reported that six-day harvest intervals reduce firmness by increasing the proportion of overripe fruit. According to Moggia et al. (2017b), fruit that remains on the bush after maturity tends to be softer at harvest and during storage, which was also confirmed by a similar trend in the present work. Strik (2019), reported that harvesting frequency of 8 and 12 days resulted in lower firmness. Similarly, the decline in firmness observed in fruit harvested every seven days, is the result of the accumulation of overripe fruit, which softens more rapidly during storage (Lobos et al., 2018; Moggia et al., 2018; Strik, 2019; Moggia et al., 2022).

In fruits, total soluble solids (TSS) and titratable acidity (TA) are the primary determinants of flavor which change during fruit ripening (Zhang et al., 2020). In this work, the increase in TSS and decline in TA in blueberries across all treatments during ripening and storage was consistent as soluble solids continued to accumulate and acids were metabolized and declined as blueberries ripened, an effect that has been previously reported by several authors (Sargent et al., 2006; Lobos et al., 2018; Moggia et al., 2018; Strik, 2019; Lin et al., 2020; Shi et al., 2023). The relatively higher TSS values in blueberries from Trt C during harvest 3 can be attributed to their advanced ripening stage (Lobos et al., 2018; Strik, 2019). Lobos et al. (2018) found that fruit harvested six days after full maturity were high in TSS and low in TA compared to fruit harvested at 100% blue stage. The overripe fruit exhibited a more dramatic decline in TSS during a 45-day cold storage period. Similarly, in the present study, TSS was higher in blueberries harvested from Trt C during harvest 3, but it declined more pronouncedly after storage. Anthocyanins are responsible for the blue pigmentation of blueberries and consistently increase during fruit ripening (Zifkin et al., 2012). The higher anthocyanin levels in Trt C can be attributed to the longer ripening period before harvest, which allows for greater pigment accumulation (Kalt et al., 2003). As blueberries ripen, anthocyanin accumulation increases alongside sugars, reaching peak concentration at stage eight, indicating full pigment development (Acharya et al., 2024). In the present work the anthocyanins concentration was significantly higher in berries from Trt C which confirms the natural progression of anthocyanin biosynthesis. This highlights the importance of balancing anthocyanin content with other quality attributes like firmness, berry weight, and susceptibility to decay which can effectively achieved by optimizing harvest intervals.

Conclusion

In conclusion, optimizing harvest intervals is critical for maintaining the quality of fresh-market blueberries during storage. This study highlights the importance of frequent, timely harvesting, especially in warm, humid climates like Georgia, where temperature fluctuations and precipitation can impact fruit ripening and postharvest physiology. Extending the interval for more than seven days between successive harvests reduces firmness, TA, and increases weight loss and damage to berries. The findings from this study provide valuable insights for blueberry growers and industry professionals. A moderate harvest interval of three days, as seen in Trt B, helps maintaining postharvest quality by minimizing weight loss, and reducing damage, while maintaining optimal firmness, TSS, and TA levels. In contrast, longer harvest intervals (e.g., seven days) may lead to increased anthocyanin concentrations but at the expense of firmness and higher postharvest damage.

Acknowledgments

We express our sincere gratitude to the managers of the University of Georgia blueberry research farms for supporting the study. Special thanks to Dr. Zhiheng Xing and Dr. Jakeline Zuluaga Acosta for reviewing and editing the manuscript.

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Table 5.1. Effects of harvest intervals on fruit quality parameters, including fruit size and incidence of berry damage, during storage at 1°C and 85% RH across 7, 14, and 21 days for the 'Brightwell' cultivar in 2023 and 2024. For each parameter, values are presented as mean ± standard error (SE), with comparisons made between treatments within each storage period. Statistically significant differences ($p \leq 0.05$) based on the Tukey's honestly significant difference (HSD) test are indicated by different letters, denoting significant differences in fruit quality at each respective storage duration.

