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Aspectos fisiológicos que determinan la variación de rendimiento entre variedades y sistemas de protección climática en arándanos.

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RAIN COVER AND NETTING MATERIALS DIFFERENTIALLY AFFECT FRUIT YIELD AND QUALITY TRAITS IN TWO HIGHBUSH BLUEBERRY CULTIVARS BY CHANGES IN SUNLIGHT AND TEMPERATURE CONDITIONS

RESUMEN

La alta variabilidad climática actual ha estimulado considerablemente el uso de cubiertas para proteger los huertos de arándanos de eventos meteorológicos adversos, pero no existe claridad acerca de cómo el tipo de material de cubierta afecta el rendimiento y calidad en este cultivo. Esta investigación evaluó el efecto de las cubiertas de plástico de polietileno de baja densidad (LDPE), rafia y malla sobre características del ambiente que rodea a la planta (luz UV, PAR, NIR y grados días de crecimiento, GDD), la planta (intercepción de luz, índice de área foliar, LAI, rendimiento y desarrollo floral), y el fruto (firmeza, sólidos solubles y acidez) para dos cultivares de arándanos. La transmisión de UV con malla fue en promedio un 11% y 43% mayor que con rafia y plástico LDPE, mientras que la radiación NIR bajo rafia y plástico LDPE fue un 8 -13% mayor que la malla, y con impacto en el incremento de la temperatura fruto-aire y de GDD. El rendimiento bajo rafia fue en promedio un 27% superior al bajo malla. La firmeza de fruto con malla fue en promedio un 12% superior al plástico LDPE. Los valores de intercepción de luz, LAI y desarrollo floral de la planta explicaron en un 64% ($p=0,0052$) la variación de rendimiento por efecto de las cubiertas. Estos resultados sugieren que el tipo de cubierta afecta diferencialmente la productividad y de calidad de frutos en arándanos, debido a condiciones específicas de luz y temperatura que se generan bajo estos generan.

Summary

The use of covers to protect blueberry orchards from adverse weather events has increased due to the variability in climate patterns, but the effects of rain cover and netting materials on yield and fruit quality have not been studied yet. This research evaluated the simultaneous effect of LDPE plastic cover, woven cover and netting materials on environmental components (UV light, PAR, NIR and growing degree days, GDD), plant performance (light interception, leaf area index, LAI, yield and flower development), and fruit quality traits (firmness, total soluble solids and acidity) in two blueberry cultivars. On average, UV transmission under netting was 11% and 43% higher compared to that under woven and LDPE plastic covers, while NIR was 8 -13% higher with both types of rain covers, with an increase in fruit air temperature and GDD. Yield was 27% higher under woven cover with respect to netting, but fruit firmness values under netting were 12% higher than those of LDPE plastic cover. Light interception, LAI and flower development explained 64% ($p=0.0052$) of the yield variation due to the cover material effect. These results suggest that the type of cover differentially affects yield and fruit quality in blueberries due to the specific light and temperature conditions generated under these materials.

CAPÍTULO 1

INTRODUCCION GENERAL

Una de las especies frutícolas de importante crecimiento en las últimas décadas en Chile es el arándano (*Vaccinium* spp.), exportando 72242 toneladas de fruta a la fecha, lo que posiciona al país como el cuarto mayor productor mundial (ODEPA, 2023). Este impulso comercial se ha debido principalmente a las características organolépticas y funcionales de este fruto, cuyos beneficios de su consumo se reflejan en su aporte de antioxidantes a la dieta (Wu *et al*., 2011), además de contribuir a la prevención de enfermedades como la diabetes, entre otros beneficios (Roopchand *et al*., 2013).

Actualmente, la especie de arándano que lidera en producción y consumo de fruta corresponde al arándano de arbusto alto (*Vaccinium corymbosum* L.), que representa el 80% de los arándanos cultivados a nivel global (Morales *et al*., 2017). El arándano es originario del hemisferio norte, entre el sur de Canadá y el norte de los Estados Unidos, existiendo una amplia diversidad de variedades. Dependiendo de su origen, estas pueden clasificarse como arándanos de arbusto alto del norte y arándanos de arbusto alto del sur, clasificación que procede según su requerimiento de frío invernal y tolerancia a bajas temperaturas. Los arándanos de arbusto alto del norte están adaptados a temperaturas frías en pleno invierno (-20°C) creciendo de forma óptima en lugares con 800 a 1000 horas frío. Por otro lado, el arbusto de arándano alto del sur no tolera temperaturas muy por debajo de los 0°C y requieren unas 550 horas de frío invernal (Retamales y Hancock, 2018). Este último, fue desarrollado a partir de la hibridación de tres a cuatro especies de arándanos (*V. corymbosum* L. x *V. darrowi* C.; *V. ashei* R.; *V. angustifolium* A.), con el propósito de disminuir el requerimiento de horas frío de la planta, consiguiendo una mejor adaptación para ser cultivada en la región sur de los Estados Unidos, sin perder las características de rendimiento comercial obtenida a partir del arándano de arbusto alto del norte (Kole, 2007). Posteriormente, se domesticó la especie silvestre *Vaccinium ashei* Reade, conocida comúnmente como arándano ojo de conejo, que alcanza una proporción de un 14% del cultivo arándanos a nivel mundial (Morales et al., 2017).

En Chile, existe una amplia diversidad de variedades de arándanos introducidas, permitiendo desarrollar este cultivo en un amplio rango territorial, desde la región de Atacama hasta Los Lagos, concentrándose mayormente en las regiones del Maule y Ñuble (Odepa, 2019). Una de las variedades más plantadas en Chile es ´Legacy´ (Odepa, 2019). Genéticamente, esta variedad pertenece al grupo varietal de los arándanos de arbusto alto del sur, cuya característica es su bajo requerimiento de frío invernal, oscilando entre las 500 y 600 horas, además de poseer cierta tolerancia a condiciones de mayor temperatura y mantener sus hojas siempre verdes en invierno (Morales *et al*., 2017). Si bien es cierto, la variedad ´Legacy´ ha demostrado buenos resultados de rendimiento y calidad de frutos, se ha impulsado el recambio varietal en huertos más especializados, incluyendo características que son priorizadas por la demanda externa y las exigencias de la industria (Morales y Ramírez, 2022). Un ejemplo de esto es la variedad ´Top Shelf´, perteneciente al grupo de variedades de arándano de arbusto alto del norte, cuyos requerimientos de frío invernal son mayores a los de ´Legacy´ (800 a 1000 horas frío). Además de presentar un marcado receso invernal con caída de sus hojas, su cosecha es concentrada y de media estación (Morales y Ramírez, 2022). Aunque el componente genético (cultivares) juega un rol relevante en el potencial de rendimiento del cultivo del arándano, el clima también ejerce un efecto significativo.

Se ha demostrado que la producción de arándanos de arbusto alto del sur cultivados en zonas geográficas con alta disponibilidad radiación solar y que no presentan heladas invernales, logran producir frutos durante todo el año (Fang *et al*., 2020). De esta forma, el comportamiento del arándano de arbusto alto está ligado a la condición climática en el que se encuentre plantado y dependiendo del cultivar en particular. En este sentido, variedades como ´O'Neal´ no alcanzan rendimientos óptimos en zona climáticas como Coquimbo, pero si lo hacen en zonas climáticas como Valparaíso, mientras que otras variedades alcanzan un similar potencial de rendimiento en ambas zonas del país (Bañados, 2009).

Dada la situación actual de cambio climático, que influye directamente en el crecimiento, desarrollo y producción de frutales (Rai e*t al*., 2015), se han incorporado diferentes estrategias de manejo agronómico que sean capaces de mitigar estos cambios. Así, la instalación de diversos materiales de coberturas se ha vuelto una alternativa interesante, del punto de vista fisiológico y productivo. Dentro de estos materiales existe la técnica que comprende el uso de mallas que filtran la radiación interceptada (Rodríguez *et al*., 2015), modificando las propiedades de reflectancia, absorbancia y transmitancia de radiación en las hojas y otorgando una función protectora para la planta (Shahak, 2008).

