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REVIEW

Environmental factors and physiological responses of sweet cherry production under protective cover systems: A review

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ABSTRACT

Climate change is increasing sweet cherry (*Prunus avium* (L.) L.) production under cover systems such as high tunnels, rain covers, and nets. The objective of this review was to provide an overview of the environmental factors and physiological responses involved in cherry production under different types of protective covering systems. The most important environmental factors affected by cover systems are photosynthetically active radiation (PAR), temperature, relative humidity, and wind speed, which in turn affect leaf gas exchange, plant water relations, tree growth, flower development, and fruit quality. The use of covering systems has a positive effect on photosynthesis by increasing the amount of diffused PAR, but a negative effect on the reproductive-vegetative tree balance due to lower total PAR availability. Increases in air temperature by cover systems alter differentially flowering and fruit set, impacting positively the ripening time and cell division of the fruits. Plant water status is improved under cover systems, allowing for greater tolerance to water deficit as well as improved potential fruit cell expansion, with an ensuing positive effect on fruit size, but decreasing fruit firmness due to lower Ca availability fruits. The multiple environmental factors and physiological responses observed in cherry production under cover systems suggest the need to adjust agronomic practices such as pruning, crop load regulation, irrigation, and nutrition according to these specific conditions.

Key words: Climate change, leaf gas exchange, netting, plastic covers, *Prunus avium*, sunlight, temperature.

INTRODUCTION

Sweet cherry (*Prunus avium* (L.) L.) is a high value fruit, being one of the most important fruits grown in temperate climates. The species is native to the Caucasus, but it is widely cultivated in approximately 70 countries and regions of the world (Habib et al., 2017), including Europe, North and South America, (Iezzoni, 2008), Asia, Africa, and Oceania (Bujdosó and Hrotkó, 2017).

As other fruit crops cultivated in temperate climates, cherry trees require a certain number of chill hours in winter and subsequent heat hours in spring for budding and flowering. In recent years, orchards with new cherry cultivars have been established, including early flowering cultivars with low chill requirements, such as ‘Cristobalina’, ‘Brooks’, ‘Ruby’, ‘Somerset’, ‘Burlat’ and ‘New Star’ (Alburquerque et al., 2008), as well as late flowering cultivars with greater chill requirements, such as ‘Bing’, ‘Garnet’, ‘Celeste’ (Gratacós and Cortés, 2007), ‘Regina’ (Vercammen and Vanrykel, 2014; Campoy et al., 2019), ‘Sweetheart’, ‘Rubin’(Vercammen and Vanrykel, 2014), ‘Emperor Francis’, ‘Early Burlat’, ‘Van’, and ‘Hedelfinger’ (Longstroth and Perry, 1996).

Even though advances in breeding programs have allowed the cultivation of cherry in different climatic environments, current climate change conditions are affecting the normal development of this crop at a global level (Measham et al., 2014). In South America fruit growing areas such as Chile, climate conditions impact widely the cherry production by frost and rain events (Rojas et al., 2021). Similarly, in Europe cherry cultivation could be seriously affected by changes in the accumulation of chill hours in winter and heat hours in spring, frequency and intensity of frost, rain and hail events during flowering and fruit set, sudden rains close to harvest, and high temperatures in summer (Blanke et al., 2017).

Fruit cracking and poor fruit set are the physiological disorders induced by climate with more impact in yield and profitability in cherries. Susceptibility to rain-induced cracking occurs 10 to 25 d before harvest (Simon, 2006), while reduced fruit set is caused by minimum and maximum temperatures in the range of 5-16 °C, since lower temperature during the flowering results in a lower activity of pollinating bees or reduced viability and germination capacity of pollen granules (Roversi and Ughini, 1996). On the other hand, temperatures over 30 °C during flower differentiation generate disorders in the development of ovaries and pistils, influencing double fruit formation (Engin and Ünal, 2008). In addition, more recent studies have indicated that when minimum and maximum temperatures ranged from 25 to 35 °C, and under water stress, negatively affect the net photosynthesis in cherry trees (Beppu et al., 2003).