Treatment[1]	Harvest	Storage Day	Berry damage[2] (%)		Berry diameter (mm)	
			2023	2024	2023	2024
Treatment A	Harvest 1	7	7.5 ± 1.1 a	5.5 ± 1.1 a	25.8 ± 0.4 a	26.1 ± 0.4 a
Treatment B	Harvest 1	7	10.5 ± 1.1 a	4.5 ± 1.1 a	25.3 ± 0.4 a	25.6 ± 0.4 a
Treatment C	Harvest 1	7	10 ± 1.1 a	4 ± 1.1 a	25.3 ± 0.4 a	25.6 ± 0.4 a
Treatment A	Harvest 1	14	15 ± 1.8 a	12 ± 2.8 a	25.2 ± 0.3 a	25.5 ± 0.3 a
Treatment B	Harvest 1	14	12.5 ± 1.8 a	11.5 ± 2.8 a	25.4 ± 0.3 a	25.7 ± 0.3 a
Treatment C	Harvest 1	14	13 ± 1.8 a	9 ± 2.8 a	24.6 ± 0.3 a	24.9 ± 0.3 a
Treatment A	Harvest 1	21	14.5 ± 2.5 a	11 ± 1.6 a	12.8 ± 0.4 a	12.9 ± 0.4 a
Treatment B	Harvest 1	21	16.5 ± 2.5 a	10.5 ± 1.6 a	12.9 ± 0.4 a	13.1 ± 0.4 a
Treatment C	Harvest 1	21	15.5 ± 2.5 a	7.5 ± 1.6 a	12.4 ± 0.4 a	12.6 ± 0.4 a
Treatment A	Harvest 2	7	21.5 ± 2.7 a	11 ± 2.4 b	30 ± 0.3 a	30.3 ± 0.3 a
Treatment B	Harvest 2	7	18 ± 2.7 a	8.5 ± 2.4 b	30.4 ± 0.3 a	30.8 ± 0.3 a
Treatment C	Harvest 2	7	27 ± 2.7 a	24.5 ± 2.4 a	24.8 ± 0.3 b	25.1 ± 0.3 b
Treatment A	Harvest 2	14	19 ± 2.2 ab	11.5 ± 1.8 ab	10.9 ± 0.3 b	11.2 ± 0.3 b

Treatment B	Harvest 2	14	15 ± 2.2 b	9 ± 1.8 b	11.4 ± 0.3 ab	11.7 ± 0.3 ab
Treatment C	Harvest 2	14	28.5 ± 2.2 a	16 ± 1.8 a	11.9 ± 0.3 a	12.3 ± 0.3 a
Treatment A	Harvest 2	21	18.5 ± 2.8 b	10.5 ± 1.8 b	14.4 ± 0.3 a	14.6 ± 0.4 a
Treatment B	Harvest 2	21	13.5 ± 2.8 b	7.5 ± 1.8 b	14.1 ± 0.3 a	14.3 ± 0.4 a
Treatment C	Harvest 2	21	37.5 ± 2.8 a	20 ± 1.8 a	14.2 ± 0.3 a	14.4 ± 0.4 a
Treatment A	Harvest 3	7	17.5 ± 2.5 b	14 ± 2.5 b	24 ± 0.3 a	24.2 ± 0.4 a
Treatment B	Harvest 3	7	8 ± 2.5 c	6.5 ± 2.5 b	23.5 ± 0.3 a	23.9 ± 0.4 a
Treatment C	Harvest 3	7	43.5 ± 2.5 a	29 ± 2.5 a	12.2 ± 0.3 b	12.3 ± 0.4 b
Treatment A	Harvest 3	14	19.5 ± 3 b	13.5 ± 2.2 b	11.3 ± 0.5 c	11.6 ± 0.5 b
Treatment B	Harvest 3	14	11.5 ± 3 b	6 ± 2.2 c	26.4 ± 0.5 a	26.8 ± 0.5 a
Treatment C	Harvest 3	14	45.5 ± 3 a	30.5 ± 2.2 a	14.3 ± 0.5 b	14.7 ± 0.5 c
Treatment A	Harvest 3	21	20 ± 2.8 b	6.5 ± 3 b	13.4 ± 0.8 a	13.6 ± 0.8 a
Treatment B	Harvest 3	21	12.5 ± 2.8 b	8.5 ± 3 b	13.3 ± 0.8 a	13.6 ± 0.8 a
Treatment C	Harvest 3	21	44.5 ± 2.8 a	31 ± 3 a	10.7 ± 0.8 a	10.9 ± 0.8 a

[1]Harvest intervals where Treatment A: 2 days. Treatment B: 3 days, and Treatment C: 7 days.

[2]100 berries from each replication were evaluated.

Table 5.2. Effects of harvest intervals on fruit quality parameters, including firmness, total soluble solids, titratable acidity, and anthocyanin concentration, during storage at 1°C and 85% RH across 7, 14, and 21 days for the 'Brightwell' cultivar in 2023 and 2024. For each parameter, values are presented as mean ± standard error (SE), with comparisons made between treatments within each storage period. Statistically significant differences ($p \leq 0.05$) based on the Tukey's honestly significant difference (HSD) test are indicated by different letters, denoting significant differences in fruit quality at each respective storage duration.