Las mallas protectoras son capaces de modificar al ambiente que protegen, además de la intensidad y la calidad de la luz solar. Además, el uso de mallas promueve diferencias con respecto a temperatura del dosel, humedad relativa, temperatura del suelo y velocidad del viento (Mupambi *et al*., 2018). Diferentes variedades de arándano mostraron comportamientos diversos bajo coberturas. Para arándanos altos (*V. Corymbosum* L.), Retamales *et al.* (2008) concluyeron que las mallas sombreadoras de colores produjeron diferencias significativas en cuanto a rendimiento, debido a un aumento en el cuajado de frutos, pero no alteraron la inducción floral ni el peso de fruto. Por otro lado, estudios realizados en arándanos ´Elliott´ mostraron un retraso significativo de la fecha de cosecha por efecto del uso de malla, lo que podría resultar interesante desde el punto de vista comercial (Lobos *et al*., 2013). Otros trabajos han observado que las mallas otorgan un aumento en la cantidad de frutos con calibres exportables (sobre 10 mm de diámetro ecuatorial) en la variedad ´Brigitta´. Sin embargo, al mismo tiempo, las mallas provocan una prolongación de la etapa de crecimiento del fruto verde, ligado a la disminución de radiación y temperatura, retrasando la maduración hasta por 16 días (Rodríguez *et al*., 2015). Otros estudios llevados a cabo en la variedad ´Bluecrop´ mostraron una mayor longitud de brotes y tamaño de las hojas al aumentar el porcentaje de sombra bajo malla. No obstante, el número de brotes, grosor de hoja y densidad de estomas se ven disminuidos por la excesiva sombra, influyendo negativamente en la capacidad fotosintética de la planta (Kim *et al*., 2011).

Otras alternativas de materiales de cobertura son el plástico y la rafia que son impermeables y que también modifican el microclima de la planta. En especies como cerezo (*Prunus avium* L.) el uso de plástico de polietileno de baja densidad permite un incremento de cerca de un 7% más de luz fotosintética que una cobertura de rafia de polietileno de alta densidad, cuando fueron evaluados en días soleados, mientras que, en días nublados, ambos materiales prácticamente transmiten la misma cantidad de luz (Bastías y Leyton, 2018). Por otra parte, la temperatura de los frutos se ve disminuida en momentos de extrema radiación solar con este tipo de materiales de cobertura, siendo eficaz en la prevención de estrés hídrico (Calderón-Orellana *et al*., 2023), mientras que las temperaturas mínimas diarias se ven incrementadas por efecto del plástico de baja densidad (Bastías y Leyton 2018). Si bien, el uso de mallas, plásticos y rafias son materiales que alteran las condiciones de luz y temperatura en diferentes cultivos, incluyendo el arándano (Retamales *et al*., 2008; Bastías *et al*., 2012; Bastías y Leyton, 2018), no existen trabajos en que analice el efecto simultáneo de los tres materiales en arándanos y cómo ello podría afectar el potencial de rendimiento y calidad de frutos para cultivares de distinto origen genético.

HIPOTESIS

Los materiales comúnmente usados en sistemas de coberturas como rafias, plásticos y mallas alteran diferencialmente el rendimiento y caracteres de calidad de frutos en plantas de arándanos a través de modificaciones específicas en las condiciones de la luz solar y temperatura que se generan en el ambiente bajo estos materiales .

OBJETIVO GENERAL

Evaluar el efecto del uso simultáneo de plástico LDPE, rafia y malla en las condiciones de cantidad y calidad de la luz solar, variación y acumulación térmica, y su impacto en componentes productivos de la planta (desarrollo floral, cuajado de frutos, rendimiento, e índice de área foliar), y atributos de calidad de los frutos (tamaño, firmeza, sólidos solubles y acidez) en variedades de arándanos de arbusto alto del sur de bajo requerimiento de frío (´Legacy´) y arbusto alto del norte con alto requerimiento de frío (´Top Shelf´).

OBJETIVOS ESPECÍFICOS

- Evaluar los componentes de rendimiento productivo de frutos entre las variedades y en función del uso de coberturas.
- Cuantificar transmisión de luz fotosintéticamente activa en ambas variedades y en condición con y sin cobertura y analizar el espectro

de luz bajo coberturas.

- Cuantificar la variación y acumulación térmica de la planta en ambas variedades y en condiciones con y sin cobertura.
- Relacionar las condiciones de luz y temperatura con componentes productivos de la planta y atributos de calidad de frutos.

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CAPÍTULO 2

Rain Cover and Netting Materials differentially affect fruit yield and quality traits in two highbush blueberry cultivars by changes in sunlight and temperature conditions.

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Keywords: Protected fruit growing; UV light; thermal accumulation; plant growth; fruit firmness, *Vaccinium corymbosum* L.

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Abstract

The use of covers to protect blueberry orchards from adverse weather events has increased due to the variability in climate patterns, but the effects of rain cover and netting materials on yield and fruit quality have not been studied yet. This research evaluated the simultaneous effect of LDPE plastic cover, woven cover and netting materials on environmental components (UV light, PAR, NIR and growing degree days, GDD), plant performance (light interception, leaf area index, LAI, yield and flower development), and fruit quality traits (firmness, total soluble solids and acidity) in two blueberry cultivars. On average, UV transmission under netting was 11% and 43% higher compared to that under woven and LDPE plastic covers, while NIR was 8 -13% higher with both types of rain covers, with an increase in fruit air temperature and GDD. Yield was 27% higher under woven cover with respect to netting, but fruit firmness values under netting were 12% higher than those of LDPE plastic cover. Light interception, LAI and flower development explained 64% ($p=0.0052$) of the yield variation due to the cover material effect. The obtained results suggest that the type of cover differentially affects yield and fruit quality in blueberries due to the specific light and temperature conditions generated under these materials.

Keywords: Protected fruit growing; UV light; thermal accumulation; plant growth; fruit firmness*, Vaccinium corymbosum* L.

1. Introduction

A wide variety of blueberry (*Vaccinium corymbosum* L.) cultivars are suitable for cultivation in a vast area of Chile, being mainly cultivated in the Maule, Ñuble and Araucanía regions [1]. One of the most planted cultivars is ´Legacy´ [1], which belongs to the group of southern highbush blueberries, characterized by its low chill requirement (500 - 600 chill hours) during winter dormancy [2]. In recent years, 'Legacy' has been replaced by other cultivars that better meet the industry requirements in terms of fruit quality, flavor, and firmness, belonging to the most demanding group of northern highbush blueberries, with requirements of 800-1000 chill hours [3].

Given the current scenario of climate change and the need to expand market opportunities for exported fruit, the production of blueberries under protected cultivation has become widespread worldwide. The most commonly used protection systems are roof covers and high tunnels, which protect crops from rain and frost, in turn accelerating fruit maturity and advancing harvest date [4]. Furthermore, netting is also an effective tool to protect orchards from sunburn, hailstorms and insect attacks [5].

The most commonly used materials in rain-protection systems are waterproof woven covers with laminated texture or low-density polyethylene (LDPE) plastic covers with a smooth texture, while porous and permeable raschel or monofilament nets are used for netting [5,6]. Ogden and van Iersel [7] evaluated LDPE plastic covers in ´Emerald´ and ´Jewel´ blueberry cultivars and concluded that this type of cover affected the synchronization of flowering and pollination, thus decreasing fruit set and yield. Conversely, other studies on the effect of LDPE plastic covers on blueberry cultivars have reported that yield of ´O'Neal´ and ´Legacy' increased by over 40% [8], while no effects were observed in ´Sampson´ and ´Duke´[9]. In ´Bluegold´ and ´Brigitta´ blueberries, the use of woven covers decreased yield by 28% and 73% compared to non-covered plants

[10]. Regarding netting, Retamales et al. [11] found that the use of white and red nets increased yield of 'Berkeley' blueberries by 84.2 and 31.9%, respectively, reporting no effects on fruit size or content of soluble solids in the fruit. Likewise, Lobos et al. [12] evaluated the effect of black, red and white nets with different shade intensities on ‘Elliott’ blueberries and concluding that red and white nets with intermediate shade intensities delay harvest without affecting yield or fruit quality.

Therefore, there is evidence that protection covers have an impact on yield and quality of blueberries, with varying effects depending on the cover material and cultivar. However, there is little information about the environmental factors that would determine differences between types of covers, while there are few studies that have analyzed different cover materials simultaneously for blueberry. It has been demonstrated that specific characteristics of the cover material, in terms of color and pattern, determine variations in the quantity and composition of the light radiation transmitted by these materials [13,14], as well as in the coefficients of heat transfer, which directly impact the environmental temperature [15]. Depending on the color and thread density, cover materials alter light transmission in the UV (280 – 390 nm) and PAR (400 – 700 nm) spectra. Thus, the use of translucent nets reduces the transmitted PAR by up to 7%, while black nets result in an 18% reduction. In addition, netting can reduce UV light transmission by 10-13% more than PAR transmission [5]. On the other hand, Salazar-Canales et al. [16] determined that blue-gray, black, and pearl-grey nets reduce radiation by 24%, 21%, and 19%, respectively.

