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Chapter

Apple Production under Protective Netting Systems

Richard M. Bastías and Alexandra Boini

Abstract

Apple crop is more and more cultivated under protective netting systems. Depending on the location and sunlight intensity, apple orchards can benefit from these installations, as they will be protected against extreme weather events. Depending on the technical features of the thread, the nets will be hail-proof, wind-proof, or rain-proof, while having different shading percentages. Modern fruit production faces high pressure also related to biotic stressors; thus, modern protective nets are designed to aid pest management. These protective systems become interesting, as they will induce changes in the orchards' microenvironment, with consequences on crop physiology. Netting mainly reduces incoming solar radiation and wind speed, altering the heat balance. Leaf gas exchanges and water relations can be positively influenced by netting in apple cultivation areas with extreme solar radiation, high temperatures, and low water availability. These considerations are important, especially if the final yield and quality are not compromised by shading. These protective systems can allow higher sustainability of apple production, lowering resource use, along with crop protection.

Keywords: *Malus domestica* borkh, protected crop, nets, sunlight, orchard management, physiology

1. Introduction

Orchard netting is a technique that has become widespread in apple production to prevent damage from adverse climatic events, such as sunburn in countries such as Chile, South Africa, the United States, and Australia [1–4], hail in countries such as Germany, Italy, and Spain [5–7], and insect attacks such as codling moth in countries such as Italy, France, and Canada [6, 8, 9]. This wide range of uses of netting in apple trees implies the adoption of different installation systems and net designs, differentially impacting microclimatic conditions of light, temperature, relative humidity, and wind speed [9–11], and with a consequent effect on plant physiological responses, such as leaf gas exchange, water relations, tree growth, floral development, and fruit quality traits [12–16]. Greater environmental and biological stress pressure due to climate change is forcing the use of netting to be essential by apple growers, but at the same time imposes the challenge of adjusting orchard management practices to the particular microclimate and physiological plant conditions that are generated under netting, such as irrigation, pruning, crop load regulation, and pest control [7, 17], as well as the need for innovation in new netting systems that are compatible with sustainable fruit production [18]. This chapter provides an overview of netting in apple orchards, including installation systems, net designs, their effects on microclimate and plant physiology, and the innovative development of photo-selective nets and sustainable netting systems.

2. Netting systems

2.1 Netting structure

The most appropriate netting structure for apple orchard covering depends on the commercial purpose, installation cost, climatic conditions, and benefits pursued [19]. The most common structure system is the anti-hail roof type (**Figure 1** left-above), which has become widespread among apple growers in countries such as Italy, Germany, and Spain [20, 21], and some South American countries such as Chile and Argentina [17]. This system allows good ventilation of the orchard and, thanks to the slope of the roof, favors the discharge of hail that slides and accumulates toward the net junction between the rows, thus avoiding damage to the installation system due to overweight from an extreme hailstorm [19–21]. A second system is the shading roof system (**Figure 1** right-above), which is widely used in apple production areas with a high incidence of solar radiation and extreme temperatures, and to protect fruits against sun damage [17]. It has the advantage of greater access to machinery between rows and lower investment costs in netting materials and structure while being

Figure 1.
Apple orchards under netting structures of anti-hail roof system (left-above), shading roof system (right-above), plot exclusion system (left-below), and single row exclusion system (right-below).

also effective in mitigating the effects of hail and wind. However, the disadvantage of this system is the low stability against extreme hailstorms, given the absence of slopes, thus not allowing hail to slide and discharge, increasing the structure tension by the hail weight [22]. Other systems are exclusion nets that can totally plot the orchard, or just single rows (**Figure 1** left-right-below). These systems offer total protection against hail, sunburn, and the impact of wind [22]. Additionally, they allow protection from the attack of pests, limiting chemical pesticide use. It has been demonstrated that the single-row exclusion system in apple orchards allows a reduction of fruit injury by codling moths near to 99%, without any application of specific insecticide, since this netting excludes the male moths flying over the tree canopy [8]. However, this type of system requires ventilation management, especially in areas with hot summers, since they can induce problems of increased temperature and relative humidity. Furthermore, these systems are more expensive, since more netting materials are needed to cover the total plots or single rows of apple orchards [21, 22]. Besides, it has been observed that these systems tend to accumulate dust on the topmost part, year after year, along with moss formation.

