Review

A Review for Southern Highbush Blueberry Alternative Production Systems

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Abstract: Southern highbush blueberry plantations have been expanded into worldwide non-traditional growing areas with elite cultivars and improved horticultural practices. This article presents a comprehensive review of current production systems – alternatives to traditional open field production – such as production in protected environments, high-density plantings, evergreen production, and container-based production. We discuss the advantages and disadvantages of each system and compare their differences to the open field production. In addition, potential solutions have been provided for some of the disadvantages. We also highlight some of the gaps existing between academic studies and production in industry, providing a guide for future academic research. All these alternative systems have shown the potential to produce high yields with high quality berries. Alternative systems, compared to the field production, require higher establishment investments and thus create an entry barrier for new producers. Nevertheless, with their advantages, alternative productions have potential to be profitable.

Keywords: *Vaccinium corymbosum* interspecific hybrids; high tunnel; greenhouse; plant factory; non-dormant; substrate; container; evergreen; high density

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1. Introduction

Blueberry (Vaccinium spp.) consumption has dramatically increased globally over the last 5 years [1]. North America is a traditional market where approximately 58% of all fresh blueberries are consumed [1]. Additionally, demand has rapidly increased in new markets, such as Europe and China. This rising demand has been accompanied by increased production in both traditional and new growing areas around the world. Southern highbush blueberry (SHB, *Vaccinium corymbosum* L. interspecific hybrids) has been instrumental to this expansion thanks to its high fruit quality for fresh market and adaptation to subtropical and tropical production areas.

New cultivars and innovative horticultural practices have enabled profitable SHB cultivation in areas where temperate crops were not common two decades ago [2,3], including parts of South Africa, Spain, Morocco, Mexico, Chile, China, Peru, and Argentina. Alternative production systems combine protected agriculture practices (climate control, precise irrigation and fertilization) and specialized canopy management to increase input use efficiency and shorten plant juvenility. This increases total productivity and can reduce the period of negative cash flow [3,4].

In this comprehensive review, we summarize publications searched with google scholar from 1987 to April 2020 related to SHB alternative production systems, including a) production in protected environments such as high tunnel, greenhouse, and plant factory; b) high-density planting production; c) evergreen production; and d) container-based production. These production systems can either be used together (Figure 1) or independently (Figure 2), according to their applicability in each region. We also used publications from northern highbush blueberry (NHB, *V. corymbosum*), rabbiteye blueberry (*V. virgatum*), and other crops such as tomato, raspberry, strawberry among others to highlight the gap existing between SHB academic studies and industry production.

Figure 1. Southern highbush blueberry planted in a combination of alternative production systems including high tunnel, high density (10,976 plants per hectare), evergreen, and containerized soilless substrate production systems in north Florida.

Figure 2. Southern highbush blueberry containerized soilless substrate production with 5,434 plants per hectare in south Florida.

2. Protected Environments

2.1. High tunnel production

High tunnel production has become popular among raspberry, blackberry, and strawberry producers [5–7]. The mesoclimate inside high tunnels has been shown to accelerate bloom, expedite

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fruit ripening, increase yields, improve berry quality, extend the harvest season, and decrease berry loss from rain and frost [2,5,6,8–10].

Southern highbush blueberry production in unheated high tunnels (Figure 3) has been studied in different countries, including Japan [11], Spain [12], Portugal [13], Chile [2], and the United States [14]. High tunnels increase soil and air temperature around the plant [6,15,16], reducing cold stress or damage [16] and enhancing heat hour accumulation during winter and early spring [11,14,16,17]. Warmer temperatures during the cold parts of the season are widely accepted as the reason for earlier fruit ripening in high tunnels [11,14,16,17]. For example, SHB cultivars 'Snowchaser', 'Emerald', 'Jewel', and 'O'Neal' grown in high tunnels were ready to harvest nearly a month earlier than the same cultivars grown in open field conditions [14,16,18]. High tunnels have supported the northward expansion of SHB cultivation, for example within the United States to areas in Mississippi where only rabbiteye blueberries were previously cultivated [19]. Additionally, the use of high tunnels can significantly reduce water usage for freeze protection, requiring only one-tenth of the total volume used in the open field [16].

Figure 3. Southern highbush blueberry in a high tunnel production system.