Regarding waterproof materials, LDPE plastic reduces PAR transmission by 15% and transmits 4% UV radiation. Likewise, it has been described that this material transmits 7% more PAR on sunny days than woven covers, with no differences between the materials on cloudy days [17]. On the other hand, Abdel-Ghany et al [15] found differences in heat transfer between different colored nets, reporting that green nets increased the convection heat transfer coefficient by 37.8%, while beige nets reduced this coefficient by 35.4%, compared to dark green and white nets. On the other hand, the maximum air temperature in greenhouses covered with LDPE plastic, polycarbonate, and glass were 23.4, 22.1, and 18.9 °C higher than the outside air temperature, respectively, when tunnels were closed, with no ventilation. [18]. Increases in maximum air temperature have also been recorded in polyethylene high tunnel-covered blueberry orchards, with increases between 3°C and 15°C when compared to non-covered plants [Ogden and van Iersel, 2009]. The present study proposes that the materials used in rain protection and netting systems differentially influence yield and fruit quality in blueberry by modifying the light and temperature conditions generated by these crop protection systems. To test this hypothesis, the objective of this work was to evaluate the effect of LDPE plastic covers, woven covers and netting on the quantity and quality of solar radiation as well as temperature variation and accumulation, determining their impact on plant performance (flower development, fruit set, yield, leaf area index), and fruit quality traits (size, firmness, total soluble solids, and acidity) in southern highbush ('Legacy') and northern highbush (´Top Shelf´) blueberries of low and high chill requirements, respectively.

2. Results

2.1. Sunlight and temperature conditions

PAR transmission (%) showed no significant differences ($p=0.154$; Figure 1) between the different cover materials. However, significant differences ($p<0.0001$) were found in terms UV transmission. Netting transmitted 76.7% of the external UV radiation, while LDPE plastic and woven covers transmitted lower UV levels, with reductions of 70.6% and 19.5% with respect to netting, respectively.

Radiation flux partitioning obtained by spectrophotometric analysis showed that the UV radiation transmitted on average during the season in the two locations, Linares and Traiguén, was 53%, 42% and 10% under netting, woven cover and LDPE plastic cover, re-spectively (Figure 2 A and B); PAR transmission reached 83%, 81% and 86% (Figure 2 C and D), while NIR transmission reached 83%, 91% and 96% under the same cover sys-tems, respectively (Figure 2 E and F).

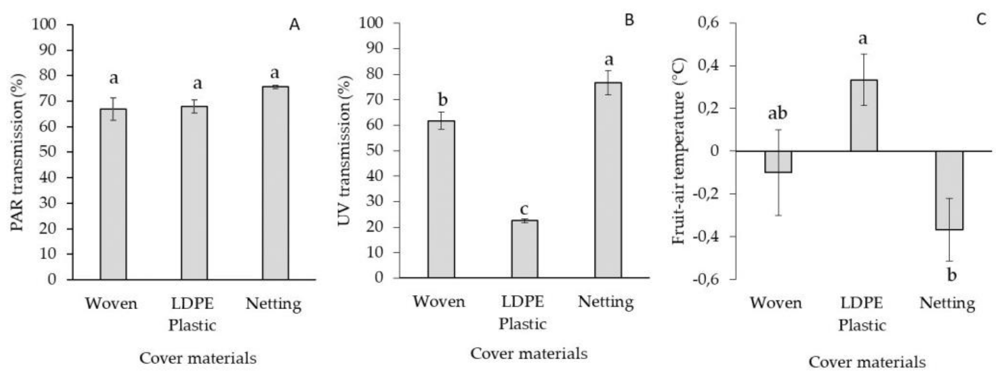

Figure 1. Influence of woven cover, LDPE plastic cover and netting on PAR (A), UV radiation transmission (B), and fruit air temperature differences (C).

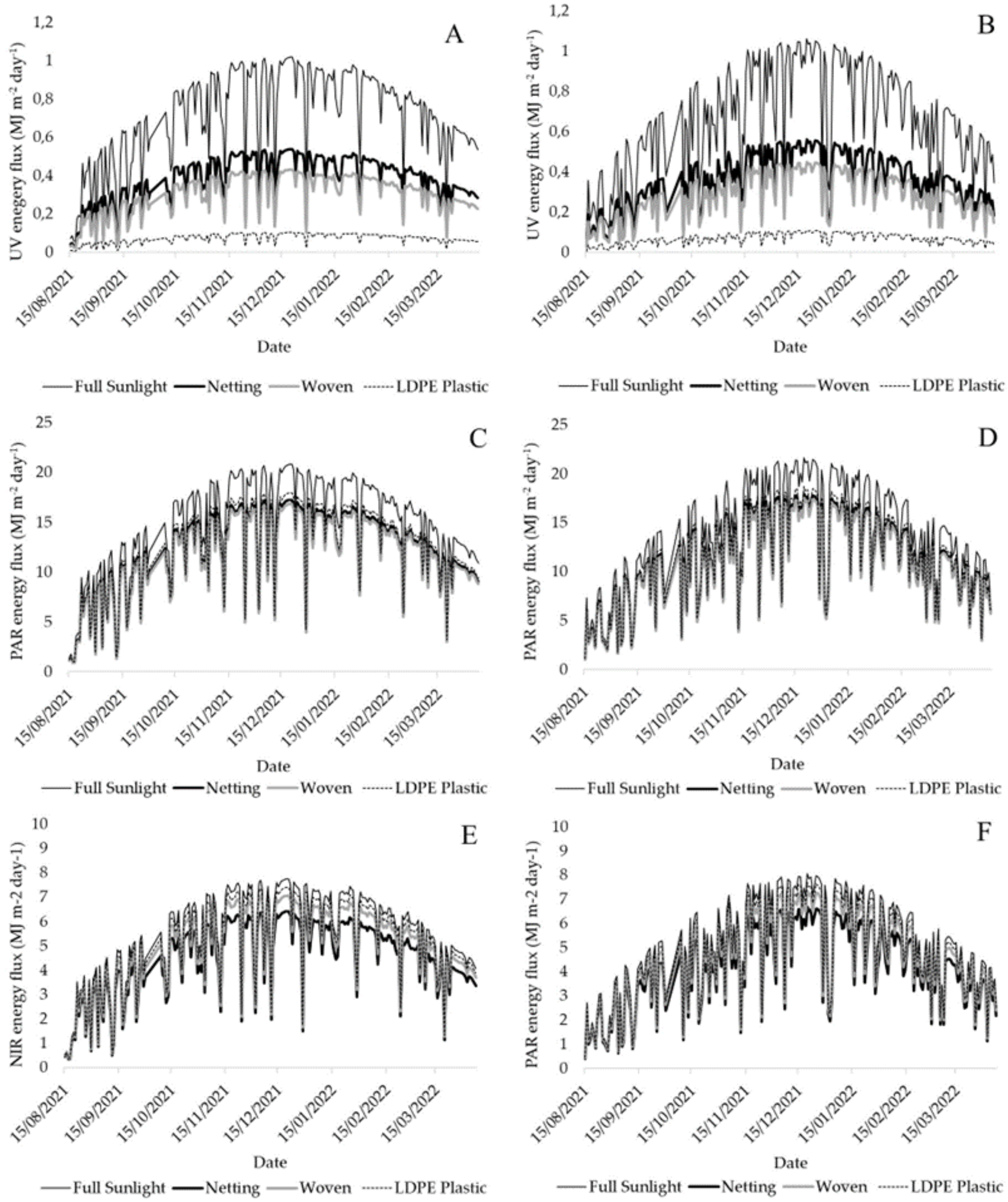

Figure 2. Variation in solar radiation flux in the range of UV, 360 – 390 nm (A and B); PAR, 400 – 700 nm (C and D); and NIR, 700 – 1120 nm (E and F) under netting, woven cover and LDPE plastic cover in Linares and Traiguén.

All the covers decreased the photosynthetic photon flux density (PPFD) transmitted inside the plant in ´Legacy´ and ´Top Shelf´ in both locations, with greater magnitude and significance from 80 cm to 140 cm from the center of the plant to the middle of the inter-row (Figures 3 and 4). In Linares, the proportion of transmitted PPFD was reduced by 46.7%, 37.9% and 22.6% in ‘Legacy’ under woven cover, LDPE plastic cover and netting, respectively (Figure 3A). In ´Top Shelf´, the transmitted PPFD decreased by an average of 43.6%, 32.1%, and 21.1% under LDPE plastic cover, woven cover and netting, respectively (Figure 3B). In Traiguén, PPFD transmission decreased by an average of 36.8%, 31.7% and 22% in ´Legacy’ (Figure 4A), while ´Top Shelf´ recorded reductions of 36.4%, 32.2% and 20.5% under the same protection covers, respectively (Figure 4B).

