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Photo-selective covers and light quality: impact on crop physiology and integrated pest management

Cubiertas fotoselectivas y calidad de la luz: impacto en la fisiología de los cultivos y en el manejo integrado de plagas

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Growing tomatoes under colored covers.

Photo: A. Hurtado-Salazar

ABSTRACT

Agricultural production faces several challenges. One of these is adverse weather conditions due to climate change. This phenomenon alters environmental conditions, including light, which is a key factor in agriculture as it directly affects the physiological processes of plants. It is crucial to implement alternatives that optimize production systems to meet the growing demand for food. Therefore, this review proposes to promote the understanding of how different light spectra and intensities influence crop growth, development and yield, as well as the production of bioactive compounds such as vitamins, antioxidants and phytochemicals. This will facilitate the development of more efficient and sustainable cropping systems. The use of photo-selective plastic films, photo-selective nets and photo-selective films in various crops is the focus of this review. This review demonstrates that plant growth and development are strongly influenced by different light signals. Light quality plays a crucial role in the regulation of these responses. Photo-selective plastic films, photo-selective nets and photo-selective films have a significant impact on the physiology of production systems under cover. However, plants respond differently to incident radiation. Additionally, the quality of light also increases the functional quality of agricultural products by improving the synthesis of organic compounds.

Additional key words: greenhouse crops; plastic film covers; protected cultivation; light signals; light effect; radiation.

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RESUMEN

La producción agrícola enfrenta diversos retos. Uno de ellos son las condiciones meteorológicas adversas debido al cambio climático. Este fenómeno altera las condiciones ambientales, entre ellas la luz, que es un factor clave en la agricultura, ya que afecta directamente los procesos fisiológicos de las plantas. Es crucial implementar alternativas que optimicen los sistemas de producción para satisfacer la creciente demanda de alimentos. Por ello, esta revisión propone promover el entendimiento de cómo los diferentes espectros e intensidades de luz influyen en el crecimiento, desarrollo y rendimiento de los cultivos, así como en la producción de compuestos bioactivos como vitaminas, antioxidantes y fitoquímicos. Esto facilitará el desarrollo de sistemas de cultivo más eficientes y sostenibles. Esta revisión se centra en el uso de películas de plástico fotoselectivas, redes fotoselectivas y películas fotoselectivas en diversos cultivos. Se demuestra que el crecimiento y el desarrollo de las plantas están fuertemente influenciados por diferentes señales luminosas. La calidad de la luz desempeña un papel crucial en la regulación de estas respuestas. Las películas plásticas fotoselectivas, las redes fotoselectivas y las películas fotoselectivas tienen un impacto significativo en la fisiología de los sistemas de producción bajo cubierta. Sin embargo, las plantas responden de forma diferente a la radiación incidente. Además, la calidad de la luz también aumenta la calidad funcional de los productos agrícolas al mejorar la síntesis de los compuestos orgánicos.

Palabras clave adicionales: cultivos de invernadero; cubiertas de plástico; agricultura protegida; señales luminosas; efecto de la luz; radiación.

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INTRODUCTION

Light is a form of electromagnetic energy characterized by wave-particle duality and various physical properties that influence how it interacts with its surroundings. Energy and color are determined by frequency and wavelength while amplitude is related to its intensity. In a vacuum, light travels at a constant speed, and its interaction with matter gives rise to phenomena such as absorption, reflection, and transmission (Mamedov *et al*., 2015).

Light interacting with matter can manifest itself in many ways. Absorption involves the capture of energy by a material's molecules, reflection occurs when light bounces off a surface, and transmission allows light to pass through a material without being fully absorbed (Pribil *et al*., 2014). Some materials, when excited by light, emit energy at a different wavelength—a phenomenon known as fluorescence—which is observed in certain plant pigments. In plants, this range of electromagnetic waves spans a spectrum from 300 to 900 nm and includes the ultraviolet, visible, and infrared regions, all of which significantly impact plant growth and development (Fig. 1) (Cardona *et al*., 2018). Fluorescence takes place in the non-photochemical (radiative dissipation) pathway, where excited chlorophyll emits photons of longer wavelength (680-760 nm) and lower energy (Murchie and Lawson 2013). Most fluorescence that is recorded in a leaf at environment temperature is emitted by chlorophyll *a* of the PSII (Murchie and Lawson, 2013).