Protecting trees with covers can prevent damage caused by adverse environmental conditions (Sotiropoulos et al., 2014). In various regions of the world, plastic covers and nets have allowed for maintaining yields in cherry by reducing the risk of rain-induced fruit cracking, fruit damage from birds, and/or tree and fruit damage from hail (Lang, 2014). There are many types of protective covers, including single- or multi-chapel systems, which are structures that cover trees without altering the normal management of the canopy (Janke et al., 2017), as well as plastic tents and high tunnels, which are mainly used in highly productive areas (Lang, 2014). Nets are among the most widely used materials in regions where fruit crops are exposed to heat stress as well as high solar radiation and wind speed (Olivares-Soto and Bastías, 2018; Salazar-Canales et al., 2021). Plastic and woven covers are mainly used for rain protection. As temperature and relative humidity (RH) can increase under these covers, there is a higher risk of disease incidence, and thus ventilation is required to prevent damage to the leaves and fruit, decreased fruit color, and fruit softening (Simon, 2006; Lang et al., 2011; Bastías et al., 2017; Bastías and Leyton, 2018). Nevertheless, other studies indicate that covers also reduce the need for fungicides during the rainy periods from flowering to the end of harvest (Børve and Stensvand, 2003). Greenhouse cultivation is a more recent practice in cherry orchards, which allows the creation of more favorable conditions for plant growth by artificially controlling air temperature and RH to extend growing seasons and improve yields (Perrin et al., 2014).

To establish adequate criteria for the agronomic management of cherry trees, it is essential to know and to understand the environmental factors and how these factors affect the physiological responses in the protected-environment cherry production (Lang et al., 2011). The objective of this review was to provide an overview of the environmental factors (light, temperature, RH, and wind speed) and physiological factors (leaf gas exchange, flower development, growth and development of the tree, and fruit quality) involved in cherry production under different types of protective covering systems.

ENVIRONMENTAL FACTORS

Light conditions

Photosynthetically active radiation (PAR) measured as photosynthetically active photon flux density (PPFD) plays a fundamental role in the process of photosynthesis. In cherry trees, the light saturation point of photosynthesis is reached at 900 µmol m^{-2} s^{-1} PPFD (Zhang et al., 2021). Depending on climatic conditions, lower PPFD intensity has been reported in covered orchards, with reductions of 15% (Balkhoven-Baart and Groot, 2005), 25% (Lang et al., 2011) and 40% (Wallberg and Sagredo, 2014). Furthermore, the use of protective covering reduced light intensity by 40% and light distribution within the canopy by 50%, reaching 6% in the lower parts of the tree canopies, which is the critical level for the proper development of processes such as floral induction (Mika et al., 2019). The exposure time of the materials also influences photosynthetic light availability. Lang et al. (2011) showed that PPFD was reduced by 25% in the third year of the use of polyethylene, indicating that leaves exposed to filtered sunlight would receive enough light for photosynthetic activity. However, leaves inside the canopy presented lower levels of light, and thus additional practices such as strategic pruning or the use of reflective orchard floor materials are required to maintain good light penetration through the canopy (Lang et al., 2011). In this sense, it is important to consider that the amount and composition of light inside the canopy change due to the effect of the optical properties of reflectance, absorbance and transmittance of the leaves (Baldini et al., 1997). These characteristics can be regulated by the type of material of the protective cover since specific light composition does not only affect photosynthesis and stomatal conductance, but also plant morphogenesis, pigment synthesis, insect activity, and other aspects (Lang, 2014). The color of nets can also alter aspects such as fruit growth or leaf stomatal conductance as observed in other fruit crops such as apples. Changes in light composition when using blue net (400-700 nm) compared to red net (600-700 nm) have been associated with higher fruit growth rates and stomatal opening of the leaves (Bastías et al., 2012; 2021). In tunnel cherry production, when incident light was reduced by up to 54% PPFD, UV-A (320-390 nm) and UV-B (280-320 nm) light levels were reduced by 22% and 2%, respectively (Schmitz-Eiberger and Blanke, 2012). Furthermore, there is evidence that changes in the UV light spectrum by polyethylene covers influences photosynthesis and the flight of pollinators, such as bees, since they have greater visibility and ability to detect floral organs in this UV light spectrum (Lang, 2014). Similarly, these variations in UV light levels also affect anthocyanin biosynthesis in the epidermis. This is relevant in yellow-fleshed cherry cultivars such as Sato Nishiki, Rainier and Early Robin because the red color of the fruits diminishes under covers with reduced UV light transmission (Mulabagal et al., 2009).

Bastías and Leyton (2018) showed that photosynthetic light transmission under cover changes on sunny and cloudy days, decreasing by 58% (due to their shading effect) and 36%, respectively (Figure 1). Differences in photosynthetic light transmission are also found between cover materials. On a sunny day, plastic can transmit about 7% more photosynthetic light than woven; however, both materials roughly transmit the same amount of light on a cloudy day (Figure 1). This indicates that the use of protective covers significantly reduces the amount of light for photosynthesis, its effect being more marked on sunny days ('shading effect') rather than cloudy days. Plastic covers can provide greater photosynthetic light availability than woven covers, and thus it is more advisable to use materials that ensure a greater transmission capacity in this light component (Bastías and Leyton, 2018).