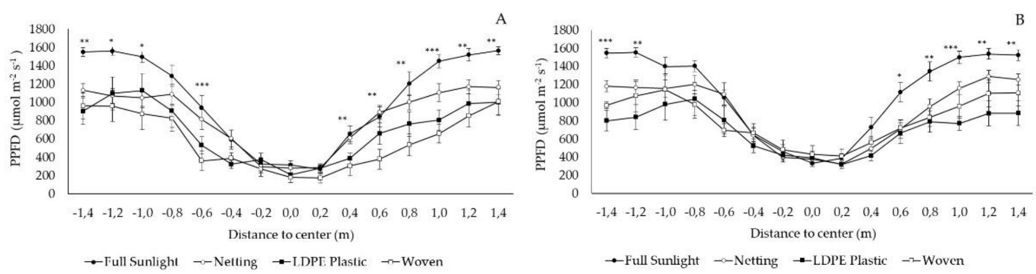

Figure 3. Transmission of photosynthetically photon flux density (PPFD) in ´Legacy´ (A) and ´Top Shelf´ (B) cultivars under netting and woven and LDPE plastic covers. Linares, Maule Region, Chile.

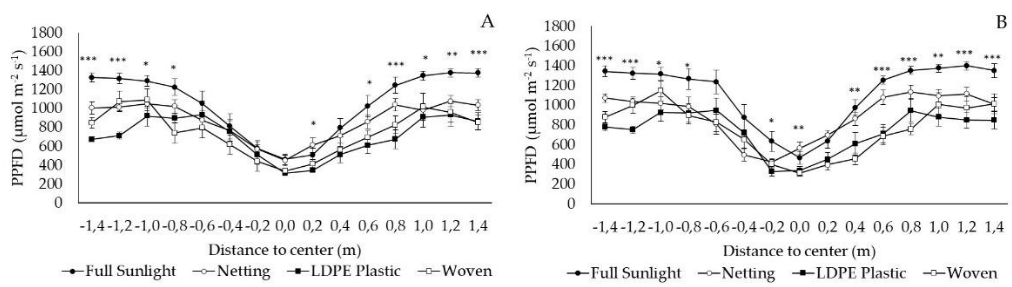

Figure 4. Transmission of photosynthetically photon flux density (PPFD) in ´Legacy´ (A) and ´Top Shelf´ (B) cultivars under netting, and woven and LDPE plastic covers. Linares, Maule Region, Chile.

In terms of leaf area index (LAI) (Table 1), values were significantly higher ($p<0.0001$) under woven and LDPE plastic covers with respect to the control (no cover) and netting, with increases of 39.3% and 38.8% in Linares and 50.5% and

54.9% in Traiguén, respectively (Table 1). When compared to the control, light interception was also significantly ($p<0.0001$) higher under woven and LDPE plastic covers, reaching increases of 44.3% and 43.6% in Linares, and 52.6% and 58.2% in Traiguén, respectively. In Linares, average values of light interception of blueberry plants grown under woven and LDPE plastic covers was 10.2% and 20.3% higher than that of netting and the control, respectively, while increases of 8.1% and 20.6% were observed in Traiguén (Table 1). In Linares, the average LAI values observed under LDPE plastic and woven covers were 20.7% and 39.1%, higher than those of netting and the control, while Traiguén recorded increases of 21. 1% and 52.7%, respectively. In addition, light interception and LAI values were significantly higher in 'Legacy' compared to 'Top Shelf' in Linares, with increases of 8% and 17.3%, respectively (Table 1).

Table 1. Influence of netting, woven and LDPE plastic covers, and cultivar on light interception and leaf area index (LAI) in blueberry plants.

Treatment	**Light Interception (%)**		**LAI**	
	Linares	**Traiguén**	**Linares**	**Traiguén**
	Cover materials (Cm)			
Control	46.18 c	37.21 b	1.78 b	1.11 b
Netting	56.3 b	49.73 a	2.05 ab	1.4 a
LDPE Plastic	66.34 a	58.85 a	2.47 a	1.72 a
Woven	66.65 a	56.8 a	2.48 a	1.67 a
p-value	<0.0001***	<0.0001***	<0.0001***	<0.0001***
	Cultivar (Cv)			
Top Shelf	56.54 b	49.74 a	2.02 b	1.45 a
Legacy	61.2 a	51.55 a	2.37 a	1.5 a
p-value	0.0016**	0.1429 ns	0.0029**	0.4643 ns
p-value Cm x Cv	0.059 ns	0.6062 ns	0.1505 ns	0.8484 ns

Fruit air temperature difference (FATD) under LDPE plastic cover was significantly higher than that recorded under netting or woven cover, reaching a value of +0.3°C, while FATD under these crop materials was significantly reduced by -0.3°C and -0.1°C, respectively (Figure 1). Accumulated growing degree days (GDD) during the season were 46% higher in Linares compared to Traiguén (Figure 5). In Linares, LDPE plastic cover increased the amount of GDD by 17% compared to the control (no cover), followed by woven cover and netting with 10% and 8%, respectively (Figure 5A). In Traiguén, the use of netting and plastic cover reduced the accumulation of GDD by about 11%, while woven cover increased the amount of accumulated GDD by 3%, compared to the control (Figure 5B).

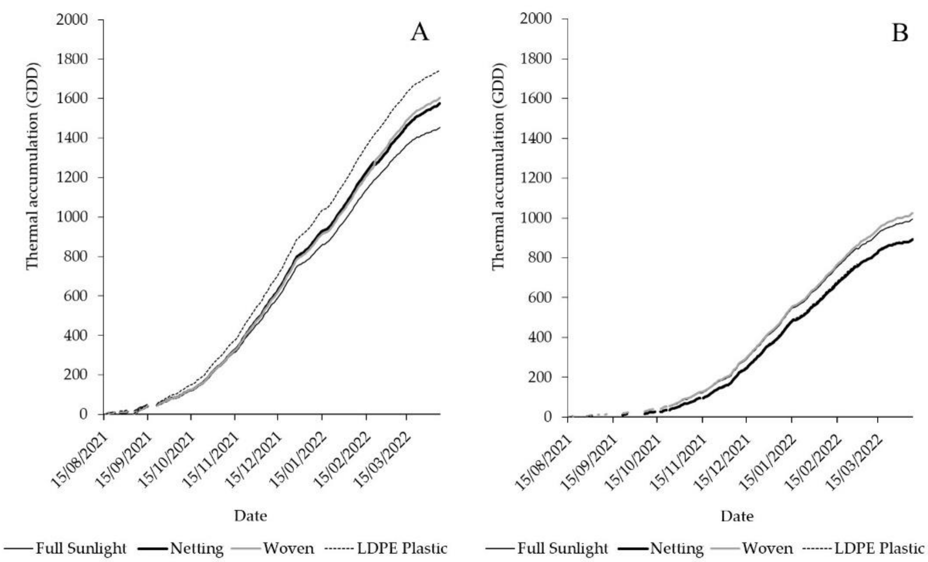

Figure 5. Variation in accumulated growing degree days (GDD) under netting, and woven and LDPE plastic covers, in Linares (A) and Traiguén (B).

2.2. Yield

Cover materials had a significant impact ($p<0.0001$) on yield in Linares and Traiguén (Tables 2 and 3). In both locations, blueberry plants grown under woven cover had higher fruit yield compared to plants grown under netting and no cover (control), with increases of 24.2% and 18.1% in Linares and 31% and 13.7% in

Traiguén, respectively. The woven cover also resulted in higher yield than LDPE plastic cover but only in Traiguén. In addition, netting led to significantly lower yield in both locations, with reductions of 18.8% and 20.8% in Linares and Traiguén for plastic and woven covers, respectively (Tables 2 and 3). Regarding cultivars, fruit yield was significantly higher (p=0.0004 and p=0.0155, in Linares and Traiguén) in ´Top Shelf´ compared to ´Legacy´, being 23% and 10.4% greater in Linares and Traiguén, respectively (Tables 2 and 3). In addition, a significant effect of the interaction of the cover material with the cultivar on yield was observed in both locations (p=0.0011 and p=0.0500 in Linares and Traiguén, respectively). In Linares (Figure 6), the interaction of ´Top Shelf´ with woven and LDPE plastic covers reached significantly higher yields in relation to the other combinations, being 25.2% and 21.4% higher with respect to non-covered ´Top Shelf´ plants and 35.9% and 31.8% higher than 'Top Shelf' under netting. In Traiguén (Figure 7), the interaction of ´Top Shelf' with woven cover recorded a significantly higher yield than the other combinations, being 13.5% and 42% greater than that of this cultivar without cover and under netting, respectively. In both locations, the interaction of ´Legacy´ and ´Top Shelf´ with netting resulted in significant reductions in yield, being 32.7% and 26.4% lower with respect to ´Top Shelf´ plants under woven cover in Linares, and 28.2% and 29.6% lower than ´Top Shelf´ under woven cover in Traiguén (Figure 7).

No significant differences were observed in terms of flower development due to the effect of covers in both locations (Table 4). However, the number of floral primordia per bud was significantly affected by the effect of the cultivar; this was 25% (p<0.0001) and 17% (p= 0.0003) higher in ´Top Shelf´ than ´Legacy´ for Linares and Traiguén, respectively. In Linares, fruit set was not significantly affected by the cover material or cultivar. In Traiguén, the plants under netting exhibited a significant increase (p=0.0183) of 11% in fruit set with respect to the control (Table 4).