2.2 Net designs

Different types of nets are used in apple orchards, which differ in their weaving and colors. The first is the "Raschel" type net, which is commonly used for shading, with flat threads joined by chains of transverse threads, called the warp, that tie the transverse flat threads, called weft (**Figure 2**), preventing them from falling apart due to the action of the wind or hail fall [20]. The second group of nets is the "Leno" type net (**Figure 1**), which is made of monofilament yarns, woven orthogonally in both weft and warp directions. The warp corresponds to a double fiber of threads that transversally encloses each thread of the weft that is positioned longitudinally (**Figure 2**). This type of net is more rigid than the previous one and is more suitable against strong hailstorms [20]. From the mechanical point of view, the "Raschel" net exhibits a very fragile and linear elastic tension in the weft direction, and higher resistance and nonlinear tension in the warp direction, while the "Leno" anti-hail net shows fragile and lineal tension in the warp direction, and higher strength nonlinear

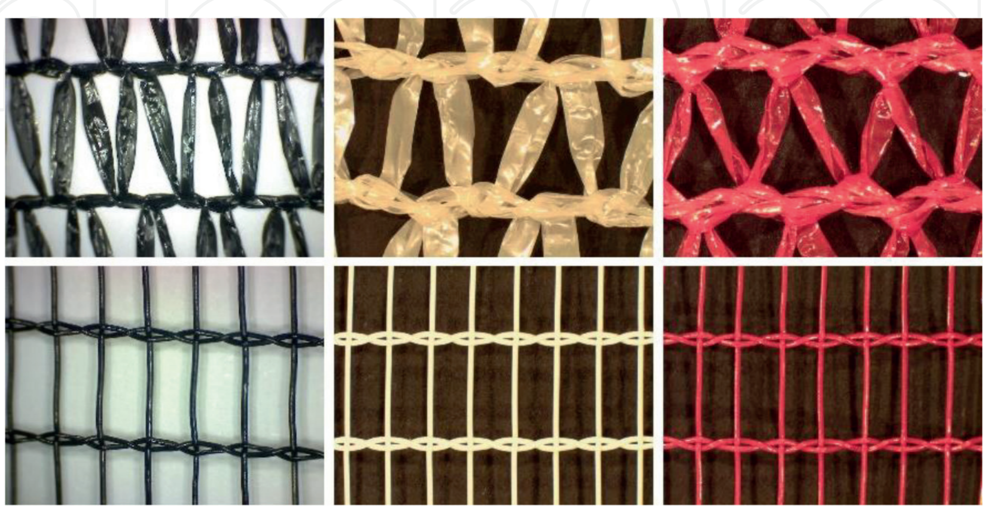

Figure 2.
Details of threads design of black, white, and red shade nets (above), and black, white, and red hail net (below) commonly used to protect apple orchards.

tension in the weft direction [23]. The color of the net is obtained by adding pigments to the HDPE polymer during the manufacture of the yarns. The most common colors of nets used in apple orchards are black, white, and red (**Figure 2**), although blue, green, yellow, and gray nets also have been used by apple growers. The color of the net exerts a selective effect on sunlight transmission, altering the light spectrum and the ratio of direct vs. diffuse light. This will ensure the effects on the plant's physiological and productive responses as has been widely evaluated in apple trees and will be analyzed in more detail during the development of this chapter [10–15].