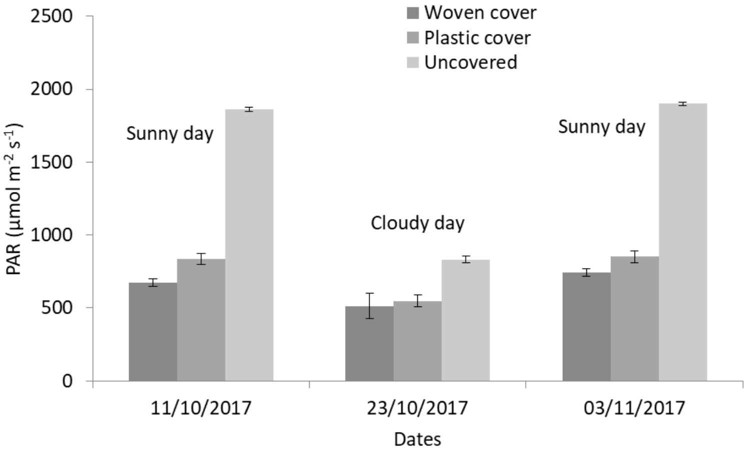

Figure 1. Photosynthetically active radiation (PAR) transmission in cherry orchards covered under woven, plastic and without cover (control) in Chile (adapted from Bastías and Leyton, 2018). Each point represents the mean ± standard error.

Temperature

In recent decades, global climate change has had impacts on temperature patterns, resulting not only in hotter and drier summers but also warmer winters, to which crops need to adapt (Kaufmann and Blanke, 2017a; 2017b) It has been reported that sustained high temperatures (35-40 °C) as a result of high solar radiation can impair key physiological processes for fruit tree cultivation, such as cell division, leaf expansion and reproductive development (Flaishman et al., 2015), which has also been observed in covered crops. There is evidence that when minimum temperatures under high tunnel exceeds in 2 °C the open field conditions can accelerate cell division and expansion during fruit development (Retamal-Salgado et al., 2015). This is particularly important in cherry crop because different growth and developmental stages, such as bud dormancy, flowering, and fruit growth, are subjected to strict temperature control or can be seriously affected by extreme temperatures (Wenden et al., 2017). In fact, sustained low temperatures below a certain threshold result in continuous but reduced shoot growth, while a marked drop in temperature can induce an immediate cessation of growth (Sønsteby and Heide, 2019).

Plastic covers allow solar radiation transmittance but prevent or limit convective and radiative heat transfer to the outside, thus retaining energy and accumulating heat (Jett, 2017). However, this principle does not always ensure the control of a marked drop in temperature. In fact, a single-layer plastic cover does not provide complete protection from phenomena such as frost because radiant energy is transmitted relatively quickly, resulting in inefficient heat retention in the orchard and no additional heat. In this way, night temperatures inside polyethylene high tunnels equilibrate relatively quickly with that outside, even dropping below the freezing point, with an increased risk of frost under the tunnel (Dekova and Blanke, 2007). However, a study by Janke et al. (2017) showed that double-layer plastic cover increased air temperature by an average of 12 °C in summer and 7.8 °C in winter, while the use of polyethylene row covers inside the high tunnel further moderated temperature fluctuation, increasing freeze protection. Furthermore, Vávra et al. (2019) found that covered cherry orchards increased the temperature by approximately 1-2 °C, helping reduce frost damage during flowering.

Considering that rain protection is required until harvest and that flower initiation and differentiation coincides with fruit ripening (Guimond et al., 1998), high temperatures during this period could affect the formation of flowers and even the following year’s yield since an excessive rise in temperature in protected environment cherry cultivation could alter flowering time, causing sterility of the embryo sac (Sønsteby and Heide, 2019), and thus resulting in reduced fruit set and yield. Temperature can also alter fruit growth and development in cover systems. If temperatures are too low, fruit ripening is delayed; if temperatures exceed 28 °C for 2 h during the first stage of fruit growth, the fruit drop rate can reach as high as 50%-60%; and if the temperature exceeds 30 °C, fruit drop could exceed 80% (Zhang et al., 2018b).