According to the multiple linear regression analysis, flower development and LAI would significantly explain (p=0.0052) 63% of the variation in yield due to the effect of 'Top Shelf' cultivar and the woven cover (Figure 10) since the highest yield values corresponded mainly to this interaction in both locations (Figures 6 and 7). In turn, light interception and flower development would significantly explain (p=0.0014) 64% of the variation in yield due to the effect of the same interaction (Figure 8). In quantitative terms, the optimal ranges to achieve high yields consist of flower development greater than 6 primordia per bud and LAI greater than 1.5. Likewise, the highest yields under covers would be obtained in plants with buds with more than 6 flower primordia per bud and with a light interception capacity greater than 50% (Figure 8).

Table 2. Influence of netting, woven and LDPE plastic covers, and cultivar on yield, fruit diameter, firmness, soluble solids (SS), acidity (A) and SS/A ratio in blueberries grown in Linares.

Treatment	**Yield (kg planta^{-1})**	**Diameter (mm)**	**Firmness (g mm^{-1})**	**Soluble Solids (SS) (°Brix)**	**Acidity (A) (% citric acid)**	**SS/A Ratio**
			Cover materials (Cm)			
Control	2.466 b	15.750 a	147.500 b	14.401 b	0.331 a	57.816 a
Netting	2.344 b	16.250 a	152.813 a	14.036 c	0.338 a	46.699 a
LDPE	2.863 a	16.750 a	138.625 d	14.604 a	0.348 a	44.893 a
Woven	2.911 a	16.125 a	143.063 c	14.394 b	0.376 a	47.666 a
p-value	<0.0001***	0.0858 ns	<0.0001***	<0.0001***	0.8907 ns	0.4418 ns
			Cultivar (Cv)			
Top Shelf	2.918 a	17.094 a	145.969 a	14.547 a	0.332 a	48.983 a
Legacy	2.374 b	15.344 b	145.031 a	14.171 b	0.365 a	49.554 a

p-value	0.0004***	0.0009***	0.1298 ns	0.0055**	0.2775 ns	0.9446 ns
p-value Cm	0.0011**	0.1434 ns	0.4779 ns	0.4613 ns	0.6198 ns	0.3320 ns

Table 3. Influence of netting, woven and LDPE plastic covers, and cultivar on yield, fruit diameter, firmness, soluble solids (SS), acidity (A) and SS/A ratio in blueberries grown in Traiguén.

Treatment	Yield (kg planta^{-1})	Diameter (mm)	Firmness (g mm^{-1})	Solid solubles (SS) (°Brix)	Acidity (A) (% citric acid)	SS/A Ratio
			Cover materials (Cm)			
Control	3.566 b	15.250 a	151.750 b	13.836 a	0.434 a	33.643 a
Netting	3.098 c	14.750 a	157.813 a	13.509 b	0.489 a	31.080 a
LDPE	3.766 b	15.375 a	137.750 d	13.324 b	0.393 a	35.509 a
Woven	4.057 a	15.438 a	142.188 c	13.484 b	0.424 a	35.222 a
p-value	<0.0001***	0.3068 ns	<0.0001***	0.0066**	0.4880 ns	0.6371 ns
			Cultivar (Cv)			
Top Shelf	3.800 a	16.688 a	156.531 a	13.549 a	0.447 a	32.439 a
Legacy	3.443 b	13.719 b	138.219 b	13.527 a	0.423 a	35.288 a
p-value	0.0155*	0.0034**	<0.0001***	0.6279 ns	0.5561 ns	0.4101 ns
p-value	0.0500*	0.7350 ns	0.0007***	0.0179*	0.8059 ns	0.8764 ns

Table 4. Influence of netting, woven and LDPE plastic covers, and cultivar on flower development and fruit set in blueberries.

Treatment	Flower development (n° primordia bud^{-1})	Frui set (%)

	Linares	Traiguén	Linares	Traiguén
	Cover materials (Cm)			
Control	6,7 a	7,3 a	75,5 a	77,3 b
Netting	6,8 a	7,8 a	77,5 a	85,7 a
Plastic	7,3 a	7,8 a	77,4 a	78,6 b
Woven	6,6 a	7,7 a	76,5 a	80 ab
p-value	0,1402 ns	0,4754 ns	0,9033 ns	0,0183*
	Cultivar (Cv)			
Top Shelf	7,6 a	8,3 a	77,1 a	80,7 a
Legacy	6,1 b	7,1 b	76,4 a	80,1 a
p-value	<0,0001***	0,0003***	0,8424 ns	0,8559 ns
p-value Cm x Cv	0,542 ns	0,7244 ns	0,6607 ns	0,9429 ns

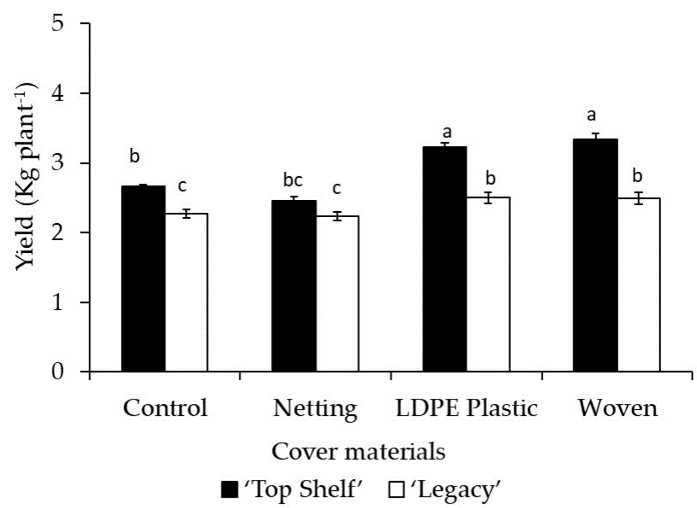

Figure 6. Influence of the interaction of crop cover material (netting, woven cover and LDPE plastic cover) with ‘Legacy´ and ´Top Shelf´ cultivars on yield in Linares.

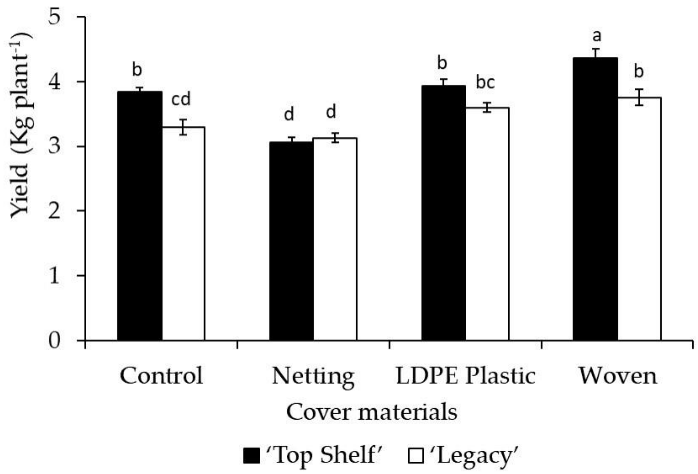

Figure 7. Influence of the interaction of crop cover material (netting, woven cover and LDPE plastic cover) with ‘Legacy´ and ´Top Shelf´ cultivars on yield in Traiguén.

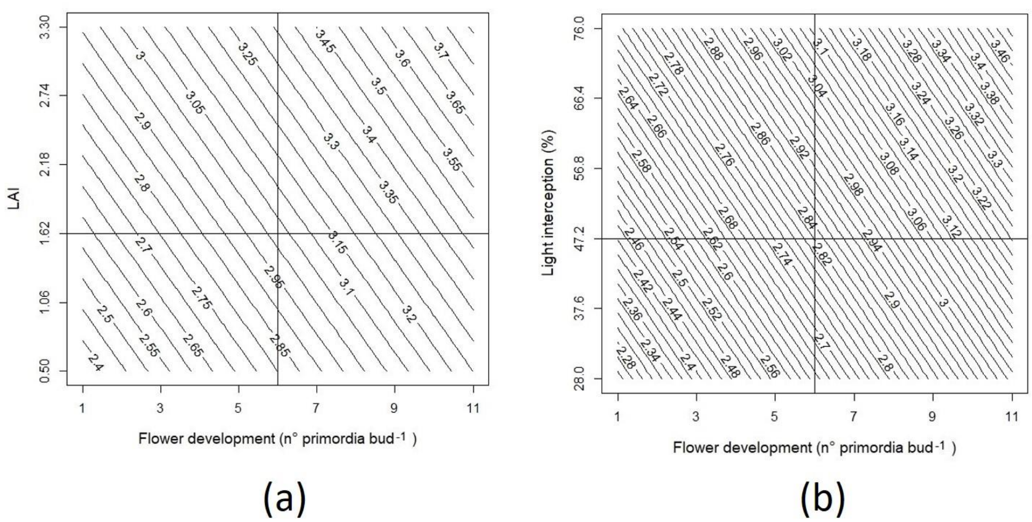

Figure 8. Graphic representation of the fit model for the multiple linear regression analysis between yield, flower development and leaf area index (LAI) (Regression model: Y = 2.16+0.09* Fert+0.2*LAI; R2=0.63*; p<0.05) (a) and between yield, flower development and light interception (Regression model: Y = 1.87+0.08* Fert+0.01*Interception; R2=0.64*; p<0.05) (b) as affected by covers and cultivars. Numbers on contour graph lines represent yield values in kg plant^{-1}.