Treatment[1]	Harvest	Storage Days	Firmness (g·mm^{-1})		Total soluble solids (%)		Titratable acidity[2] (%)		Anthocyanins concentration[3]	
			2023	2024	2023	2024	2023	2024	2023	2024
Treatment A	Harvest 1	7	161.4 ± 5.8 a	165.4 ± 6 a	12.6 ± 0.8 a	13 ± 0.7 b	0.8 ± 0.1 a	0.8 ± 0.1 a	208.8 ± 1.8 a	208.5 ± 1.9 a
Treatment B	Harvest 1	7	167.3 ± 5.8 a	171.5 ± 6 a	15.9 ± 0.8 a	16.1 ± 0.7 a	1 ± 0.1 a	1 ± 0.1 a	207.4 ± 1.8 a	207.4 ± 1.9 a
Treatment C	Harvest 1	7	154.6 ± 5.8 a	158.4 ± 6 a	14.8 ± 0.8 a	15 ± 0.7 ab	0.9 ± 0.1 a	0.9 ± 0.1 a	209.6 ± 1.8 a	210.3 ± 1.9 a
Treatment A	Harvest 1	14	143.4 ± 4.1 a	147 ± 4.3 a	14.2 ± 0.5 a	14.3 ± 0.5 a	0.8 ± 0.1 a	0.8 ± 0.1 a	208.4 ± 2.2 a	208.4 ± 2.7 a
Treatment B	Harvest 1	14	134.7 ± 4.1 a	138.8 ± 4.3 a	15.5 ± 0.5 a	15.7 ± 0.5 a	1 ± 0.1 a	1 ± 0.1 a	209.9 ± 2.2 a	210 ± 2.7 a
Treatment C	Harvest 1	14	126.7 ± 4.1 a	129.9 ± 4.3 a	14.5 ± 0.5 a	14.6 ± 0.5 a	0.8 ± 0.1 a	0.8 ± 0.1 a	208.3 ± 2.2 a	208.1 ± 2.7 a
Treatment A	Harvest 1	21	121.8 ± 4.6 a	124.8 ± 4.7 a	16.3 ± 0.7 a	15.9 ± 0.6 a	0.9 ± 0.1 a	0.8 ± 0.1 a	208.2 ± 2.3 a	208.3 ± 2.1 a
Treatment B	Harvest 1	21	131.5 ± 4.6 a	134.7 ± 4.7 a	15.5 ± 0.7 a	15.6 ± 0.6 a	1.1 ± 0.1 a	1.1 ± 0.1 a	208.5 ± 2.3 a	208.4 ± 2.1 a
Treatment C	Harvest 1	21	122.2 ± 4.6 a	125.3 ± 4.7 ab	15.1 ± 0.7 a	15.2 ± 0.6 a	1 ± 0.1 a	1 ± 0.1 a	204.5 ± 2.3 a	204.7 ± 2.1 a
Treatment A	Harvest 2	7	169 ± 3.3 ab	172.7 ± 3.4 a	13.7 ± 0.7 a	13.8 ± 0.7 a	1.3 ± 0.2 a	1.3 ± 0.2 a	223.2 ± 1.9 b	222.9 ± 2.3 b
Treatment B	Harvest 2	7	173.5 ± 3.3 a	177.7 ± 3.4 a	13.3 ± 0.7 a	13.4 ± 0.7 a	1.2 ± 0.2 a	1.2 ± 0.2 a	222.7 ± 1.9 b	222.3 ± 2.3 b
Treatment C	Harvest 2	7	157.6 ± 3.3 b	161.5 ± 3.4 b	14.2 ± 0.7 a	14.1 ± 0.7 a	0.9 ± 0.2 a	0.8 ± 0.2 a	248 ± 1.9 a	259.6 ± 2.3 a
Treatment A	Harvest 2	14	159.1 ± 4.3 b	163 ± 4.4 b	14.8 ± 0.4 b	15 ± 0.4 ab	1.3 ± 0.1 ab	1.3 ± 0.1 a	222.2 ± 2 b	222.2 ± 1.3 b
Treatment B	Harvest 2	14	176.8 ± 4.3 a	181.3 ± 4.4 a	15.7 ± 0.4 a	15.7 ± 0.4 a	1.4 ± 0.1 a	1.4 ± 0.1 a	223.8 ± 2 b	223.8 ± 1.3 b
Treatment C	Harvest 2	14	147.1 ± 4.3 b	150.5 ± 4.4 b	14.1 ± 0.4 b	14.2 ± 0.4 b	1.1 ± 0.1 b	1 ± 0.1 b	249.5 ± 2 a	269.4 ± 1.3 a
Treatment A	Harvest 2	21	164.5 ± 5.9 ab	171.3 ± 6.5 ab	15.5 ± 0.4 a	15.7 ± 0.4 a	1.2 ± 0.1 a	1.1 ± 0.1 a	221.4 ± 1.7 b	221.6 ± 1.5 b
Treatment B	Harvest 2	21	191.3 ± 5.9 a	195.6 ± 6.5 a	15 ± 0.4 a	15.2 ± 0.4 a	1.2 ± 0.1 a	1.2 ± 0.1 a	222.3 ± 1.7 b	222 ± 1.5 b
Treatment C	Harvest 2	21	150.6 ± 5.9 b	154.3 ± 6.5 b	14.7 ± 0.4 a	14.9 ± 0.4 a	1.2 ± 0.1 a	1.1 ± 0.1 a	253.4 ± 1.7 a	261.6 ± 1.5 a