Poor fruit set and double fruit formation are the most serious problems affecting cherry production due to temperature increase, which has accelerated due to global warming (Imrak et al., 2014). However, the occurrence of double fruit has rarely been observed in cherry cultivation under covering systems such as plastic greenhouses, which are used to anticipate harvest dates, even in warm regions. This occurs because the use of protective covers results in earlier flower differentiation, preventing double fruits due to high temperatures during the summer (Beppu et al., 2001). In fact, these systems have been used to reduce the incidence of double fruits. In this sense, Imrak et al. (2014) reported that the use of green netting with 55% light transmission reduced air temperature between 1.9 and 3.1 °C diminishing the pistil or double fruit formation by 60% and 28%, respectively. Furthermore, covers such as nets reduce incident radiation during bud differentiation and may reduce maximum air temperatures below thresholds for abnormal pistil development (Beppu and Kataoka, 2000; Whiting and Martin, 2008; Imrak et al., 2014). The same effect can be achieved with the use of plastic and woven covers, with reductions of 3-4 °C in fruit temperature due to lower incident solar radiation (Bastías and Leyton, 2018).

In greenhouse cherry cultivation, Zhang et al. (2018b) determined that the optimal temperature ranges were 5-18 °C for budding, 17-19 °C for flowering, and 22-25 °C during fruit development for ‘Red Lamp’, ‘Tieton’, ‘Summit’, ‘Van’, ‘Lapins’ and ‘Santina’. In the same experiment was also determined that, compared to the reduction of the photoperiod by darkening with thick mats, the accumulation of cold was more effective in terms of fruit set and yield (Zhang et al., 2018b).

Another important aspect to consider when using protective orchard covering systems is the effect of temperature on good pollination and fruit set. A study conducted by Zhang et al. (2018a) showed that pollen hydration and germination were poor under low temperatures, while ovule viability decreased with increasing temperature. Highly productive cultivars such as Rainier and Sweetheart were more tolerant to warmer temperatures than Tieton and Benton (low productivity cultivars), suggesting that warm temperatures, which accelerate ovule senescence, are the main factor in the low productivity of some cherry cultivars. Likewise, temperature could affect the chemical characteristics of the fruit. In this sense, an increase in the content of phenolic compounds was observed in cherries grown under cover, being attributed to extremely high temperatures, particularly on days of intense solar radiation, limited air circulation, and stress associated with the plant (Schmitz-Eiberger and Blanke, 2012).

Avoiding overheating is a key issue in protective covering systems. The cover system commonly used in cherry orchard is the roof type which allows good ventilation thanks to the slope of roof and the spacing between rows (Børve et al., 2003). In high tunnel systems, the ventilation implies a high economic cost due to the fact that side covers need to be removed or layers of polyethylene need to be rolled when it is not raining, requiring a high amount of labor (Meland et al., 2017).

Relative humidity

Plastic covers and high tunnels are among the most popular covering systems in highly productive areas. They do not only modify the orchard environment but also RH, which plays an important role in certain development stages of cherries (Lang, 2014). During flowering, RH should be maintained in the range of 50% to 70% under controlled environments. If humidity is higher, pollen becomes “sticky”, while it dries and loses viability at very low humidity levels (Zhang et al., 2018b). The literature has described that high tunnels increase both RH and air temperature (Lang et al., 2016; Blanco et al., 2019b), affecting flowering and fruiting, and resulting in a negative impact on yield and fruit quality (Lang, 2014; Meland et al., 2017; Blanco et al., 2021a). Both temperature and RH determine the values of vapor pressure deficit that are reached under a protective covering, which plays an important role in leaf stomatal conductance (g_s), and thus in plant transpiration rate and photosynthesis (Righi et al., 2012). An increase in g_s of ‘Prime Giant’ cherry trees was observed under high RH and low vapor pressure deficit when the soil was at field capacity (Blanco et al., 2018). In this sense, it has been reported that RH reached maximum and minimum mean values that were 5% and 16% higher in high tunnels compared to open field conditions, respectively, with a slight decrease in vapor pressure deficit inside the tunnels (Blanco et al., 2021b). Furthermore, RH reached a lower maximum and minimum mean values in rain covers compared to values recorded under open field conditions (Bastías et al., 2017).

The RH is related to lower Ca concentration in cherries grown under high tunnel production systems because trees are exposed to higher RH and lower vapor pressure deficit, which may influence Ca absorption and distribution during fruit development (Blanco et al., 2021a), since the Ca presents lower mobility at phloem level and therefore is mainly transported to plant organs via xylem tissue and by transpiration driving force. Furthermore, this occurs due to a lower fruit transpiration rate (Winkler et al., 2020) and an increase in the vegetative growth of shoots rather than fruits (Blanco et al., 2021a).