2.3 Fruit quality traits

Fruit size, measured as diameter of the fruit, was not significantly affected by cover materials (Tables 2 and 3). However, the cultivar had a significant impact on this parameter, with ‘Top Shelf' exhibiting the best performance and reaching values that were 11.4% and 21.6% higher than those recorded by 'Legacy' in Linares and Traiguén, respectively (Tables 2 and 3).

Fruit firmness (in g mm^{-1}) was affected by the cover material (Tables 2 and 3). Netting presented significantly ($p<0.0001$) higher values than the control (no cover) in Linares and Traiguén (3.6% and 4% higher, respectively). Conversely, woven cover resulted in a significant decrease ($p<0.0001$) by 3% and 6.3% with respect to the control for Linares and Traiguén, respectively. Furthermore, significantly ($p<0.0001$) lower values were observed in plants grown under LDPE plastic cover, with values that were 6% and 9.2% lower than those recorded in the control for Linares and Traiguén, respectively (Tables 2 and 3). In Traiguén, there was a significant effect ($p<0.0001$) of the cultivar on this parameter, with firmness being 13.2% higher in ´Top Shelf´ compared to ´Legacy´ (Table 3). In the same location, a significant effect ($p=0.0007$) of the interaction of the cover material with the cultivar was also observed (Figure 9). The interaction of 'Top Shelf' with netting reached the highest value of fruit firmness, being 5.8% higher than the control. Conversely, significantly lower values were observed in the interaction of ´Legacy´ with LDPE plastic cover, with firmness being 12.8% and 20% lower than that observed in non-covered plants of ´Legacy´ and ´Top Shelf´, respectively (Figure 9).

The concentration of soluble solids of the fruits (measured as °Brix) was also affected by cover materials (Table 2 and 3). In Linares, the fruits grown under LDPE plastic cover presented a significantly higher value ($p<0.0001$) than the control (1.4% higher), while the fruits under netting recorded values that were 2 .5% lower than the control (Table 2). In Traiguén, all the cover materials significantly reduced (p=0.0066) the content of soluble solids in the fruit, being 3.7%, 2.5% and 2.3% lower in blueberries grown under LDPE plastic cover, woven cover, and netting, respectively (Table 3). In addition, there was a significant effect (p=0.0179) of the interaction of the cover material with the cultivar in Traiguén (Figure 10). The interactions of ´Top Shelf´ with LDPE plastic cover and ´Legacy´ with netting presented significantly lower values of soluble solids in the fruit, decreasing by 4.3% and 4.6%, respectively, with respect to the control (Figure 10). In addition, the concentration of soluble solids was significantly affected (p=0.0055) by the cultivar only in Linares, being 2.7% higher in ´Top Shelf´ compared to´Legacy´ (Table 2).

It is interesting to note that no significant differences were observed in terms of acidity content or total soluble solid and acidity ratio, either due to the effect of cover material or cultivar (Tables 2 and 3).

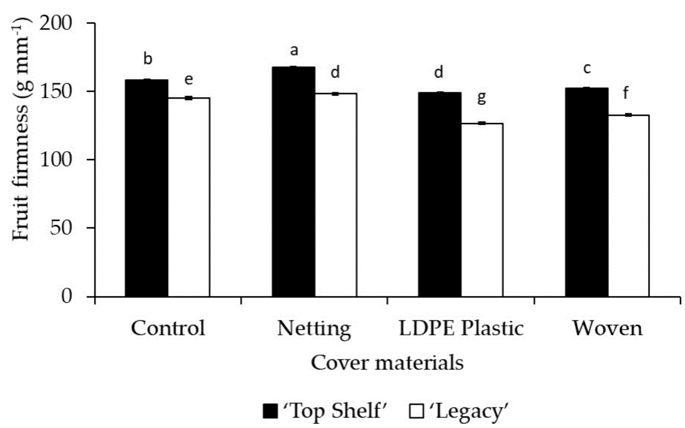

Figure 9. Influence of the interaction of cover materials (netting, woven and LDPE plastic) with ´Legacy´ and ´Top Shelf´ cultivars on fruit firmness of blueberries in Traiguén.

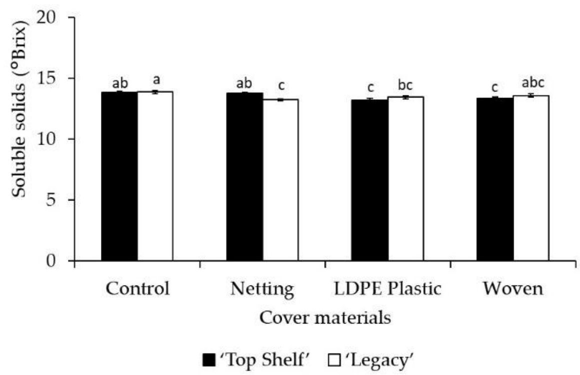

Figure 10. Influence of the interaction of cover materials (netting, woven and LDPE plastic) with the 'Legacy' and 'Top Shelf' cultivars on the content of soluble solids of blueberries in Traiguén.

3. Discussion

Blueberries grown under LDPE plastic and woven covers reached a significantly higher yield compared to those under netting in both locations (Table 2 and 3). These results could be attributed to the light microclimate under woven and LDPE plastic covers (Figures 1 and 2). In this sense, it has been described that plant growth and leaf development increase due to reduced light levels, which is known as shade avoidance syndrome, as a response to a reduction in red to far-red light ratio mediated by phytochromes, a decrease in blue-to-red light ratio mediated by cryptochromes or by the decrease of UV light mediated by the action of a specific UVR8 receptor, which is activated or deactivated depending on the intensity of UV-B light [18]. In our research, there was a significant increase in LAI in both Linares and Traiguén for plants under woven and plastic covers (Table 1), which were the materials that most effectively blocked the amount of UV radiation (Figures 1 and 2). These results coincide with previous studies in eggplant and pepper crops, where the use of UV-blocking covers resulted in an increase in stem length and plant height. In plants such in chrysanthemum (*Chrysanthemum indicum* L.), there was also an increase in plant height under UV-blocking covers due to a greater number of internodes [19]. On the other hand, leaf area and dry matter increased in cucumber (*Cucumis sativus* L.) [20], broccoli seedling (*Brassica oleracea L.* var. italica) and turnip (*Brassica rapa* L.) [21] grown under protection covers with decreased UV transmission [22]. Similarly, another study showed that high UV radiation reduced leaf area in blueberry plants by decreasing the number of buds and leaves [23]. LAI, defined as m^2 of leaves over m^2 of land, determines the relationship between light interception and yield; thus, a rapid increase in LAI is desirable in young orchards to allow for greater light interception for photosynthesis and assimilate partitioning, which significantly increase yield [24, 25]. In the present study, PPFD intercepted by blueberry plants was favored by an increase in LAI under woven and LDPE plastic covers (Table 1), enhancing the availability of PAR light for plant photosynthesis, which directly favors the yield potential of the crop [26]. This would explain why blueberry plants under woven and LDPE plastic covers reached higher yields, which coincides with previous studies in which specific conditions of low red to far-red light ratio under covers favored a greater development of leaf area by phytochrome action, thus allowing a greater capacity to intercept light for photosynthesis in young apple plants (Malus do-mestica Borkh.), with a positive impact on dry matter yield and fruit growth under this type of cover material [27].