While temperature increases during winter and early spring enhance SHB growth, air and soil temperatures inside high tunnels can quickly surpass plant optimal temperatures during late spring and summer. Air temperatures above 30 °C reduce photosynthetic rates in blueberry [20]. Additionally, warm night temperatures (21 °C) can decrease fruit set [21]. Optimal temperature ranges vary among SHB cultivars, and cultivars with recent introgression of subtropical wild species might exhibit greater tolerance for high temperatures [22]. Late-developing cultivars might be particularly challenged by air temperatures inside high tunnels, where poor fruit set could reduce productivity [13].

High tunnels are passively heated and cooled structures. Thus, temperature regulation inside high tunnels relies on ventilation and radiation. Tunnels are commonly ventilated as soon as air temperatures reach around 10 °C. This is a labor-intensive practice if automated roll-up sidewalls are absent. Conversely, higher temperatures in high tunnels may be insufficient for freeze protection during the winter or early spring in the absence of automatic heating systems [23]. Radiative cooling inside high tunnels varies with the weather (cloudy day vs clear day) and type of plastic covering material, for example long-wave-blocking plastic can retain more heat [14,23]. Besides, high tunnels reduce the exchange of convective heat with the surrounding air and thus the cooling impact from pine bark beds (if used) may have increased effects on the plant-level temperature compared to the effects of bark bed in the open field [24]. Therefore, where temperatures drop below 1 °C (34 °F),

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growers use micro-sprinklers to increase air humidity inside the tunnel and provide additional freeze protection [16].

Closed, warm high tunnels during early spring are ideal for plants but challenging for some pollinators. Foraging activities of European honeybees (Apis mellifera) peak at 20 °C [25]. Thus, the mesoclimate inside high tunnels might affect the performance of this common blueberry pollinator. Insufficient pollination may cause a lower average fruit set inside high tunnels than in open fields [11,26]. Roll-up side walls can be used to create optimal temperatures and improve pollinator access during the day. Alternatively, bumble bees (Bombus impatiens) and/or native pollinators could be brought inside the tunnels. Where native pollinators are abundant, they willingly venture into the protected structure [8]. Considering SHB cultivars differ in their ability to self-pollinate [27], long term solutions to poor pollination inside high tunnels may include using self-fertile or parthenocarpic prone cultivars. Additionally, plant growth regulators could be investigated.

2.2. Greenhouse and plant factory (growth chamber) production

In contrast to high tunnel production, environmental conditions such as temperature, humidity, light, and CO_2 concentrations can be controlled in greenhouses and plant factories, making it possible to produce fruit year-round, especially in plant factories [28].

In current literature, most SHB research in greenhouse or plant factory conditions is focused on investigating plant growth, photosynthetic ability, and fruit quality by adjusting photoperiod, temperature, humidity, and other environmental factors [28–31]. Studies exploring the potential yield in greenhouse production is limited to a study conducted by Motomura et al. [32] in Volcano, Hawaii. They evaluated a key greenhouse production component, pot size, without controlling environmental parameters. Hence, there is a lack of research on optimizing management practices to maximize SHB yield in greenhouse or plant factory production. However, there are many factors to consider in this system, including temperature, relative humidity, light quality, and photoperiod. Controlling temperature is more feasible in plant factories than in a greenhouse [28,29,33,34]. Spann et al. [34] compared plant growth under 28 °C and 21 °C and discovered flower bud initiation and whole-plant carbohydrate concentration was significantly reduced at 28 ºC. Aung et al. [29] found the optimal temperature for SHB cultivars 'Misty' and 'Sharpblue' during dark periods should be around 15 °C and in light periods around 25 °C, which is agreed on by Kameari et al. [33] and Cho et al. [28]. Relative humidity ranging from 40% to 80%, according to experiments on SHB cultivars 'Misty' and 'Sharpblue', can avoid stomatal closure under low humidity and disease pressure under high humidity [28,29]. Artificial lighting can be used to supplement sunlight in order to extend photoperiod in the greenhouse, or as an exclusive light source for a plant factory. Different cultivars had varying reactions to natural sunlight and artificial light, but photosynthesis rates under artificial light were found to be more constant [29]. Although photosynthesis rates increase with light intensity from 0 to 1,000 $\mu mol.m^{-2}.s^{-1}$, temperature also increases with light intensity and thus more energy is consumed [29]. High pressure sodium lamps or LED lights at an intensity of 300 to 500 $\mu mol.m^{-2}.s^{-1}$, or at even lower light intensities of 150 to 350 $\mu mol.m^{-2}.s^{-1}$, have been reported to provide enough radiation for sufficient photosynthesis and plant growth [28–30]. Light quality is able to induce different responses in blueberry flowering characteristics, with blue light (approximately 450 nm) advancing flowering and red light (approximately 630 - 660 nm) delaying flowering. SHB cultivars 'Misty' and 'Sharpblue' exhibited earlier and more abundant flowering under half blue and half red LED lights during flower bud differentiation (FBD) than plants under sole blue, sole red, or artificial white light [28]. Conflicts existed in photoperiod required to promote SHB flowering. According to Spann et al. [30,34], flower bud initiation (FBI) in SHB is a short day/long night phytochrome-mediated response and thus no flower buds were observed under a 16-hr photoperiod in their study. Once flower buds are initiated, the differentiation of flower buds can be enhanced under long days [30,34]. However, opposite settings have been seen in the Cho et al. [28] study with a 14-hr photoperiod during FBI and a 10-hr photoperiod during FBD, where flowers were present. Each of these studies used the same SHB cultivars, 'Misty' and 'Sharpblue', and the inconsistent results may be due to the use of shorter long day settings in the study from Cho et al. [28].