For controlled greenhouse conditions, the optimum ranges of RH for proper budding, flowering, and cherry fruit development are 60%-80%, 50%-70%, and 50%-60%, respectively (Zhang et al., 2018b). An increase of 10% to 15% in RH can induce flower and fruit drop under rain covers due to excess water condensation, resulting in disease appearance (Blanke and Balmer, 2008) In addition, humidity control during fruit ripening is key to preventing fruit cracking. If RH increases above 75%, frequency of microcracks on the fruit surface increases exponentially (Knoche and Peschel, 2006). Conversely, Zhang et al. (2018b) showed that maintaining RH at values between 50% and 60% during mesocarp expansion effectively reduces the formation of cracks.

Wind speed

Wind is another factor that affects cherry production. In fact, the use of protective covers is essential in regions where wind limits production, affecting crop photosynthesis as well as respiration and transpiration rates (Girona et al., 2012). In this sense, Lang (2014) reported a reduction between 5 and 20 km h^{-1} in wind speed in a high tunnel system. Reduced wind speed and increased RH under protective covering can cause negative effects on crops (Castellano et al., 2008), but positive aspects such as reduced evapotranspiration and a more efficient C acquisition have also been identified (Lang et al., 2016). Furthermore, reduced damage by wind results in lower bruising incidence and fruit rotting in orchards grown under covers (Lang, 2014). It should be noted that the type of covering system influences both wind speed and air circulation. Differences in wind speed between types of covering systems have been observed (Arthurs et al., 2013), particularly considering that ventilation allows reducing wind intensity, helping air move with less resistance under the covering (Blanke et al., 2017).

The extent to which protective covering systems influence light, temperature, RH, and wind depends on the type of covering, location, and management of the system by cherry growers (Table 1). In this sense, even when the use of rain covers is preferred because it is economically more convenient than uncovered orchards (Simon, 2006), it is important to evaluate their potential benefits and limitations for cherry production in order to determine the cost-benefit ratio.

Table 1. Influence of different protective covering systems on environmental conditions in sweet cherry (*Prunus avium*). PAR: Photosynthetically active radiation; RH: relative humidity.

Variable	Cover system	Response	Reference
Temperature	Rain protective shelter	Increased	Børve et al., 2003; Børve and Stensvand, 2003; Simon, 2006; Schmitz-Eiberger and Blanke, 2012
Temperature	Woven shade	Decreased	Beppu and Kataoka, 2000
Temperature	Green plastic nets	Decreased	Imrak et al., 2014
Temperature	Hight tunnel	Increased	Blanke and Balmer, 2008; Blanco et al., 2019a; 2021a; 2021b
Temperature	Greenhouse	controlled	Zhang et al., 2017
PAR	Tunnel	Decreased (15%-40%)	Balkhoven-Baart and Groot, 2005; Blanke and Balmer, 2008; Lang et al., 2011; Lang, 2014; Overbeck et al., 2017; Mika et al., 2019
PAR	Poly tunnel	Decreased (up to 54%)	Schmitz-Eiberger and Blanke, 2012
PAR	Hygrove Poly tunnel	Decreased (16 to 25%)	Overbeck et al., 2017
PAR	Shelter plastic cover	Decreased (up to 58%)	Overbeck et al., 2018
PAR	Gabled (Vöen^{TM}) crop covers	Decreased (40%)	Wallberg and Sagredo, 2014
RH	Hight tunnel	Increased	Blanke and Balmer, 2008; Blanco et al., 2019b;
RH	Umbrella type covers	Increased	Børve et al., 2003

PHYSIOLOGICAL RESPONSES

Leaf gas exchange

Maximum net CO_2 assimilation (A_n) of most C_3 species is saturated with a relatively low amount of photosynthetically active radiation (PAR) (600-900 μmol m^2 s^{-1} PPFD), representing 30%-40% of total sunlight (1500-2000 μmol m^2 s^{-1} PPFD). Temperature is one of the factors that can influence A_n; in many deciduous trees, a reduction in A_n due to temperature increase occurs because of an increased respiration rate (Lakso, 1994). Beppu et al. (2003) showed that A_n decreased when cherry trees grown under low temperatures were subjected to temperatures above 25 °C, while trees grown at high temperatures reached maximum A_n at 30 °C, decreasing to a smaller extent even up to 35 °C, which demonstrates that there is temperature acclimatization of the photosynthesis of cherry tree leaves. This effect of temperature on leaf gas exchange can be exacerbated by conditions of low soil moisture in summer, decreasing A_n, transpiration rate (E) and g_s, and resulting in a decrease in carbohydrate accumulation (Beppu et al., 2003).