3. Microclimate conditions

3.1 Light conditions

The main microclimate impact of netting is in the reduction of incoming photosynthetic active radiation (PAR), which could be affecting the most important physiological process determining the fruit yield and quality in apples, such as photosynthesis and carbon allocation [24]. The influence on nets in the PAR reduction is widely affected by the net design; thus, translucid-type nets reduce up to 7% of PAR light availability, while PAR under black anti-hail is reduced by 18%. In addition, the combination of thread colors also influences the quantity of PAR light reduction under netting. White-green net reduces up to 13% of PAR transmission, while under red-black nets the reduction of PAR availability is near 16% [25]. These differences in PAR availability among nets are due to the fact that the color of the threads alters the diffuse light proportion concerning total light transmitted under netting. In this sense, it has been shown that apple orchards covered with a pearl net provide 4% more PAR light available than those covered with a red net, due to the increase in diffuse light [26]. In this case, the pearl net increases the proportion of diffuse light by up to 15% compared to the red net (**Figure 3**).

On the other hand, the color of nets has a direct influence on the spectra transmission of sunlight [11, 27]. White, gray, or black color nets do not alter the spectral transmission of light at any of the wavelengths (**Figure 4**), while red and blue netting differentially alter light transmission in the specific wavelengths. The red net reduces

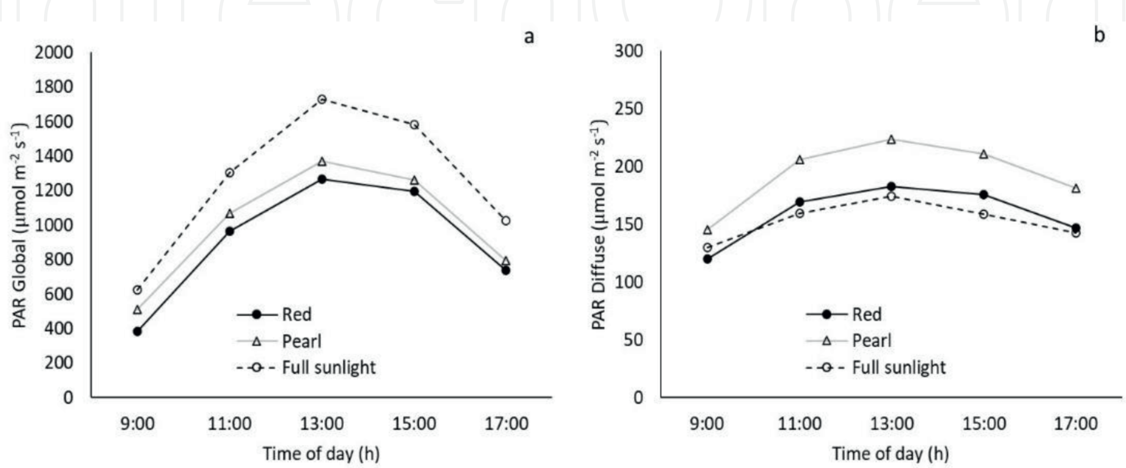

Figure 3.
Total (a) and diffuse (b) photosynthetic light incident in "Gala" apple orchard under pearl and red netting (adapted from Umanzor et al., 2017).