Treatment A	Harvest 3	7	196.1 ± 5.7 a	200.2 ± 6.2 a	14 ± 0.4 a	14.5 ± 0.3 a	1.7 ± 0.1 a	1.7 ± 0.1 a	224.7 ± 3 b	224.6 ± 3.5 b
Treatment B	Harvest 3	7	191.1 ± 5.8 a	193.2 ± 6.2 a	14 ± 0.4 a	14.2 ± 0.3 a	1.3 ± 0.1 ab	1.3 ± 0.1 b	225.3 ± 3 b	225.6 ± 3.5 b
Treatment C	Harvest 3	7	145.3 ± 5.7 b	147.7 ± 6.2 b	12.4 ± 0.4 b	12.3 ± 0.3 b	1 ± 0.1 b	1 ± 0.1 b	268.9 ± 3 a	262.2 ± 3.5 a
Treatment A	Harvest 3	14	168.9 ± 5 b	173 ± 5.2 b	16.5 ± 0.5 a	16.7 ± 0.5 a	1.4 ± 0.1 a	1.4 ± 0.1 a	225 ± 3.1 b	224.9 ± 2.9 b
Treatment B	Harvest 3	14	193.1 ± 4.9 a	197.7 ± 5.2 a	14.1 ± 0.5 b	14.3 ± 0.5 b	1.4 ± 0.1 a	1.4 ± 0.1 a	224.1 ± 3.1 b	223.9 ± 2.9 b
Treatment C	Harvest 3	14	146.8 ± 5 c	148.7 ± 5.2 c	12.9 ± 0.5 b	12.8 ± 0.5 b	1 ± 0.1 b	1 ± 0.1 b	257.9 ± 3.1 a	266 ± 2.9 a
Treatment A	Harvest 3	21	186.1 ± 5 a	190.8 ± 4.9 a	16.5 ± 0.7 a	16.5 ± 0.8 a	1.7 ± 0.1 a	1.7 ± 0.1 a	224.9 ± 3.9 b	224.5 ± 2.3 b
Treatment B	Harvest 3	21	181.6 ± 5.1 a	184.3 ± 4.9 a	14.9 ± 0.7 b	15.1 ± 0.8 a	1.4 ± 0.1 b	1.4 ± 0.1 a	227.4 ± 3.9 b	227.7 ± 2.3 b
Treatment C	Harvest 3	21	132.3 ± 5 b	135.3 ± 4.9 b	13.5 ± 0.7 b	13.7 ± 0.8 b	0.9 ± 0.1 c	1 ± 0.1 b	262.8 ± 3.9 a	263.7 ± 2.3 a

[1]Harvest intervals where Treatment A: 2 days. Treatment B: 3 days, and Treatment C: 7 days.

[2]Titratable acidity (TA) is expressed as percent citric acid.

[3]Anthocyanin concentration in mg·L^{-1} cyanidin-3-glucoside.