Light plays multiple roles in the plant environment, acting as the primary energy source through photosynthesis. For this process, plants specifically utilize visible light in the range of 400 to 700 nm, known as photosynthetically active radiation (PAR). In this process, light energy is primarily absorbed by two pigments: chlorophyll and carotenoids (Pribil *et al*., 2014).

In addition to being a source of energy, light acts as an environmental signal that plants use to regulate their physiological responses throughout their life cycle, influencing morphogenesis. Factors such as light quantity, direction, and daily duration (photoperiod) are crucial. Plants perceive these signals through photoreceptors that allow them to adapt to different environmental conditions and undergo key developmental transitions (Kami *et al*., 2010).

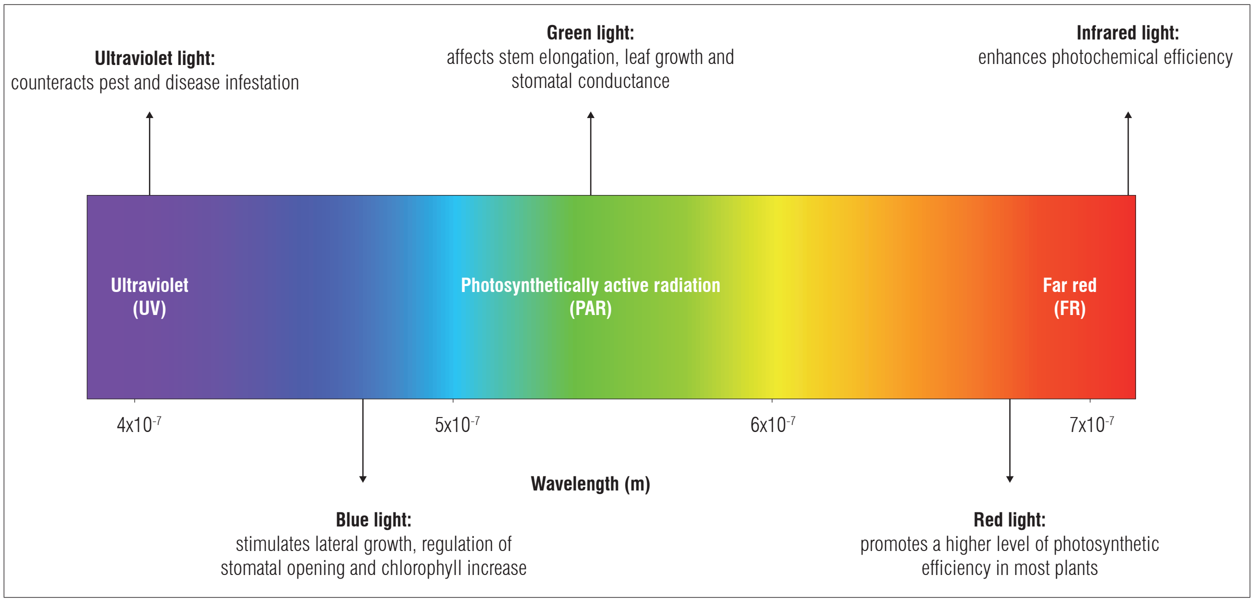

Figure 1. Electromagnetic spectrum and its main effects on plants. Prepared by the authors based on Azcón-Bieto and Talón (2008) and Cardona *et al*. (2018).

LIGHT RECEPTION IN PLANTS

When a chlorophyll molecule absorbs a photon, an electron becomes excited and transitions to a higher energy state. This state is unstable and can follow three paths: transferring the energy to another chlorophyll molecule until it reaches the reaction center of the photosystem, returning to its ground state by releasing heat, or emitting a photon of longer wavelength in a process known as fluorescence (Lambers *et al*., 1998; Stirbet and Govindjee, 2012).