3. High-density planting production

Southern highbush blueberry is traditionally planted with 2.75 m to 3.00 m between beds and 0.76 m to 0.9 m between bushes within the row. This spacing leads to plant densities between 3,587 and 4,323 plants per hectare [35]. There is great interest in increasing SHB planting densities to optimize space use inside high tunnels, bird nets, and other protective structures. Previous studies have investigated double rows per bed planting with spacing between 0.75 and 0.45 m between plants within row (equivalent to 7,173 and 11,854 plants/ha), while single row planting with spacing between 1.5 m and 0.45 m between plants (equivalent to 2,154 and 7,173 plants/ha) [35–37]. In these studies, across-bed spacings are typically 3 m. Commercial growers with container production in some cases have increased single row planting density by reducing across-bed spacing. Although close spacing may reduce yield and/or biomass per plant, overall yield and/or biomass per hectare increases due to the larger plant population [37,38]. For example, when plant spacing was reduced from 1.2 m to 0.45 m, cumulative yield doubled from year 3 to year 7 [36]. Similarly, planting in double row beds as opposed to single row beds led to higher yield per area unit [35]. Notably, higher planting densities do not seem to reduce the berry weight or size [35,36].

A critical advantage of high-density plantings is that they can reduce the time required for a field to reach maximum production potential and profit per unit of area. While there is no evidence to suggest that the development of each individual plant is accelerated, large populations of small plants can attain significant yields. SHB cultivation systems have high establishment costs [39,40]. Thus, the profit potential of growing blueberries can be enhanced by increasing productivity in the early years of production [41]. High density SHB plantations can reach peak commercial yields in less than 4 years [38].

While high density plantations might increase water and fertilizer use efficiency and improve weed control [37], high plant densities can create new challenges in SHB management. High density plantations might be more sensitive to drought stress due to increased plant-to-plant competition for water [36]. Additionally, high-density plantings might restrict light penetration into the plant canopy [42], affecting photosynthesis and other light-dependent responses. Cultivar choice and/or light reflection could be used to improve light penetration. SHB canopy architecture ranges from upright to spreading [43,44]. Varieties with upright growth such as 'Abundance', 'Chickadee', and 'Meadowlark' might be better suited to high density plantings than those with a spreading growth habit. Alternatively, reflective plastic mulches can be used to increase photosynthetically active radiation in the lower parts of the canopy [45], improving photosynthetic rates and increasing fruit quality [45–47]. High density plantations inside high tunnels have the advantage that plastic glazing diffuses sunlight, improving light distribution through the canopy [48].