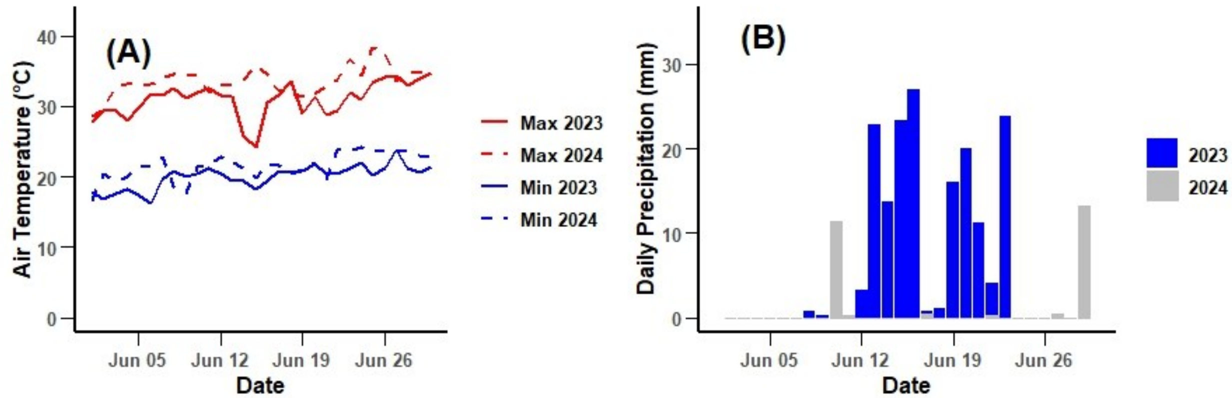

Figure 5.1. Maximum and minimum daily air temperature (A) and daily precipitation (B) in 2023 and 2024 from June 1 to June 31 at Blueberry Research Farm Alma, Bacon County GA. Weather data from the UGA Weather Network.

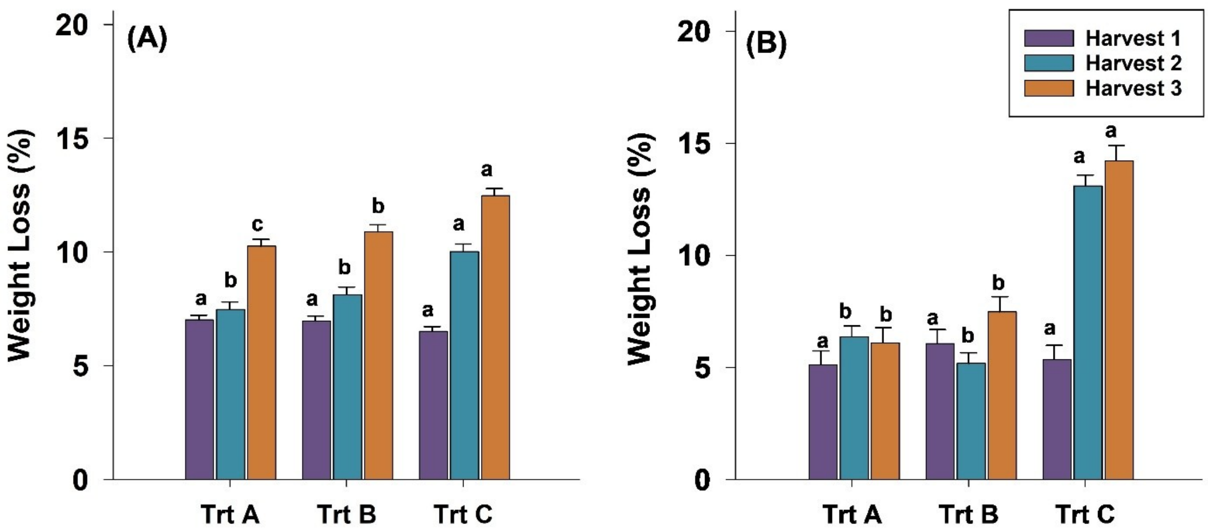

Figure 5.2. Effect of three different harvest intervals on Total weight loss (%) during 21 days of cold storage in 2023 (A), and 2024 (B). Three harvests were conducted on each treatment (Harvest 1: green, Harvest 2: purple. and Harvest 3: blue). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Tukey's honestly significant difference (HSD) test.