In photosystem II, the absorbed energy initiates a series of chemical reactions, such as the photolysis of water, resulting in the release of oxygen and electrons. Excited electrons are transferred from chlorophyll P680 to the primary acceptor, pheophytin (Phe), and then to other electron transport chain molecules like plastoquinone (PQ) and cytochromes. During this process, oxygen (O_2) and its derivatives, such as superoxide (O_2^-), can act as additional oxidants. The energy generated in this transport chain drives the synthesis of ATP and NADPH, which are essential for the Calvin cycle. In this cycle, carbon dioxide is converted into glucose and other sugars. This provides the plant with energy and contributes to the formation of organic matter necessary for its growth and development (Pribil *et al*., 2014; Mamedov *et al*., 2015).

In this phase of electron transfer and transport, photosystem II (PS II) pigment-protein complex is one of the two primary photosynthetic chain enzymes in thylakoid membranes of oxygenic organisms (Wydrzynski *et al*., 2005). Murchie and Lawson (2013) describe PS II as a water-plastoquinone oxidoreductase that catalyzes the light-induced stable charge separation, resulting in the formation of an ion-radical pair between the primary electron donor P680 and the first quinone acceptor QA: $P680^+QA^-$. The study by Allakhverdiev *et al*. (2010) showed that prior to $P680^+QA^-$ formation, an electron is transferred from P* (P680*) to a pheophytin (Phe) molecule and then to QA. The formation of $P680^+QA^-$ leads to two chemical processes: oxidation of water to molecular oxygen (after four PS II changes) and reduction of plastoquinone to plastohydroquinone (after two PS II changes). These reactions are spatially separated, occurring on different sides of the reaction center in the thylakoid membrane (Murchie and Lawson, 2013).

Carotenoids play a crucial role in protecting the photosynthetic system through energy dissipation and quenching mechanisms, in addition to their secondary function of absorbing energy in the blue and green wavelengths (Pribil *et al*., 2014; Mamedov *et al*., 2015). Additionally, photosynthetic activity and its efficiency increase with higher light intensity, temperature, and CO_2 levels.

According to Cardona *et al*. (2018), in the field, light intensity (the amount of light) and spectral profile (the quality of light) can change rapidly and unpredictably throughout the day, for example, due to passing clouds or wind-shaken leaves. Meanwhile, Vass (2012) reports that variations in light intensity, particularly during abiotic stresses that inhibit carbon fixation, can lead to overexcitation, forming excited chlorophyll triplet states that can react with O_2 to produce damaging reactive oxygen species (ROS) (Fig. 2). To prevent or mitigate damage, many different protective mechanisms operate on different time scales and at different points in the excitation and electron transfer processes to maximize the efficient use of light and minimize damage (Takagi *et al*., 2016). These include modifying cofactor energetics in PSII to prevent dangerous reverse reactions (Brinkert *et al*., 2016) and activating non-photochemical quenching (NPQ) mechanisms to dissipate excess excitation in light-harvesting complexes as heat (Cardona *et al*., 2018). Therefore, to achieve good crop development and increased productivity, proper and adequate lighting must be ensured. Besides its role in photosynthesis, light also acts as a key environmental signal through specialized photoreceptors in the plant (Fig. 2). These photoreceptors enable the plant to perceive its surroundings, allowing it to direct adaptive responses to change environmental conditions. When activated, photoreceptors trigger specific signaling pathways that regulate various physiological processes (Folta and Carvalho, 2015).

There are three main types of photoreceptors identified in plants. Phytochromes absorb red and far-red (FR) light and play a crucial role in modulating germination. They are primarily involved in the synthesis and signaling of gibberellin (GA), as well as in processes such as de-etiolation and shade avoidance responses (Galvão *et al*., 2019). Cryptochromes are sensitive to blue light and ultraviolet A (320-400 nm), influence hypocotyl growth, promote cotyledon development and opening, and are involved in the initiation of chloroplast development, leaf growth, and the photoperiodic control of floral initiation and circadian rhythms (Tóth *et al*., 2001; Wang *et al*., 2022). Phototropins respond to blue/UV-A light and play an important role in differential cell growth. They also optimize photosynthetic capacity by influencing processes such as stomatal opening, leaf flattening, and chloroplast movement to align with the direction of incident light (Folta and Carvalho, 2015).