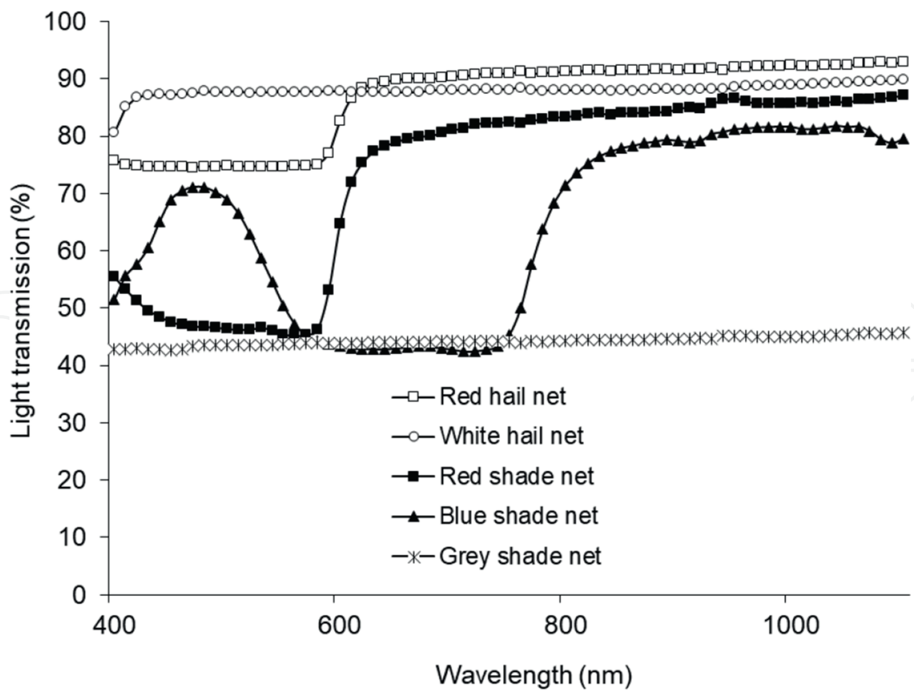

Figure 4.
Spectra light transmission of colored hail and shade nets commonly used to protect apple orchards (adapted from Bastías et al., 2012; 2021).

transmission in the blue light spectrum (400–500 nm) and increases it in the red (600–700 nm) and far-red (700–800 nm) light spectrum, whereas the blue net alters light transmission in the opposite way (**Figure 4**). It has been shown that these changes in the wavelength of light transmission modify different vegetative and reproductive responses in apple orchards grown under red and blue nettings, such as shoot and fruit growth, and leaf gas exchange, and that they are probably governed by the activity of specific photoreceptors such as phytochromes and cryptochromes [11, 12, 28].

UV radiation is another component of sunlight that is affected using nets and that plays an important role in the apple fruit quality, by stimulating the synthesis of anthocyanins, the pigment responsible for the red color of the fruit [29], as well as for its action on the photo-oxidative damage that originates in the apple sunburn due to overexposure to direct sunlight [30]. It has been shown that, depending on the color and weave of the threads, the nets used to cover apple orchards reduce UV light transmission by 10–13% more than PAR light, due to the additives that are incorporated during its manufacturing to increase its durability and resistance to UV rays. Thus, for a transparent and black monofilament net that reduces PAR light by 7 and 18%, the reduction of UV light with these nets is 20 and 29%, respectively [25].

3.2 Temperature, relative humidity, and wind speed

Covering netting mainly reduces the global solar radiation incoming and wind speed, thus altering the heat balance in the orchard and with the consequent impact on air and canopy temperatures [31]. The density of net weaving directly affects the magnitude of temperature changes under netting. No significant changes in environmental temperature were observed under nets with low thread density and with shade levels between 20 and 25% [10, 31], while the use of 50% shade nets reduces the air temperature by up to 1–3°C, and especially with 50% black nets [32].

The effect of the nets on the relative humidity in apple orchards depends on the climatic condition, planting system, and geographical location. In more arid environments such as Australia, the use of netting increased the relative humidity by up to 15% [33], but in other arid environments such as the state of Washington, the relative humidity did not change in apple trees under different net colors [10], while in more humid environments such as Germany, the relative humidity was reduced from 3 to 5% in apple orchards grown under netting [28].

Protecting apple orchards with netting also reduces wind speed at the tree canopy level, and its effect depends on location, planting system, and density of the net weaving. In the States of Washington and Australia, a reduction of about 50% in wind speed was reported in apple trees growing under 20% shade nets [32, 34], while in Chile, the use of 23% shade net reduced the wind speed by 69% with a direct impact on the reduction of loss of sensible heat flux in apple orchards [31]. Finally, the use of colored nets at 50% shade allowed to reduce wind speed by up to 89% when compared to the condition nets [34].