Canopy management in high density plantations can also be challenging. Based on the estimation of Strik and Buller [36], it takes at least 37% more time to prune NHB plants with 0.45 m in-row spacing than those with 1.2 m. Additionally, leaf disease incidence can be aggravated because of the environment created by warmer temperatures and humidity due to plant transpiration, restricted outside air exchange, and lower airflow between plants in a high-density environment [35,37,49]. Fungal foliar diseases can develop under these conditions, including anthracnose, Septoria leaf spot, target spot, rust, and others, typically requiring fungicide applications for control [50]. Cultural practices to help minimize disease include using disease-resistant varieties, maintaining a pest-free environment to mitigate the transmission of insect vectored pathogens, good weed control to eliminate alternate hosts, and good sanitation practices [51].

4. Evergreen production

Southern highbush blueberry can be grown as an evergreen thanks to its tropical and subtropical parental species [52]. Evergreen blueberry production focuses on preventing defoliation during the colder periods of the year by optimizing winter fertilization and pest and disease management [50,53,54]. A full canopy of healthy leaves for at least the last 70% of the flowering-to-ripening interval is a prerequisite for producing high yields of high-quality berries early in the season[55]. This production system is only feasible in areas with light or no winter freezes, or under high tunnels [53–

55]. Evergreen blueberry production has rapidly expanded in the United States (California, Florida, and Hawaii) as well as some parts in Australia, Spain, China, Argentina, Mexico, and Morocco [2,56–59], because evergreen plants can be managed to produce berries all year long or to target high-value market windows [2,57].

There are management and physiological differences between deciduous and evergreen SHB production systems (Figure 4). While in deciduous systems fertilization ramps down during fall and winter [60], in evergreen systems nitrogen (N) application continues throughout the season [61]. Nitrogen fertilization and healthy leaves promote high photosynthetic rates and carbohydrate synthesis at a time when deciduous SHB consumes its carbohydrate reserves [53,61]. Carbohydrate availability might be the reason for the shorter period between flower bud initiation and floral budbreak between evergreen and deciduous SHB [61]. This plant response can be managed to accomplish early harvests (Figure 5).

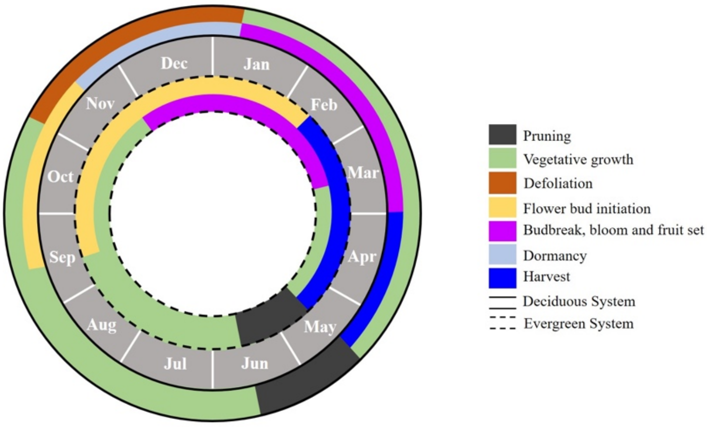

Figure 4. Timing comparison of the different stages of fruit production for Southern highbush blueberry under an evergreen production system (inner ring) and a deciduous production system (outer ring) in Florida.

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Figure 5. Southern highbush blueberry plants in February 2018 flowering in deciduous system (A), while carrying ripe berries in evergreen system (B).

The presence of leaves in evergreen SHB might also cause other responses. Since leaves are the organ where photoperiod perception takes place [62], leaf retention extends short-day perception and flower bud initiation into the winter (Figure 4) [61,63,64]. Protracted flower bud initiation not only increases flower bud number but also lengthens the harvest season [53]. High flower bud density and fruit number decreases reserve carbohydrates, and any additional carbohydrate availability tends to be used for new flower bud initiation rather than increasing cell division, so vegetative growth as well as fruit size and quality can be negatively affected [53,65]. Fruit thinning can be used where concentrated production is important for mechanization or to meet market demands [53]. Both fruit and flower thinning can reduce fruit numbers and improve fruit size, but given the continuous flower bud initiation in evergreen SHB, flower removal is less effective at ameliorating sink competition [53].