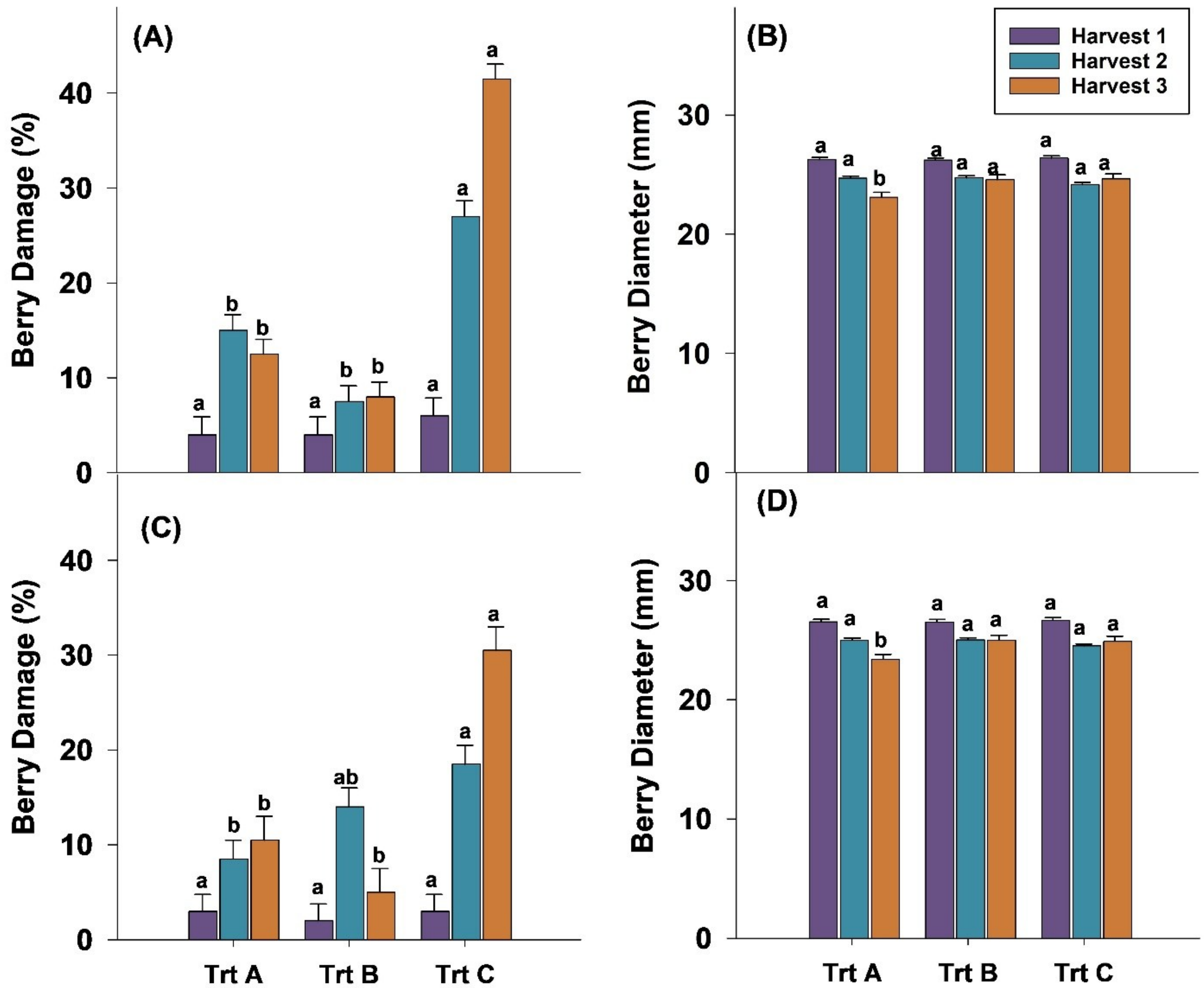

Figure 5.3. Effect of three different harvest intervals on Percentage of berry damage in 2023 (A) and in 2024 (C), and Berry diameter in 2023 (B) and in 2024 (D) on 'Brightwell' cultivar at harvest. Three harvests were conducted on each treatment (Harvest 1: green, Harvest 2: purple. and Harvest 3: blue). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Tukey's honestly significant difference (HSD) test.