4. Physiological tree responses

4.1 Leaf gas exchange

The influence of the use of the nets on apple leaf net photosynthesis rate (A_n) and stomatal conductance (g_s) has been reported with different responses, depending on the netting system, cultivar, and climatic conditions (**Table 1**). In South Africa, the use of 20% shade black net decreased A_n and g_s by 14 and 21% compared to the condition without netting, and attributable to morphological changes of the leaves growing under netting [35]. Similar results were observed in Germany under cloudy day conditions with the use of 12% shade green-black net in the cultivar "Fuji." In this case, the A_n was 21% lower in apple leaves growing with this net [28]. Under more extreme environmental conditions with greater intensity of solar radiation and high temperatures, the use of netting has been favorable in increasing A_n and g_s in apple trees (**Table 1**). In the state of Washington, covering "Honeycrisp" apple trees with

Net system/climate condition	Cultivars	Variation of A_n with respect to control (%)	Variation of g_s with respect to control (%)	References
20% black net/Sunny condition	"Royal Gala"	(−) 14	(−) 21	[35]
12% green-black net/ Cloudy condition	"Fuji"	(−) 21	—	[28]
22% blue net/Sunny and hot condition	"Honeycrisp"	(+) 30	(+) 31	[36]
22% pearl-gray net/ Sunny and hot condition	"Brookfield Gala"	(+) 54	(+) 52	[31]
22% black net/Sunny and warm condition	"Golden Delicious"	(+) 60	(+) 80	[37]

Table 1.
Variation in net photosynthesis rate (A_n) and stomatal conductance (g_s) in apple cultivars grown under different climate conditions and netting systems.

a blue net at 22% shading allowed an increase of about 30% in the leaf A_n and g_s, when the trees grew under hot conditions [36]. Similar results were obtained in Chile in "Brookfiel Gala" apple trees covered under a 22% pearl-gray net and in which A_n and g_s increased by 54 and 52%, respectively, when the conditions of temperature and solar radiation were widely extreme [31]. In Portugal and under Mediterranean climate conditions, the use of black netting at 22% shade in "Goden Delicious" apple allowed an increase of A_n and g_s by 60 and 80%, respectively [37].

Differential response in A_n and g_s under netting may be due to the particular light conditions that are generated under the nets and that affect the leaf function and morphology [12], as well as to the temperature conditions that prevail in the apple-growing area [36]. In this sense, the color of the net affects these responses, as has been shown in "Fuji" apple trees growing under 40% shade blue and red nets. In this research, it was shown that the g_s in leaves growing under the blue net increased by 21% compared to the red net, and attributable to the effect of blue light on the stomatal opening stimulus [12]. In the same study, it was also shown that this increase in g_s resulted in a similar increase in the rate of transpiration (E), but without a significant effect on An, implying a lower efficiency in the water use of the leaves that grow under the blue net. Another study indicates that the increase in g_s and A_n by about 50% in apple trees due to the use of 22% shade pearl-gray net also allowed for a 25% higher water use efficiency measured as A_n/E [31]. These results indicate that the selection of the color and percentage of shading are very relevant to consider in apple cultivation under areas with extreme solar radiation, high temperatures, and low water availability [12, 31, 36, 37].

4.2 Water relations

As previously said, net application in orchards will impact the microclimate; thus, the tree's responses will also differ in terms of water use. Since there is a decrease in the incoming solar energy, the leaves will need less water for evaporation, a consequence of necessary heat loss to manage the entering energy. This amount of outcoming water flux by evaporation from the apple orchard under netting depends on the quantity of light determined by the shading percentage of the net, but also by the quality of light determined by the color of the net. Higher radiation leads to higher latent heat flow; thus, there will be higher heat dissipation [13, 38–40]. In unlimited water availability scenarios, water loss for cooling purposes will take as long as the optimum leaf temperature is maintained. However, when water is limited, stomata will close to prevent excessive water loss, thus preventing dehydration [13, 39]. Apple sap flow studies showed that trees under a 20% shading net indeed have higher xylem water transport rates, compared to trees under a 50% shading net [13]. Another study showed improved water status for apple trees under a 50% shading net [41], compared to those without net, or even to those under a 20% shading net [42]. In these cases, trees experiencing higher incoming light may have reached, or exceeded, the "threshold" at which transpiration was higher than root water uptake. Stomata closure to avoid dehydration resulted in more negative water potentials. It is likely that trees under 50% shading are growing in less stressful conditions, than those grown under lighter shading, or no shading at all. It is expected that, in a more shaded orchard, a certain amount of water may still be available in the soil [40].