These photoreceptors are widely distributed in plant tissues. While some physiological responses are triggered by a single photoreceptor, in many cases, multiple light sensors ensure a coordinated response (Kami *et al*., 2010; Sakamoto and Briggs, 2002). Plants absorb certain ranges of incident radiation and transmit the non-absorbed radiation to neighboring plants. The

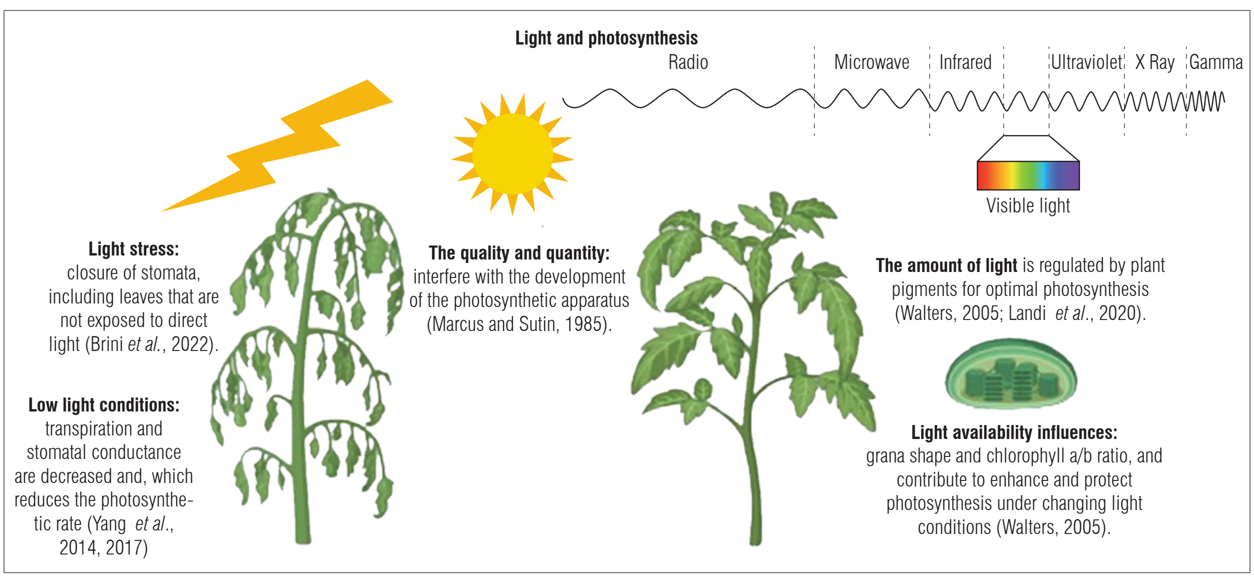

Figure 2. Impact of light on photosynthesis. By Biorender®.

quality of light received by the plant in terms of intensity and the number of daily hours of exposure are determining factors that influence the plant's overall response to its light environment (Nguy-Robertson *et al*., 2015).

The time of exposure or the number of hours of light required for a crop to develop and reach flowering varies depending on the species. All plants need light, and below a certain threshold, very few can survive. Both excess light and insufficient light can have harmful effects on plants (Velez-Ramirez *et al*., 2011; Cardona *et al*., 2018).

PHOTO-SELECTIVE COVERS

The use of controlled conditions has advantages in mitigating abiotic factors that limit agricultural production, such as adverse weather conditions, including high precipitation, mechanical effects of hail, frost and strong winds (Flórez-Hernández *et al*., 2023). Ceballos-Aguirre *et al*. (2024) reported that macro tunnels minimize fertilizer leaching and reduce the volume and frequency of pesticide and fungicide applications. In addition, the system increases ambient temperature by 2-5°C, which accelerates the start of production and provides protection against mechanical damage from rain and frost (Ceballos-Aguirre *et al*., 2024). This system offers significant benefits, including increased productivity and fruit quality, as it allows for higher planting density and enables cultivation at any time of the year. Additionally, it enhances pest and disease management by reducing their incidence (Perilla *et al*., 2011).

The use of shade nets has increasingly become a viable alternative to protect crops and create a suitable microclimate by controlling humidity, shade, and temperature. This coverage has been shown to mitigate extreme climatic fluctuations, reduces stress and damage caused by heat, cold, and wind, and acts as a physical barrier against hail and birds (Shahak *et al*., 2009; Pandey *et al*., 2023).