The use of protective covers can differentially alter leaf gas exchange depending on the material used. Bastías et al. (2011; 2021) showed that, regardless of PAR intensity, the use of blue netting resulted in an increase in A_n, E and leaves in apple (*Malus domestica* (Suckow) Borkh.) compared to the use of red netting, affecting photosynthetic capacity due to changes in the amount and quality of light. On the other hand, the use of low-density plastic covers in blueberries (*Vaccinium corymbosum* L.) grown in a high tunnel system increased g_s values compared to those grown under open field conditions, which can be attributed to a greater availability of diffuse PAR under cover (Retamal-Salgado et al., 2015). In general, even though polyethylene films used in greenhouses or tunnels can reduce total PAR transmission they increase the amount of diffuse PAR, which is beneficial for photosynthesis and crop productivity (Li et al., 2014).

In cherry, there are differences in the photosynthetic adaptation to low light conditions (Wang and Hu, 2014). A recent study conducted by Zhang et al. (2021) revealed that using the plastic covers with ability of 55% of PAR transmission resulted in decreases of 43% and 45% in A_n in ‘Tieton’ and ‘Brooks’ cherry, respectively, due to insufficient light under cover. On the other hand, it has been reported that using plastic cover with ability of 85%-87% of PAR transmission increased A_n in ‘Santina’ and ‘Van’ (Sotiropoulos et al., 2014; Blanco et al., 2021b), demonstrating that photosynthetic responses of tree cherry under cover systems is widely influenced by the characteristics of cover materials and cultivars.

Water relations

There are different studies on water relations focused on irrigation strategies aimed at improving water productivity without reducing crop yield and quality (Blanco et al., 2019a). These studies and strategies should be adjusted in orchards under covers since protected environmental conditions tend to reduce water evaporation from the soil, resulting in greater availability of water for irrigation (Janke et al., 2017). When transpiration demand is high under open field conditions without covering, in dwarfing rootstocks there is greater hydraulic resistance to supply water to the leaves, leading to decreases in plant water potential and g_s. Blanco et al. (2021b) with ‘Santina’ cherry trees on ‘Colt’ (*P. avium* × *P. pseudocerasus*) rootstock showed that minimum stem water potential recorded in trees grown in high tunnels reached -0.83 MPa, while uncovered trees recorded a value of -1.15 MPa. Furthermore, water potential of fruit depends to a large extent on stem water potential (Blanco et al., 2019c), while it is related to environmental variables such as vapor pressure deficit (Measham et al., 2014; Blanco et al., 2018). In this sense, it has been reported that high tunnel cultivation improves plant water status by reducing vapor pressure deficit and losses due to water evaporation, increasing midday stem water potential. This would lead to an increase in the water potential and turgor of the fruit, promoting higher growth rates (Blanco et al., 2021b).

Flower development

The use of netting allows reducing incident solar radiation during flower differentiation, which would mitigate the negative effect of high summer temperatures, e.g., abnormal development of pistils and fruits (Beppu and Kataoka, 2000; Whiting and Martin, 2008; Imrak et al., 2014). Tunnel closure during flower development increases air temperature during the spring (Blanke et al., 2017), which can induce abnormal late flowering and poor fruit set; furthermore, heat stress during flowering. It has been estimated that when air temperature exceed 1 to 3 °C in comparison to normal conditions, it can reduce fruit set because temperature increase promotes accelerated growth of the pollen tube, a reduced number of pollen tubes that grow in the style, ovule degeneration and decreased stigmatic receptivity (Hedhly et al., 2007), demonstrating the importance of ventilation practices in cherry production under cover systems, especially during spring with warm conditions or the use cover materials with more ventilation ability such as netting systems. In addition, it has been indicated that high temperatures of early summer can lead to the suppression of flower initiation in cherry production under covering (Sønsteby and Heide, 2019), while the increase in temperature at the end of bud breaking allows advancing the flowering date, resulting in a positive impact on advance in harvest date and better prices in the market, therefore a positive impact in the profitability without increase in the costs of fruit production (Dekova and Blanke, 2007). In this sense, to balance the negative and positive effects of temperature increase, it is advisable to grow cultivars with abundant flower buds and high and stable yield, such as ‘Summit’ and ‘Lapins’ (Zhang et al., 2018b).

Tree growth and development

It has been described that winter dormancy in cherry trees is controlled by the interaction of photoperiod and temperature (Heide, 2008). Covers with an impact on light quality, such as colored nets, alter the amount of light in the blue, red, and far-red spectra, affecting shoot growth and bud break patterns, mediated by the interaction of photoreceptors as phytochromes and cryptochromes (Bastías and Corelli-Grappadelli, 2012). Limited sunlight conditions under protective covering favor shoot growth over fruit development, with an impact on the balance of vegetative and reproductive growth of the tree. In this case, covers that reduce the amount of red light *vs*. red-far light promote greater shoot development, while those that increase this proportion allow a more balanced control of shoot growth, positively influencing fruit growth (Bastías et al., 2012).