Light transmission under woven and LDPE plastic covers was lower comparted to values observed with netting and and the control (Figures 3 and 4). This demonstrates that, when these types of covers are used, PAR reaching the soil surface is lower in the sections closest to the inter-row; based on discontinuous canopy, this indicates that the plants grown under these covers would present greater uptake of PPFD through the canopy, being directly dependent on the increase in LAI [28]. In addition to light interception, blueberry yield is also determined by the efficiency of converting light into biomass by the plant, which largely depends on the photosynthetic capacity of the leaves [29]. In plants, it has been determined that a high incidence of UV radiation can cause damage at the cellular level, affecting the integrity of the thylakoid membrane, the photosystem II (PSII) and decreasing the net assimilation of CO_2 [30], thereby reducing the photochemical efficiency of PSII and net photosynthesis [31]. In fruit species such as mango (Mangifera indica L.), the increase in UV radiation decreases leaf transpiration rate, stomatal conductance and resistance, reducing intercellular CO_2 concentration, affecting CO_2 assimilation, and resulting in a decrease in photosynthesis caused by stomatal restriction, with a negative impact on yield and fruit quality [32]. Even though the present study did not evaluate photosynthetic aspects of the leaf, the fact that leaf development was affected by differences in UV radiation transmitted by cover materials indicates that leaf photosynthetic aspects may also be affected, which requires further investigation.

Temperature is another factor that would influence yield of blueberries grown under covers. Different studies have shown that GDD are linearly correlated with shoot growth and leaf area per shoot in species such as apple [33], cucumber (Cucumis Sativus) and sweet pepper (Capsicum annuum L), being a good predictor of LAI in crops [34]. GDD accumulation reached higher values with woven and LDPE plastic covers in Linares (Figure 5A), where the highest LAI and light interception values were recorded (Table 1). In Traiguén (the location with the lowest GDD accumulation), however, the covers evaluated showed no clear effect on this measure, except for the woven cover. It has been described that the effect of covers on temperature can vary depending on local environmental conditions. Accordingly, differences in heat loss due to local weather conditions impact the temperature of buds and leaves [35]. In the present study, both LDPE plastic and woven covers increased fruit temperature above air temperature. However, this behavior was more stable in terms of GDD for warmer conditions like those of Linares (Figure 1).

On the other hand, the interaction of woven cover with 'Top Shelf' resulted in the highest yield in both locations (Figures 6 and 7), indicating that yield of blueberries would depend on internal factors such as genetics, and external factors such as management practices and climate, as previously reported in other crops [36]. Given that fruit diameter and number of flower primordia per bud were significantly higher in´Top Shelf´ (Tables 2 and 3), and also considering that plants under woven covers presented higher GDD values compared to non-covered plants in both Linares and Traiguén, the results of the present study would indicate that the higher yield achieved by 'Top Shelf' under woven cover would be explained by the interaction between genetic and environmental components; the former corresponding to fruit size and fertility of flower buds, and the latter corresponding to lower transmission of UV radiation and greater accumulation of GDD, which favor a greater LAI and PPFD interception under these particular light and temperature conditions. In fact, this was confirmed through a multiple linear regression analysis (Figures 8 and 9), demonstrating that the highest yield values are obtained in a specific range of number of flower primordia per bud, LAI and of light interception, whose variables would explain more than 60% of the variation in crop yield of both blueberry cultivars under the three types of covers evaluated in this research. This type of analysis has also bee applied to other fruit species such as cranberry (Vaccinium macrocarpon Ait.), demonstrating that variables such as light and temperature allow predicting fruit growth and yield [37]. Similarly, there is evidence that the number of flower buds in blueberry (Vaccinium corymbosum L.) is a good predictor of the number of fruits, while variables related to light interception, LAI and flower primordia per bud are also strongly correlated with yield [36]. Therefore, according to previous research and our results, this suggests that it is possible to develop predictive models of yield for different blueberry cultivars grown under different types of covers based on the quantification of variables related to flower development, LAI and light interception of plants grown under these environmental conditions.

The differences in fruit firmness (Tables 2 and 3) observed with the use of different covers could also be associated with UV light exposure. Martin and Rose

[38] described that the cuticle provides protection against excessive sunlight, and that fruits exposed to higher UV radiation, which is particularly harmful, have a thicker cuticle as a defense mechanism. During development and ripening of tomato, protection against UV radiation is also enhanced by cuticle thickening and the accumulation of phenolic compounds [39]. In grapes, the accumulation of cuticular waxes is significantly higher in fruits exposed to full sun compared to shaded fruits [40]. Furthermore, increased cuticle thickness has also been observed in blueberry fruits exposed to the sun [41].

Apart from being a physical barrier that protects plants and fruits from biotic and abiotic stresses, the cuticle also has a mechanical function and provides protection against fruit bruising [42]. In fact, this membrane provides structural support for fruits lacking hard internal tissue, being an external structural element that adds mechanical support for tissue integrity, thus playing an important role in fruit firmness during harvest and postharvest [43]. In the present study, fruits were significantly firmer under higher UV radiation levels, as observed in the control (no cover) and netting, while fruits grown under covers with lower UV light transmission capacity, such as LDPE plastic cover, presented lower firmness (Tables 2 and 3; Figures 1 and 2). These differences could be attributed to changes in fruit cuticle thickness and should be studied in future research. Temperature is another environmental factor that could explain the differences in fruit firmness due to the effect of cover materials. NIR transmission under LDPE plastic and woven covers was higher than that of netting (Figure 2E and 2F), which was also reflected in the difference between fruit and air temperatures by these materials (Figure 1C). It has been determined that an increase in temperature above 32°C negatively affects fruit firmness in blueberries [44]. This has also been reported in species such as cherry [45], grape [46], avocado [47] and apple [48]. Being a climacteric fruit, changes in fruit firmness in blueberry are mainly related to the water loss [49] due to respiration and transpiration processes, mainly triggered by a temperature increase [50]. Fruit softening is also associated with cell wall hydrolysis, activated by enzymes that depolymerize components, and whose transcription can be induced by heat stress [51]. Therefore, it seems that temperature under covers also plays a role in fruit firmness. However, this was a partial effect, only observed in Linares, where the use of LDPE plastic and woven covers (decreased fruit firmness) increased the accumulation of GDD with respect to the control and netting (Figure 5). In both Linares and Trainguén, however, netting always presented the lowest GDD values with respect to the control or the other cover materials, which is explained by a greater capacity to block NIR and reduce fruit temperature (Figures 1 and 2), probably because of the benefits of black shade netting for plants. In fact, black nets have a greater capacity to decrease air temperature compared to other colors [15], which would also explain why fruits were significantly firmer under this type of cover compared to the others (Tables 2 and 3). It is important to note that the interaction of ´Top Shelf´ with netting recorded the highest fruit firmness values in Traiguén (Figure 10), while ´Top Shelf´ fruits presented higher fruit firmness compared to ´Legacy´ in both locations (Tables 2 and 3). This would indicate that the genetics of the crop facilitates the response to higher levels of UV light or lower temperatures under netting as an adaptation mechanism to heat stress, increasing cuticle thickness as external structural support, also due to improved temperature conditions that allow reinforcing cell walls and internal structural support; therefore, differences in the chemistry of the membranes could give rise to differences in heat and UV radiation tolerance between cultivars [52]. In blueberries, the composition of the cuticle varies depending on the cultivar, allowing for certain heat or solar radiation tolerance thanks to the different composition of membrane lipids [53]. Accordingly, it would be interesting to study these physiological and biochemical aspects of fruits and evaluate crops under covers using cover materials with different light transmission capacity in the UV and NIR spectra as this could help select or develop materials to achieve the highest fruit firmness potential according to the cultivar or climatic condition. This is particularly important considering that firmness is an attribute that determines the quality of fruits, including blueberries (43).

Finally, the effect of cover materials on total soluble solids in fruits varied between locations. Although cover materials have a significant effect on this quality trait, the type of cultivar also played a role, resulting in greater variability of the results (Figure 11). Synthesis, degradation and translocation of sugars and organic acids at ripening stage cause changes, resulting in differences depending on the genetic origin for these processes [54]. Previous studies conducted on apple trees reported a great variability in the concentration of soluble solids between cultivars under cover [55], concluding that this quality trait is often more influenced by the environmental conditions in each growing season, promoting typical responses to shade under netting in the presence of variations in light and temperature conditions [56], which could explain the results of this research on blueberries.

4. Materials and methods

4.1. Study sites

The present study was carried out during the 2021-2022 season. The experiment was repeated in two locations of central-southern Chile, with different environmental conditions: Linares, Maule region (35°49'4.34"S 71°32' 26.91"W) and Traiguén, La Araucanía region (38°19'52.62”S 72°41'35.47”W). Linares is located in the Central Valley, characterized by a warm temperate climate with a dry subhumid moisture regime. The average annual rainfall is 1137 mm, with a dry period of 5 months. The maximum temperature reaches 29.1 °C in January and the minimum temperature goes down to 3.5 °C in July of [57]. Traiguén has a warm temperate mesothermal climate, with a dry subhumid moisture regime. The average annual precipitation is 1133 mm, with a dry period of 5 months. The maximum temperature reaches occurs 26°C in January and the minimum temperature is 4.1°C in July [57]. Soil texture corresponds to clay loam and silty clay in Linares and Traiguén, respectively.