Additionally, the use of covering materials or filters can alter both the quantity and distribution of incident radiation, providing certain advantages (Castilla, 2003). Casierra-Posada and Peña-Olmos (2015) suggest that passive light filters of different colors can offer economical alternatives for farmers by stimulating physiological responses that lead to a higher-quality product. Furthermore, polymeric materials can boost production and enhance product characteristics.

Plastic films

Plastic films alter the relative proportions of the radiation spectrum, acting as selective filters on the wavelengths that reach the crop. At the same time, they allow incoming light to be scattered and converted into diffuse light, which improves the penetration and distribution of the modified light spectrum within the plant canopy (Pandey *et al*., 2023). The use of plastic films has the potential to selectively modify the spectrum of incident light and trigger physiological responses in plants, resulting in higher yields, improved fruit quality and reduced pest and disease susceptibility (Pandey *et al*., 2023). As shown in table 1, the effects of plastic films depend on the species and stage of plant development.

In horticultural production systems, red plastic covers have been shown positive effects on the ontogenesis of crops such as broccoli, beet, and strawberry, with significant increases in biomass accumulation, which reflects better photosynthetic efficiency (Casierra-Posada and Rojas, 2009; Casierra-Posada and Pinto-Correa, 2011; Casierra-Posada *et al*., 2012b, 2014a). On the other hand, far-red covers negatively impact the growth of various horticultural and ornamental species, reducing the total height of the plants; in some species, a decrease in flowering and crop yield has even been observed (Murakami *et al*., 1997; Li *et al*., 2000; Wilson and Rajapakse, 2001a). The behavior of phytochrome, a key molecule in light perception, may be responsible for this effect. Phytochrome exists in two photoconductive states: the inactive form (PR), absorbing red light, and the active form (PFR), absorbing long wavelength red light. Red-colored coatings promote the PR form of phytochrome, reducing auxin degradation and consequently promoting stem elongation (Schmitt *et al*., 1999; Francescangeli *et al*., 2007).

Table 1. Physiological effects of photo-selective plastic films on different crops.

Color	Cover specifications	Crop	Effects on crops	Authors
Red (R) 600-700 nm	PAR transmission: 78.2% Opacity: 48%	Broccoli	During the seedling stage, greater dry weight (better performance in the field)	Casierra-Posada and Rojas, 2009
	PAR: 467.67 μmol m^{-2} s^{-1} Opacity: 48.73%	Beets	Greater leaf area, total soluble solids, root diameter, and total dry weight	Casierra-Posada and Pinto-Correa, 2011
	PAR: 86.95 μmol m^{-2} s^{-1} Opacity: 71.01%	Strawberry	Greater leaf area and dry matter accumulation	Casierra-Posada *et al*., 2012b, 2014a
	R/FR: 1.51	Golden shrimp	A 9% increase in height	Wilson and Rajapakse, 2001a
Far red (RF) 700-800 nm	Transmission PAR: 84% R/FR: 3.8	Strawberry	Longer crop duration and more compact plants with shorter petiole length	Fletcher *et al*., 2004
	Transmittance: 61% R/FR: 2.33 YCE Tints: #80, #75, #65 respectively: R/FR: 1.6, 2.3, 3.7 Transmittance: 0.75, 0.78, 0.81	Cucumber Tomato Pepper Chrysanthemum	Height reduction	Murakami *et al*., 1997; Li *et al*., 2000
	Transmittance: 61% R/FR: 2.33	Cucumber Tomato	Delay in flowering and harvest	Murakami *et al*., 1997
	Estimated photostationary state (Pfr/P): 0.604	Chrysanthemum Snapdragon Mouth	Increase in leaf area Reduction in height and internode length	Van Haeringen *et al*., 2008
	R/FR: 0.65	Golden shrimp Cat's whiskers Persian shield	Decrease in leaf area and dry weight	Wilson and Rajapak-se, 2001a
	R/FR Ratio: 0.65 Estimated photostationary state (Pfr/P): 0.66	Golden shrimp	10% reduction in height	Wilson and Rajapakse, 2001a
	R/FR Ratio: 0.65 Estimated photostationary state (Pfr/P): 0.66	Cat's whiskers	20% reduction in height	Wilson and Rajapakse, 2001a
	Unspecified	Sage	Reduction in: height, internode length, and stem dry weight	Wilson and Rajapakse, 2001b
	PAR Transmission: 71.2% R/FR Ratio: 1.21 Phytochrome Photostationary state (φ): 0.73	Snapdragon Chrysanthemum Cucurbits Solanaceae	Reduction in height	Brar *et al*., 2020; Khattak *et al*., 2004; Rajapakse *et al*., 1999; Li *et al*., 2000
Blue	Tints 1, 2, and 3%, respectively: PAR Transmission: 40, 33, and 25% Phytochrome Photostationary state: 0.64, 0.61, 0.57	Chrysanthemum	Reduction in: height, total dry weight, number of leaves, leaf area of the main stem, axillary shoots (related to increased pigment concentration)	Oyaert *et al*., 1999