Lang et al. (2011) demonstrated that high tunnel cultivation of sweet cherry allowed for greater growth and development of trees, resulting in more rapid filling of allotted space with increases of 24% and 20% in tree height and leaf size, respectively. Similar results were found in previous studies on cherry trees grown under cover, showing more vigorous growth (Blanke and Balmer, 2008) or increased crown volume and growth of new shoots (Rubauskis et al., 2013) compared to uncovered trees. However, more recent studies have described that there is no detectable difference in vegetative growth under covers (Blanco et al., 2019b). Even though the greater increase in growth and development of trees under covers can be mainly attributed to light conditions (Bastías and Corelli-Grappadelli, 2012; Bastías et al., 2012), this could also be regulated by temperature. Lang (2014) demonstrated that high tunnel covers increased growing degree day (GDD) by 10%. This agrees with Retamal-Salgado et al. (2015) and Sønsteby and Heide (2019), who found that shoot growth increases with the increase in exposure time to high temperatures in the greenhouse, resulting from air temperature increase. It should be noted that excessive vegetative growth of cherry trees grown in high tunnels could negatively affect light interception and distribution within the canopy, reducing fruit quality and flower differentiation for the following season (Ayala and Lang, 2017). In addition to what is mentioned above; during flower development the air temperature increases, which can induce abnormal late flowering and poor fruit set; in addition, heat stress during flowering.

Fruit quality traits

The use of protective covers increases fruit size, which is attributed to the effect of light conditions on the balance between shoot and fruit growth (Bastías et al., 2012), or to the temperature increase during flowering and fruit set, which promotes higher cell division during the first growth stage (Retamal-Salgado et al., 2015; Bastías and Leyton, 2018). Lang et al. (2011) indicated that fruit weight in ‘Rainier’ cherry trees grown in tunnels was higher compared to non-covered trees. This increase in fruit size due to the effect of covers has been reported in different studies on ‘Lapins’ (Wallberg and Sagredo, 2014), ‘Samba’, ‘Bellise’ and ‘Rita’ (Overbeck et al., 2017), ‘Burlat’, ‘Samba’ and ‘Prime Giant’ (Schmitz-Eiberger and Blanke, 2012), ‘Ulster’ (Cline et al., 1995), and ‘Royal Down’ and ‘Santina’ (Bastías and Leyton, 2018); these results would be indicating that reducing fruit quantity due to lower fruit set under covers, as was mentioned above, would be resulting in better fruit quality in terms of fruit size.

Regarding color development, the results are contradictory. There are studies that report low color values in cherries grown under covers under climate conditions with lower sunlight availability such as Norway, Germany and southern of Chile (Børve et al., 2003; Dekova and Blanke, 2007; Wallberg and Sagredo, 2014), while other studies report higher values of fruit colors in cherry orchards cultivated under climate conditions with more sunlight availability such as Greece and central-northern of Chile (Kafkaletou et al., 2015; Bastías et al., 2017). It should be noted that covers have an important impact on fruit color, particularly in bicolor cherries such as ‘Rainier’ (Lang, 2009).

Regarding fruit firmness, there is evidence that this parameter is not affected in cherry cultivation under covers in warm climate when were only installed during the critical periods of rain-cracking (Kafkaletou et al., 2015; Mika et al., 2019).

However, several studies have reported that when protective covers are installed in cherry orchards for the whole period and from flowering to harvest, fruits tent to be softer (Dekova and Blanke, 2007; Wallberg and Sagredo, 2014; Bastías and Leyton, 2018). Similarly, Meland et al. (2017) reported that fruit from trees covered from the straw-yellow fruit stage to harvest was firmer than fruit covered from flowering to harvest. In addition, the presence of firmer fruits under cover has been reported only in early stages of harvest of cherries grown in countries in which the weather present lower or moderate temperature conditions such as Norway and Germany (Cline et al., 1995; Dekova and Blanke, 2007; Schmitz-Eiberger and Blanke, 2012).

Finally, Blanco et al. (2021a) described lower firmness in ‘Santina’ sweet cherries under plastic covers, which is associated with lower Ca concentrations in the fruit, probably induced by the high tunnel microclimate (high RH) that reduces fruit transpiration rate (Winkler et al., 2020) and increases vegetative growth, leading to Ca imbalances in the fruit.

Regarding sugar content, higher levels of glucose, fructose and sorbitol have been reported in cherries grown under cover (Usenik et al., 2009), with higher levels of total soluble solids (Børve et al., 2003; Usenik et al., 2009; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Meland et al., 2017).