There are several open questions regarding fertilization for evergreen production. Unlike deciduous system, an advanced vegetative bud break might be not helpful as long as overwintered leaves stay healthy, instead increasing source competition between the reproductive growth and new vegetative growth. Thus, the ideal fertilizer rate during reproductive stage is to keep old leaves healthy but delay vegetative bud break to maximize yield and berry quality. Reeder et al. [63] tested three N rates 84 (equivalent to 0.215 g/plant/week), 168, or 252 kg/ha/yr in year 1, and 168, 252, or 336 kg/ha/yr in year 2 for evergreen SHB production in Florida with the rate of N, phosphorus (P) (0.039 g/plant/week), and potassium (K) (0.155 g/plant/week) reduced by half during the period from December to March. They found that trials using up to 252 kg N /ha/yr had increased plant canopy volume, longer leaf retention, and advanced vegetative buds break, but there seemed to be no effect on yield. A research on rabbiteye blueberry showed a negative impact of P application during dormant season on shoot growth [66]. There is a lack of research on exploring the effect of P and K rates, the NPK ratio, and/or micronutrient concentrations during flower and fruit development stages on yield and berry quality.

5. Container-based production

Southern highbush blueberry is most productive in soils with low pH and high organic matter content [4]. Agricultural soils rarely meet these requirements. Thus, growers traditionally prepare fields with the addition of sulfur, organic matter, or other amendments [67–69]. Even with these inputs, SHB soil preferences limit the areas where it can be planted. Recently, containerized SHB production has gained popularity as the use of soilless substrates makes blueberry production possible virtually anywhere in the globe. Container-based production also allows growers to move and adjust plant spacing based on growth [70,71]. Also, soilless substrates allow fine control of nutrient concentrations in the rhizosphere and prevent soil-borne issues like pests and toxic residues [71,72]. There are several factors to consider for this type of growing system.

Container size and shape are important for this production system. Research on optimum container size for blueberry production is limited. Whidden [70] reported 56L to 95L was the container size commonly used in commercial blueberry production in central Florida. Studies using container size within this range reported first-year yields ranging from 0.9 kg/plant to more than 2 kg/plant based on different cultivars and fertilizer rates [19,73]. Containers smaller than 38 L have been shown to negatively affect yields [32]. Nevertheless, considering the diversity in SHB plant shape and vigor, it is conceivable that smaller and larger container sizes might be suitable for commercial cultivation depending on the cultivar used. An additional challenge for cultivation in smaller containers is plant anchorage. Under high wind conditions, plants in smaller containers might blow over, requiring trellising or other anchorage mechanisms (Figure 6) [70,74]. Also, if high density of planting is part of the goal, the container size chosen will affect the maximum potential planting density.

Figure. 6. Example of trellis for plant anchorage used in container-based production system for southern highbush blueberry.

Plants growing in containers have restricted space for root growth, unlike those grown in traditional field environments [70]. Reduced rooting volume can result in physiological and morphological changes, affecting root and shoot growth, photosynthesis, nutrient uptake, root respiration, flowering, and biomass accumulation and partitioning (reviewed in Poorter et al. [75]). Generally speaking, as container size increases, shoot and root biomass increase [76]. At a given volume, the height of the container has a positive effect on the free-draining water content [77]. A shorter container tends to have less water suction at its surface, which leads to larger pores in the substrate that would then fill with water [77], causing a higher risk of hypoxia for plant roots. However, with the increase of container height, the water from surface to bottom is less evenly distributed [78]. Water distribution, together with temperature fluctuation inside the container, results in unevenly distributed root systems [75]. Additionally, media pore space gradually decreases as roots occupy more space in the pot, which negatively affects both the water holding capacity and aeration.

Sphagnum peat moss, coconut coir, and perlite are commonly used for container-based blueberry production. Peat moss is widely used for SHB rooting and germination in nurseries [79–

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81] due to its low native pH and high water holding capacity. Coconut coir (also called coconut fiber or coconut pith) is a biodegradable substrate that also contributes high water holding capacity to substrate mixes. Perlite is an inorganic material that is not greatly affected by acids or microorganisms [82]. However, when pH is low, perlite can release toxic Al into the root zone [82]. Given their relative strengths and weaknesses, these materials are commonly combined in custom mixes. Recent studies have focused on media composition for blueberry production [83,84]. Media composed of 60% or more peat or coconut coir enhance vegetative growth in SHB [83]. However, there is evidence that some varieties might perform better in peat-based, rather than coco coir-based media [84]. Perlite content seems to only affect substrate-water relations [84]. In areas where tree barks are available and affordable, this material has also been used to improve media aeration [85,86].