Continued

Continued Table 1. Physiological effects of photo-selective plastic films on different crops.

Color	Cover specifications	Crop	Effects on crops	Authors
Green	PAR: 78.87 μmol m^{-2} s^{-1} Opacity: 73.7%	Strawberry	Growth reduction. Increased accumulation of chlorophyll *a*	Casierra-Posada *et al*., 2011b, 2014a
	PAR: 78.87 μmol m^{-2} s^{-1} Opacity: 73.7%	Calla lily	Greater accumulation of dry matter	Casierra-Posada *et al*., 2012a
	Shading: 42.7% Light diffusion: 42.1%	Basil	Increase in height	Stagnari *et al*., 2018
Yellow	Shading: 28.3% Light diffusion: 42.0%	Basil	Increase in biomass accumulation	Stagnari *et al*., 2018
	PAR: 234 μmol m^{-2} s^{-1} Opacity: 52.4%	Swiss chard	Increase in relative growth rate (RGR)	Casierra-Posada *et al*., 2014b
UV blocking	Spectrum > 400nm, PAR Transmission: 92% PAR Transmission: 80%, Spectrum > 385nm	Tomato	Reduction in trips and whitefly attacks decreases *Alternaria solani* sporulation	Doukas and Payne, 2007; Kumar and Poehling, 2006; González *et al*., 2001; Vakalounakis, 1991
	Transmission: 250-400 nm: 7% 400-1100nm: 54%	Peach	Reduction in aphid attacks	Chyzik *et al*., 2003
	Transmission: PAR: 82% UV-B: 36% UV-A: 7%	Raspberry	Reduction in Japanese beetle attacks	Cramer *et al*., 2019
	Spectrum: 500 - 700 nm Transmittance: 83.16% UV-A Radiation: 0.1 UV-B Radiation: 1.4	Eggplant	Increase in: height, leaf area, 20% increase in production with larger and higher-quality fruits	Kittas *et al*., 2006
	Spectrum: 400-700 nm	Strawberry	Decrease in flavonoid content, delayed fruit ripening but increased final productivity	Casal *et al*., 2009
	Spectrum > 400 nm	Tomato Radish	Lower chlorophyll content	Tezuka *et al*., 1993

PAR: photosynthetically active radiation; R: red; FR: far-red; R/FR: ratio red/ far-red.

Yellow and green covers enhance dry weight, height, and chlorophyll *a* accumulation in certain vegetables. However, in the case of crops like chrysanthemums, blue light has not shown favorable effects on various growth and development variables (Casierra-Posada *et al*., 2014a; Stagnari *et al*., 2018). Casierra-Posada *et al*. (2014c) reported that plants grown under the yellow cover showed a higher water use efficiency compared to the other treatments (blue, red, green and control). Yellow-covered plants showed increased foliar dry matter accumulation. The same author reports that the different responses of plants to light quality can be explained by contrasts between different species, cultivars, or even the characteristics of the light sources used. The root to shoot ratio of all the plants grown under a cover (yellow, blue, red, green) showed lower average values than those found for the control plants grown without a canopy. This reduction ranged from 18.7 to 44.7% compared to controls. However, a significant difference was only found between control plants and the yellow, blue and green film treatments (Casierra-Posada *et al*., 2014c).