4.2. Plant material and Experimental design

The study was conducted on 'Legacy' and 'Top Shelf' blueberry cultivars. In Linares, the plants were established in October 2018, at a plant spacing of 3 meters between rows and 1 meter between plants. In Traiguén, the plants were established in November 2017, at a plant spacing of 3.2 meters between rows and 1 m between plants.

Both cultivars were protected by three different covers: high-density laminated woven (Agrosystems S.A., Chile); LDPE plastic (Agrosystems S.A., Chile); and black monofilament net at 20% shade (Delsantek S.A., Chile) (Figure 11). A control treatment (no cover) was also included.

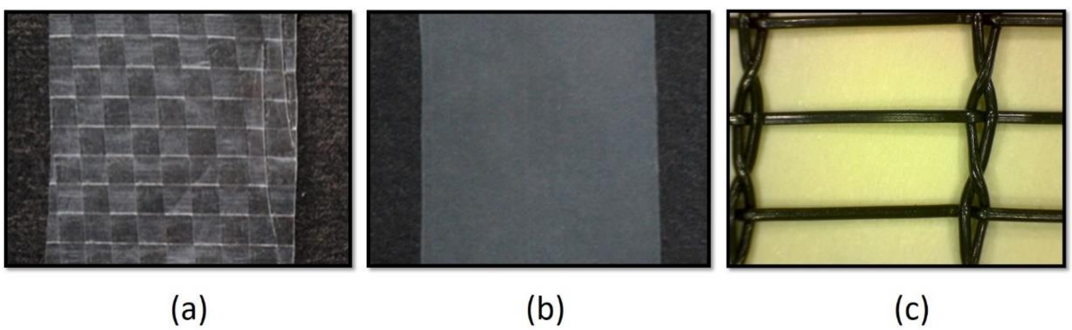

Figure 11. Details of woven (a), LDPE plastic (b) and netting (c) cover materials used in protected cultivation trials in blueberries.

The covers were installed on a roof-type structure with a height of 3 m from the ground, a width of 2.5 m and an inclination angle from the roof edge of 28°. These were extended from the beginning of flowering (August 15) to the beginning of leaf fall (April 15), covering three rows per plot of 12 and 15 plants in Linares and Traiguén, respectively. In both locations, the experiment was conducted in a completely randomized block experimental design with a divided plot arrangement, with four replicates and two plants as the experimental unit, cover materials being the main plot and cultivars being the subplot.

4.3. Light and temperature conditions

An SP-110 pyranometer (Apogee, Utah, USA) was installed in each location for the continuous recording of the variation of global solar radiation (W m^{-2}) in the range of 360 -1120 nm; information was stored in an Em50 datalogger (Decagon Devices, USA), being recorded during the whole period in which covers remained installed. The radiometric characteristics of the cover materials were evaluated according to the methodology proposed by Olivares-Soto et al. [58]. For this, a 1x1 m sample of material was placed at a height of 1.5 m from the ground and spectral light transmission was determined in full sun during solar noon (12:30 - 13:30), and in the same wavelength range of the pinanometer. For the measurement, UV-VIS-IR spectrophotometers (models BLUE-Wave and DWARF-Star) were connected to a CR2 cosine receptor (StellarNet INC., Tampa FL, USA). Simultaneously, transmission of photosynthetic light (PAR, µmol m^{-2} s^{-1}) and ultraviolet light (UV, W m^{-2}) was estimated using an MQ-200 quantum sensor (Apogee Instruments Inc., Logan, UT, USA) and an ultraviolet MU-250 sensor (Apogee Instruments Inc., Logan, UT, USA), respectively; measurements were randomly repeated three times. Based the information obtained, solar radiation flux partitioning in the range of UV light (360 - 399 nm), PAR (400-700 nm) and NIR (701 - 1120 nm) was estimated under the different cover materials in field conditions and using the coefficients of transformation of energy to radiant flux proposed by Nobel [59].

Once harvest was finished, photosynthetically active photon flux density (PPFD, µmol m^{-2} s^{-1}) was measured using an AccuPAR LP-80 ceptometer (Decagon Devices, USA) according to the methodology proposed by Wünsche et al. [60]. For this, two hours before solar noon (11:00), at solar noon (13:00) and two hours after solar noon (15:00) the ceptometer rod was passed at ground level and under the canopy of the plant and from the midpoint of the inter-row to the other midpoint of the following row and every 20 cm, leaving the unitary sensor of the ceptometer in full sun as a reference. Based on the information obtained, the amount of PPFD transmitted (%) by the plant, light interception (%) and leaf area index (LAI) were determined under the different covers.

Simultaneously, to spectrophotometry measurements, the temperature emission capacity of the cover materials was estimated, following the methodology proposed by Abdel-Ghany et al. [15]. For this, the skin temperature of an apple fruit (°C) and the air (°C) were measured after being exposed to full sun at a distance of 30 cm from the cover material. Temperature measurements were made with an SI-111-SS infrared radiometer (Apogee Instruments Inc., Logan, UT, USA), which was placed 10 cm from the fruit and pointing directly at the fruit surface. The information obtained was used to estimate fruit air temperature difference (°C) under each cover; measurements were repeated three times. At the field level, a record of the air temperature (°C) was carried out at 15-minute intervals, using iButton DS1923 meteorological sensors (Maxim/Dallas Semiconductor Inc, USA), which were installed inside a screen sun protection at a height of 1.5 m above ground level. The accumulation of GDD (base 10°C) was calculated according to the methodology proposed by McMaster and Wilhelm [61].

4.4. Yield components and fruit quality traits

During the winter recess and before pruning, a sample of three shoots per plant was taken, and flower development was evaluated (number of flower primordia bud^{-1}) using a stereomicroscope (Olympus ®, model SZ61, Tokyo, Japan) equipped with a digital camera (Olympus®, LC30 Tokyo, Japan). Fruit set was estimated during the flowering stage. For this, three shoots per plant were marked and flowers per cluster were counted; after 3 weeks, fruits were counted, and thus fruit set percentage (%) was determined.

At harvest, all the fruits were picked and the accumulated yield in kg plant^{-1} was determined using a precision balance model PCE-PCS 30 (PCE Instruments, Santiago, Chile). In total, 6 harvest events were carried out from December 3, 2021 to January 4, 2022 in Linares and from December 23, 2021 to January 27, 2022 in Traiguén.

For each of the harvest events, a sample of 20 fruits was taken and fruit diameter (mm) and firmness (g mm^{-1}) were measured using a Firmpro texturometer (HappyVolt, Santiago, Chile). For this, each fruit was placed with the cheek side on the texturometer tray, being compressed once by a flat probe at a pressure force of 800 g, with an error of less than 0.35 g and on a spatial resolution of 0.0025 mm with a spatial error of less than 0.04 mm. Subsequently, the content of soluble solids (SS, °Brix) and acidity (A, % citric acid) were determined using a digital refractometer model PAL-BX ACD1 Master Kit (ATAGO, Tokyo, Japan). For this, the initial sample of 20 fruits was taken and total soluble solids were measured in each berry. Next, the 20 fruits were crushed to obtain 10 g of juice to which 40 g of distilled water were added, forming a solution as a composite sample to measure acidity, and then estimate the SS/A ratio.

4.5. Data analysis

Data were analyzed by an analysis of variance (ANDEVA), while normality of residuals and homoscedasticity of the variance were previously tested. Differences between means were determined using Tukey's test with a significance level of 0.05. In order to find a linear relationship between the dependent variable Y= yield, and the independent variables (X), light and plant performance, a multiple linear regression model was applied, including dependent variables as fixed effects and locations as random effects, with a coefficient of determination (R^2) at a significance level of 0.05. All the analyzes were performed with Infostat [62] and R [63] software using the “agricolae” package version 1.3-5 [64].

5. Conclusions

The results obtained suggest that the type of cover material accounts for differences in yield of 'Top Shelf' and 'Legacy' blueberry cultivars in Linares and Traiguén. This is directly related to the decreased UV light transmission and increased accumulation of GDD observed with the use of woven and LDPE plastic covers, causing an increase in LAI as a plant response to such conditions, as well as greater light interception, with a positive impact on yield. On the other hand, differences between cover materials in terms of UV and NIR transmission and accumulation of GDD also had an impact on fruit firmness. Greater firmness was observed under netting probably due to the effect of increased UV radiation; conversely, significantly lower values were recorded in fruits grown under LDPE plastic cover due to the reduction of UV light transmission or the significant increase in fuit temperature by this cover. These results suggest that this behavior could be modeled to predict potential yield and fruit quality based on the light and temperature conditions of each type of cover. Since the introduction of new cultivars is necessary to meet the changing needs of consumers as well as growers, the modeling of production systems would allow reaching the highest yield and quality potential, which is particularly relevant given the findings reported in this study and the benefits of protective cover systems under the current climate change scenario.

6. References

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