These results suggest that apple trees in shaded environments are able to lower their water requirements. Since reference evapotranspiration (Et_0) is with doubt lower the more shade there is [43, 44], K_c will be lower for apple trees in more shaded orchards (**Figure 5**) [45, 46].

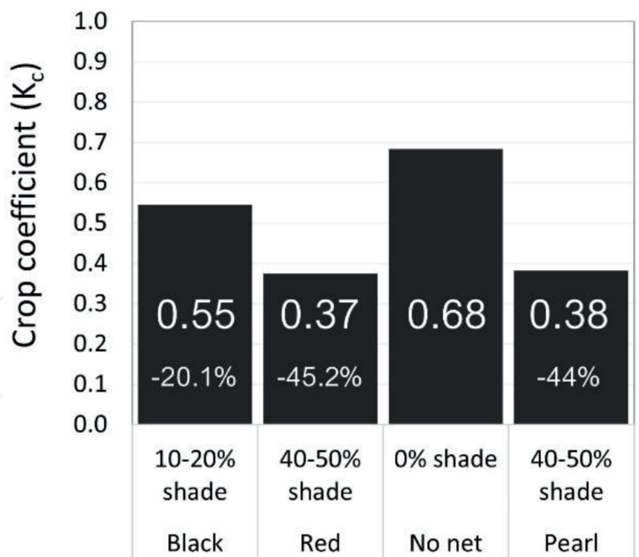

Figure 5.
Estimated crop coefficient (kc) values and percentages for different light environments in a "Gala" orchard (adapted from Boini et al., 2018).

The resulting crop evapotranspiration (Et_c) will decrease, compared to less shaded growing conditions. Apple trees can be more efficient in terms of water use, under shaded environments [37], even in conditions of water shortage [18]. Anyhow, increasing shade along with irrigation volumes that reflect Et_c will lead to similar water potentials (**Figure 6**).

When the different wavelengths of the solar spectrum are manipulated (with photoselective nets, e.g.), water relations can be influenced according to a photomorphogenic effect. Hence, a low-red/far-red light environment will generate higher water uptake [13]. There will be a tendency to have less negative water potential [12, 13]; thus in unlimited water conditions, certain wavelengths increase tree water consumption. On the other hand, blue light was found to maintain a better water status (midday stem and leaf water potentials), compared to no shading [36], although

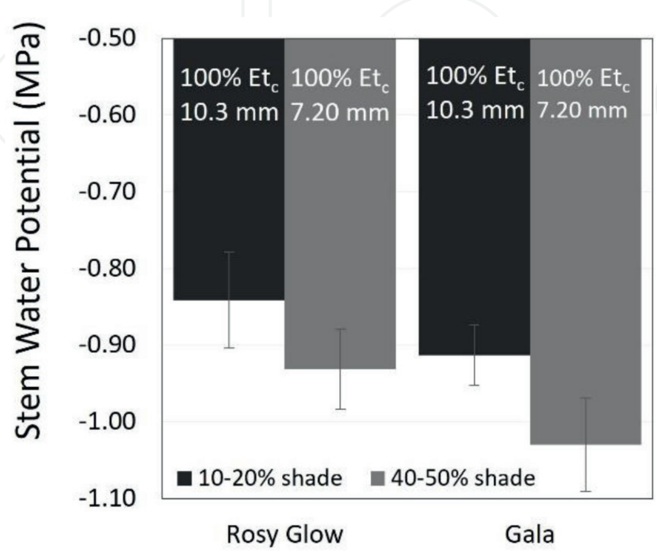

Figure 6.
Daily average stem water potential for two apple cultivars in two different netted environments (unpublished data).

there were no other colored nets as a comparison. When a photoselective net is thicker in order to increase the shading percentage (40–50% shading), the more intense certain wavebands will be. This can heavily impact the responses described. If the nets are designed to maintain a lighter shading percentage (max 20%), it is possible that the intensity of such wavebands is not strong enough to induce a visible effect, at least in the short term. Other factors will markedly dictate orchard responses, such as the pruning history and the weather Yield and fruit quality of apple cv. "Jonagold" under hail protection nets [18, 47].