Colored plastic covers (yellow, blue, red, green) increase the chlorophyll content index (CCI) between 31.5 and 50.5% compared to uncovered (control) plants (Casierra-Posada *et al*., 2014c). Plant growth and development could be co-regulated by photoreceptors and other endogenous factors such as hormones and a temperature-sensing system (Facella *et al*. 2012). This suggests a complex relationship between different factors regulating plant morphology and physiology and underscores how plant species differ in their interactions with the environment.

Covers that block ultraviolet light are particularly important for the health of some fruit crops, as they help mitigate the damage caused by pests such as thrips, whiteflies, aphids, Japanese beetles, and even fungi like *Alternaria solani* (González *et al*., 2001; Kumar and Poehling, 2006; Doukas and Payne, 2007). In horticultural crops, the results regarding production physiology under these covers have been variable (Kittas *et al*., 2006; Casal *et al*., 2009). Blocking ultraviolet light is advantageous because it affects insects' vision, movement and ability to locate hosts (Meyer *et al*., 2021). In addition, some fungi depend on UV light to complete their multiplication and reproduction cycles and are therefore also affected by the exclusion of this radiation (Meyer *et al*., 2021).

Shade nets

Current nets are made of polypropylene or polyethylene threads with different fiber dimensions and holes, which allow for a mix of natural and spectrally modified light. Additionally, they transform direct light into scattered/diffuse light. The relative content of diffuse light, as well as the shading factor, are defined by the fabric design, density, and chromatic additives (Castellano *et al*., 2008; Shahak, 2014).

The red net has shown positive effects on the vegetative growth rate of various ornamental species and is also associated with an increase in the height of crops like lettuce and turmeric. In other crops, higher productivity has been observed, reflected in an increase in both the number and quality of fruits (Shahak *et al*., 2004; Ilić *et al*., 2012; Harish *et al*., 2022).

On the other hand, the blue net has led to a decrease in the height of several crops, and dwarfism has been observed in ornamental plants (Oren-Shamir *et al*., 2001). However, in crops like apples, an increase in photosynthesis and transpiration has been recorded (Bastías *et al*., 2012). Additionally, in other crops, increases in chlorophyll content and the concentration of phytochemicals and essential oils have been reported, suggesting that blue light could enhance the functional quality of some crops (Oliveira *et al*., 2016; Ilić *et al*., 2017).

The pearl net has been especially beneficial in crops like bell pepper, promoting a higher concentration of bioactive compounds and an increase in overall yield, in addition to reducing susceptibility to fungal infections. Positive results have also been reported in increased chlorophyll levels and enhanced antioxidant activity (Shahak *et al*., 2008; Selahle *et al*., 2015). As shown in table 2, the effects of photo-selective nets on different crops will vary depending on the species and stage of plant development.

Regarding green and gray nets, although they have been less studied, an improvement in fruit quality and plant branching has been noted, with greater compactness of the latter (Oren-Shamir *et al*., 2001). Finally, the yellow net has shown contrasting effects on the synthesis of aromatic compounds and chlorophyll content, with increases reported in ornamentals like marigold and violet and decreases in crops like pepper. Additionally, this net has promoted greater growth in ornamental plants, highlighting the differential response of various crops to the light spectrum (Shahak *et al*., 2009; Abbasnia *et al*., 2019).

Table 2. Physiological effects of photo-selective nets on different crops.