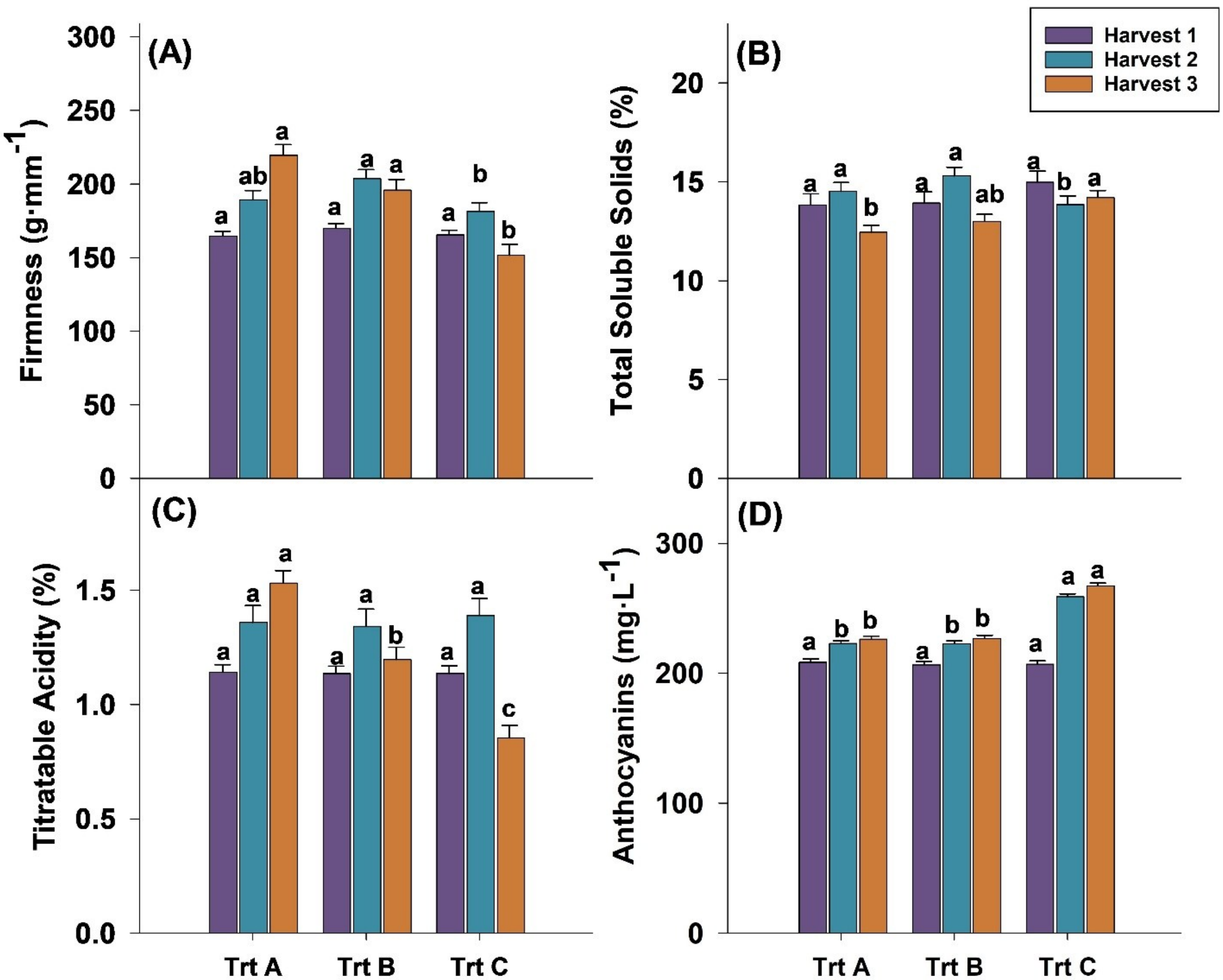

Figure 5.4. Effect of three different harvest intervals on Berry firmness (A), Total soluble solids (B), Titratable acidity (C, and Anthocyanin concentration (D) on the 'Brightwell' cultivar at harvest in 2023. Three harvests were conducted on each treatment (Harvest 1: green, Harvest 2: purple, and Harvest 3: blue). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Tukey's honestly significant difference (HSD) test.