However, Suran et al. (2019) found a lower content of soluble solids in cherry cultivation under cover, while other studies have reported adequate total soluble solids and titratable acidity relationships (Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Zhang et al., 2018b). Furthermore, the covering system could also have an influence on sugar content, thus fruit from trees covered with umbrella-type cover recorded a lower content of soluble solids compared to the fruit from trees under sloped-roof covering (Børve et al., 2003).

In summary, the effect of covers on fruit quality parameters differs depending on the type of cover, location, and management of the system. This information is a key tool to support the decision making by cherry growers (Table 2).

Table 2. Influence of different cover materials on sweet cherry (*Prunus avium*) quality parameters.

Variable	Material	Response	References
Firmness	Plastic cover	Higher	Cline et al., 1995; Meland et al., 2017
Firmness	Plastic cover	Lower	Dekova and Blanke, 2007; Blanke and Balmer, 2008; Maria et al., 2008; Lang, 2014; Wallberg and Sagredo, 2014; Bastías et al., 2017; Meland et al., 2017; Bastías and Leyton, 2018; Blanco et al., 2019b; Suran et al., 2019; Blanco et al., 2021a
Firmness	Plastic cover	Without difference	Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Mika et al., 2019
Firmness	Woven cover	Decreased	Maria et al., 2008
Color	Plastic cover	Increased	Cline et al., 1995; Dekova and Blanke, 2007; Schmitz-Eiberger and Blanke, 2012; Bastías et al., 2017
Color	Plastic cover	Decreased	Børve et al., 2003; Simon, 2006; Dekova and Blanke, 2007; Mulabagal et al., 2009; Wallberg and Sagredo, 2014; Mika et al., 2019
Color	Plastic cover	Without difference	Blanco et al., 2021b
Soluble solids	Plastic cover	Lower	Børve et al., 2003; Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Zhang et al., 2018b; Blanco et al., 2019a
Soluble solids	Plastic cover	Higher	Børve et al., 2003; Usenik et al., 2009; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Bastías et al., 2017; Meland et al., 2017; Bastías and Leyton, 2018
Soluble solids	Plastic cover	Without difference	Overbeck et al., 2017; Blanco et al., 2021b
Size	Plastic cover	Increased	Cline et al., 1995; Schmitz-Eiberger and Blanke, 2012; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Overbeck et al., 2017; Blanco et al., 2019a
Size	Plastic cover	Decreased	Blanke and Balmer, 2008
Size	Plastic cover	Without difference	Meland et al., 2017
Weight	Plastic cover	Without difference	Børve et al., 2008; Usenik et al., 2009; Sotiropoulos et al., 2014
Weight	Plastic cover	Higher	Balkhoven-Baart and Groot, 2005

CONCLUSIONS

The use of protective covers is an effective strategy for the control abiotic stress in sweet cherry (*Prunus avium* (L.) L.) trees, particularly rain and other climate hazards. However, covers alter environmental conditions of light, temperature, relative humidity, and wind, affecting the physiological responses of the tree, depending on climate conditions and characteristics of cover materials. Protective covers increase the amount of diffused photosynthetically active radiation, benefiting the photosynthetic activity of cherry trees due to protection from excessive direct radiation, but generating an imbalance between vegetative and reproductive growth. This occurs because covering systems decrease the total amount of available light to the plant, negatively affecting light distribution in the canopy. Excessive increase in temperature under covers during flowering and flower set can negatively affect crop yield, while it can positively affect cell division, also anticipating harvest date by accelerating fruit ripening. Cherry trees under cover have a better water status compared to uncovered trees, showing better tolerance to water deficit and improved fruit turgor potential, with positive impacts on fruit size. Regarding fruit quality parameters, covers increase fruit size due to their positive effect on cell division (temperature) and expansion (hydric status), but they decrease fruit firmness, apparently due to the lower availability of Ca in the fruits. Increasing of fruit size by covers could also to be related to reduction of fruit load and regulated by the temperature conditions during the flowering and fruit set. The effect of covering systems on color and sugar content has not been fully determined yet. The multiple environmental factors and physiological responses observed in cherry production suggest the need to adjust agronomic practices such as pruning, tree management, crop load regulation, irrigation, and nutrition according to the specific conditions for each protective covering system.

Author contribution

Conceptualization: R.M.B. Methodology: R.M.B., Y.S. Formal analysis: R.M.B., Y.S. Investigation: Y.S. Resources: R.M.B Data curation: Y.S. Writing-original draft: Y.S. Writing-review & editing: R.M.B. Visualization: Y.S. Supervision: R.M.B. Project administration: R.M.B. Funding acquisition: R.M.B. All co-authors reviewed the final version and approved the manuscript before submission.

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