4.3 Vegetative and reproductive growth development

Protective netting leads to higher shoot development and elongation, depending on the intensity of the external sunlight and the shading percentage of the nets. In general, lower PAR environments trigger shade-avoidance responses, to different extents [11]. As specified in the previous sub-section, shaded canopies experience low R/FR ratios, pushing shoots in search of richer PAR areas. However, there are cases that report no differences in "Fuji" shoot growth, comparing light-shading nets with uncovered controls [28], probably due to the well-known alternate bearing behavior of this cultivar.

Other vegetative growth and development features include leaf area and thickness. These characteristics will vary based on the quantity of filtered light and also on its quality. In this case, discriminating between these two properties of shading nets appears easier. Heavy shading produces smaller and thinner leaves, typical of inner canopy foliage, while the more exposed ones generate extra palisade layers, to better manage the higher incoming solar energy. In fact, extra palisade cells were found in PAR and blue-rich light environments under netting [12]. A wider leaf area is also typical of highly illuminated environments, although nets with higher PAR, or blue light, transmittance will generate bigger leaves [11, 28].

Effects of shading can occur on reproductive growth. Return bloom will be primarily influenced, as light is essential for flower bud formation; however, the responses could vary on the cultivars and the shading percentage. No differences were found for "Rosy Glow" apple, when comparing different percentage of shading (Boini, unpublished work); "Gala," "Fuji," and "Granny Smith" apple cultivars can be negatively affected by shading, with significantly fewer flower buds under more shade [28, 48, 49]. To overcome this possibility, installing reflective mulches will increase PAR distribution in the canopies, with positive results the following year [49]. Fruitlets will have to compete with vegetative shoots, for growth resources, especially in the first weeks after full bloom. In fact, this period is so crucial, and growers will not open protective netting before 3–4 weeks after full bloom. The timing depends on the location of the orchard; thus, some may see the nets open more than a month after full bloom. After such a period, there will still be competition between vegetative and reproductive organs [15]. The spur canopy needs good light interception, in order to increase the leaf area, so as to have higher photosynthates products to be sent to fruitlets. In this case, white or pearl nets with high scattering properties would improve these agronomical aspects.

4.4 Fruit quality traits

The location of the orchard will be the most important aspect. Different cultivating areas cannot be compared, as the tree's physiological responses will change, although the protective netting may be the same. The responses of apple fruit's final quality to shade can be conditioned by the color of the nets and by their light scattering properties. Considering black, gray, and white (pearl), the results can be different when looking at certain traits and can be considered cultivar-dependent [50].

Red color development for summer varieties can be penalized or delayed by certain protective nets, exclusion nets, for example, as daily thermal excursion may not be enough to induce anthocyanin synthesis. Nevertheless, the protective netting is beneficial against sunburn damage, as it has been demonstrated that this physiological disorder is related to high solar intensity along with high air temperatures [3]. It has been shown that the effectiveness of sunburn control through netting is related to lower photoinhibition at the level of the skin of the apple. Thus, in the cultivars "Fuji" and "Gala," the photochemical efficiency of the PS-II of the skin of the fruits that grew under nets was 3% and 12% higher in comparison with the fruits that grew exposed to full sunlight, respectively [16]. The protection of the fruits against sunburn through netting causes different responses in the composition of color pigments and antioxidants in the apple skin, which depends on the cultivar and type of net. While in "Gala" apples the use of red net favors the accumulation of anthocyanins and antioxidant capacity, and in "Fuji" apples the use of pearl net decreases the accumulation of anthocyanins and antioxidant capacity in the fruit skin [1]. Due to changes in the transmission of PAR and UV light, the antioxidant composition of anthocyanins and vitamin C is widely altered in apples that grow under the netting systems. It has been reported that the anthocyanin content was 2–6 times lower in "Fuji" apples grown under red and blue 40% shade net, in comparison with uncovered trees [51]. In the same way, it has been shown that the vitamin C content decreased by 31% in apples under the black-green net, and only by 10% under the white-red net, while in white translucent net, the vitamin C content was increased by 5% [52].