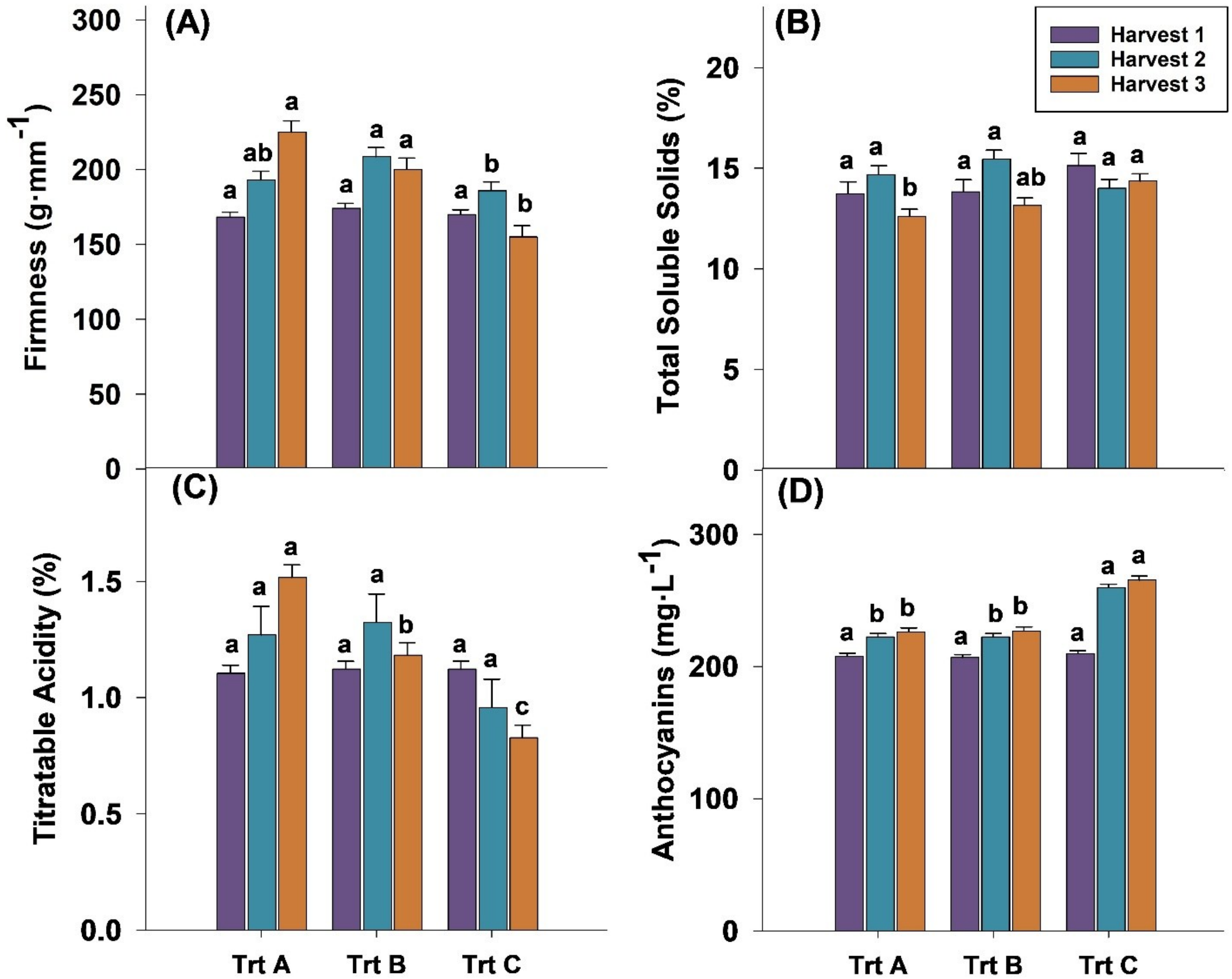

Figure 5.5. Effect of three different harvest intervals on Berry firmness (A), Total soluble solids (B), Titratable acidity (C), and Anthocyanin concentration (D) on the 'Brightwell' cultivar at harvest in 2024. Three harvests were conducted on each treatment (Harvest 1: green, Harvest 2: purple, and Harvest 3: blue). The means followed by the different letters are significantly different at $p \leq 0.05$ based on the Tukey's honestly significant difference (HSD) test.

CHAPTER 6
CONCLUSION

This research provides a comprehensive analysis of the impact of photoselective devices and different harvest intervals on the production and fruit quality of southern highbush and rabbiteye blueberries in Georgia. By implementing photoselective devices like Opti-Gro and ChromaGro, we observed significant improvements in plant morphology, photosynthetic efficiency, yield, and key fruit quality traits such as berry diameter and total soluble solids. The use of photoselective treatments also increased net photosynthesis and stomatal conductance, electron transport rate, and quantum yield of photosystem II suggesting enhanced physiological performance under modified light environments.

The assessment of harvest intervals revealed that extending the time between harvests to seven days led to increased weight loss, reduced firmness, and higher incidences of fruit damage, emphasizing the importance of optimized harvest frequency. A three-day interval provided a balanced approach, maintaining fruit firmness and reducing postharvest quality degradation. These insights are critical for blueberry growers in managing harvest schedules and adopting new technologies to enhance productivity while maintaining fruit quality.

Overall, this study highlights the potential of integrating photoselective devices into blueberry production systems to mitigate environmental stressors and optimize light quality. It also underscores the necessity of strategic harvest management to minimize postharvest losses. The findings contribute valuable knowledge to the blueberry industry, promoting more sustainable and efficient production practices under challenging climatic conditions.