To date, there are several open questions regarding substrate choice for container-based production. As the first plantations come of age, research should emphasize substrate longevity and its impact on productivity. Decomposition of organic materials can cause substrate compaction and shrinkage, which affects water distribution in the container. This might be particularly pressing for substrates with high pine bark contents, as this material traditionally has high carbon to nitrogen ratios. Another area of interest is the impact of substrate choice on reproductive growth and fruit quality. Studies on strawberry and tomato indicate substrate composition can affect yield and fruit characteristics like firmness, total soluble solids, titratable acidity, and phenolic compounds content [87,88], but no published study for blueberry exists up to now.

Watering systems commonly used in container-based blueberry production are drip and overhead irrigation [70]. Drip tapes and drip emitters are the main tools for irrigation and fertigation in this system. Overhead irrigation is usually used as a supplement to reduce air temperature at plant level in summer or provide freeze protection in winter. Drip tape can be stretched over the row of containers, usually with two tapes per container. Where emitters are used, better water distribution can be achieved by increasing the number of emitters per container, with 4 emitters per container commonly seen in commercial plantings around the globe. In container-based systems, both an excess and lack of water are common due to the low rooting volume and lack of access to subsurface water. Thus, irrigation rates are dynamically adjusted according to plant growth and environmental conditions. In ornamental or vegetable container production [89,90], growers schedule irrigation events and duration according to substrate matric potential, however, research is lacking to facilitate this practice in blueberry. Instead, irrigation rates are generally adjusted based on drainage volume [71,83]. The target leaching fraction (the ratio of drainage to the applied water) should typically be between 15% to 25% [71,83].

In container-based blueberry production, mineral nutrients are delivered through fertigation or granular fertilizers. Optimum N rates are cultivar dependent. For example, optimum yields in SHB cultivar 'Star' in 95 L containers are attained with 30 g N/plant/year while cultivar 'Misty' had the highest yield at 20 g N/plant/year [73]. Up to 36 g N/plant/year has been observed with 56 L containers [19], but it was probably due to the use of slow-release fertilizer. Additionally, Wilber and Williamson [73] compared applications of 12N-1.8P-6.6K and 12N-5.2P-9.9K and found the additional P and K did not affect vegetative or reproductive growth. Additional research is necessary to determine optimum nutrient rates and timing for container-based blueberry production. Previous research has documented heterogeneous nutrient content in soilless media [91] and media effects on nutrient uptake [83,84]. Thus, fertility recommendations for soil-based production might not cross over appropriately to container-based systems.

6. Conclusions

Southern highbush blueberries were once a regional crop in the United States, but now they are a specialty crop cultivated throughout the world. This expansion in the crop's range has been fueled by increasing demand for blueberries worldwide, the availability of adapted cultivars, and the adoption of new, intensive production systems. Compared to the field production, alternative blueberry production systems detailed above require higher investments. Structures, glazing, temperature control and irrigation equipment represent additional fixed costs. Plants, containers, soilless substrates, fertilizers, and pest control are increases in variable costs that will depend on plant density. Ultimately, establishment can be as high as $120,000 per hectare, excluding land cost [1]. While this high establishment cost constitutes a barrier for entry, initial investments can be justified by higher yields per acreage, commercial yields in the early years of production, and/or adjusting the harvest season to meet market windows with high fruit prices. Intensive systems that combine container-based, high-density planting inside high tunnels can be profitable in some markets [92].

To date, research focusing on these production systems is still in its infancy, but there is a growing body of literature focusing on system design. However, there is a lack of research focusing on system operation. Fertilization, pruning, and pest management recommendations are imperative to help growers close the gap between investment and profits. Additionally, it is important that the deep and diverse gene pool in SHB breeding programs is exploited to develop cultivars that are specifically well-suited for cultivation to the different alternative systems, for example narrow crowns for high density. Finally, alternative blueberry production systems could also benefit from the incorporation of cutting edge technologies such as solid set canopy delivery [93] and automated irrigation scheduling [94]. Together, these innovations can position blueberry at the forefront of horticultural technology.

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