Another quality trait that is affected by the use of netting in apples is the size of the fruit, in which effect varies depending on the climatic condition, cultivar, and type of net. In Spain, the use of black 25% shade net reduced the fruit size in "Mondial Gala" apples [53], while in Brazil the use of white 18% shade net increased the fruit size in "Gala" and "Fuji" apples [48]. In Italy, the use of blue 40% shade net increased the fruit size in 'Fuji' apples, compared to the use of red 40% shade net [14]. In Chile, the use of a pearl-gray net at 22% of shading factor also increased fruit size in "Brookfield Gala" apples, attributed to the higher net assimilation of CO_2 found under this net and which provides greater availability of carbohydrates for fruit growth [31].

Finally, changes in fruit firmness have also been reported in apples under netting, which are closely linked to changes in light conditions. The use of a black 15% shade net increased fruit firmness in "Fuji" apples, while black 55% shade net decreased it [54]. The differential effect of the color of the net on fruit firmness in apple trees has been attributed to the role played by the light quantity and quality on changes in the size and density of cells during the fruit growth and development process [55].

5. Photoselective nets

In the last decades, advances in netting systems have focused on the development of photoselective materials with the capacity to transmit selectively the solar radiation to promote positive physiological responses and improve the yield and fruit quality through the addition of specific colors during the manufacture of the nets [56]. In the first studies carried out on apple trees, it was verified that the use of the

Figure 7.
Detail of trial in commercial "Granny Smith" apple orchard under combined pearl-gray, blue-gray, and blue-pearl nets, in comparison with black net. Maule region, Chile.

photo-selective blue net allowed to increase in fruit growth in comparison with the red net, and through the promotion of greater photosynthesis and partition of assimilates toward the fruit [14]. Photoselective nets also affect the sap flow and water use in apple trees; the use of the pearl net was more effective in reducing water consumption in relation to the red net, with a direct effect on decreasing the sap flow [13]. Other more recent works demonstrate the potential of using photoselective colored nets in the biological management of the codling moth in apple orchards. In this case, the parasitoid capacity of the moth larva was affected by the color of the nets; females found their host faster under red and pearl nets when compared to black nets [57]. In recent years, new photoselective net materials have been incorporated with the specific purpose of controlling sunburn on apple orchards through the reduction of light transmission in the UV and IR spectra, which are based on combined colored pearl-gray, blue-gray, and pearl-blue nets (**Figure 7**); its use in commercial apple orchards allowed reducing sun damage in fruits with an effectiveness of 49%, 45%, and 33% in the "Granny Smith," "Cripps Pink," and "Fuji" cultivars, respectively, and in relation to the use black netting [17].

6. Conclusion

Netting systems can increase the sustainability of apple production, limiting the use of resources, from water to chemical treatments for pest control. For this reason, this technology has been widely expanded in different apple-producing areas of the world, with different alternatives in installation structures, net design, and color that offers the possibility of differential management of the orchard microclimate and crop physiology to obtain certain benefits such as the use of water, availability of photo-assimilates, vegetative and reproductive growth control, and regulation of some fruit quality traits. The existing knowledge to date about the impacts of netting systems on plant physiology offers the possibility of exploring new applications (photoselective nets) in apple production and under different climatic conditions, but at the same time, it raises some questions from the environmental sustainability point of view. The question arises whether the actual production of the nets is going to compromise an environmentally sustainable fruit production process. The first concerns outweigh the agricultural benefits of netting on natural predators in integrated pest management [58]. A second point is related to how the netting system works well with recycling and re-uses the HDPE for constructing a series of elements, such as pumps, valves, and pipework, which is one of the best strategies [59]. Finally, increasing interest in biobased and sustainable netting systems leads to the development of polymers containing polysaccharides and raw materials. However, these biodegradable materials were still less than 1% of the produced plastics and eco-friendly additives that could extend their lifespan are still far from being produced [60].

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