Color	Nets specifications	Crop	Effects on crops	Authors
	Shading: 20% PAR: 678 μmol m^{-2} s^{-1} R/FR: 0.90	Avocado	Accumulation of phenols	Tinyane *et al*., 2018
Red	Shading: 25% UV Blocking	Turmeric	Greater height and number of leaves	Harish *et al*., 2022
	Shading: 50% PAR: 641 μmol m^{-2} s^{-1}	Marigold and violet	Greater leaf area	Abbasnia *et al*., 2019
	Spectrum > 580 nm Shading: 30%	Ornamentals	Increase in vegetative growth rate Shorter flowering time	Oren-Shamir *et al*., 2001; Shahak *et al*., 2009
	Shading: 40% PAR Transmission: 66.2%	Tomato	Increase in the number of fruits per plant, with larger size and higher lycopene content	Ilić *et al*., 2012
	Shading: 50% Transmittance: R + FR Dispersion: ++	Lettuce	Greater reflectance (lighter colors). Increase in height and fresh weight	Ilić and Fallik, 2017
	Unspecified	Grape	Accumulation of dry matter in the fruits	Pallotti *et al*., 2023
	Shading: 30%	Tomato Pepper	Increase in fruit yield and improved the quality	Ben-Yakir *et al*., 2012
	Shading: 30% Dispersion PAR: 18% UV: 35%	Apple tree	Higher photosynthetic rate	Shahak *et al*., 2004
	Shading: 30% Dispersion PAR: 18% UV: 35%	Apple tree Peach	Greater fruit set	Shahak *et al*., 2004
	Shading: 40% PAR: 744.13 μmol m^{-2} s^{-1} Shading: 40% R/FR Ratio: 0.85 PAR: 221.67 μmol m^{-2} s^{-1}	Tomato Cilantro	Greater synthesis of aromatic compounds	Tinyane *et al*., 2013; Buthelezi *et al*., 2016
Blue	Shading: 20% PAR: 552 μmol m^{-2} s^{-1} R/FR Ratio: 0.81	Avocado	Increase in commercial yield and accelera-tes fruit ripening	Tinyane *et al*., 2018
	Shading: 50% Transmittance: sunlight Dispersion: 60%	Lettuce	Shorter stem length	Ilić and Fallik, 2017
	Shading: 50% PAR: 947 μmol m^{-2} s^{-1}	Basil	Reduced branching, leaf size, fresh mass per plant	Milenković *et al*., 2019
	PAR Shading: 59% Indirect light: 47.8%	Ornamentals	Induces dwarfism	Oren-Shamir *et al*., 2001
	Shading: 54.2% Light Dispersion: 62% R/FR Ratio: 0.68	Flowers	Delay in flowering, shorter stems, and inflorescences with smaller diameter and flower weight	Ovadia *et al*., 2009
	Shading: 50% Transmittance: sunlight Dispersion: 60%	Lettuce	Increase in chlorophyll a and total chlorophyll	Ilić and Fallik, 2017

Continued

Continued Table 2. Physiological effects of photo-selective nets on different crops.

Color	Nets specifications	Crop	Effects on crops	Authors
Blue	Shading: 25% UV Blocking	Turmeric	Increase in chlorophyll content in terms of SPAD value, number of tillers, and curcuminoid content	Harish *et al*., 2022
	Spectrum: 400 - 450 nm	Red amaranth	Increase in stimulation of antioxidant activity and total phenols	Khandaker *et al*., 2010
	Shading: 47% PAR: 736.9 μmol m^{-2} s^{-1} R/FR Ratio: 0.87	Apple tree	Increase in transpiration and net carbon exchange rate Increase in net photosynthesis Increase in fruit size	Bastías *et al*., 2012
	Shading: 50% PAR: 238.33 μmol m^{-2} s^{-1} Shading: 50% Spectrum: 400 - 540 nm	Lemon balm Basil	Increase in essential oil content	Oliveira *et al*., 2016; Martins *et al*., 2008
Pearl	Shading: 40% PAR: 827.56 μmol m^{-2} s^{-1}	Tomato	Increase in fruit weight, greater firmness, and an increase in bioactive compounds	Tinyane *et al*., 2013
	Shading: 35% Dispersion PAR: 38% UV: 48%	Apple tree	Increase in fruit size and overall yield	Shahak *et al*., 2004
	Shading: 50% PAR: 1100 μmol m^{-2} s^{-1}	Basil	Greater leaf area index (LAI) and dry matter accumulation	Milenković *et al*., 2019
	Shading: 50% Transmittance: B + G + Y + R + FR Dispersion: +++	Lettuce	Higher contents of chlorophyll *b*, carotenoids, total phenols, and flavonoids	Ilić *et al*., 2017
	Shading: 40% PAR: 401.2 μmol m^{-2} s^{-1} R/FR Ratio: 0.46 PAR transmission: 40% Shading: 35%	Pepper	Post-harvest: Higher ascorbic acid and chlorophyll content increased antioxidant activity, fruit color, and firmness reduced weight loss during storage decreased fruit susceptibility to fungal infections	Selahle *et al*., 2015; Mashabela *et al*., 2015; Alkalia-Tuvia *et al*. 2014; Goren *et al*., 2011; Kong *et al*., 2013
	Shading: 20% PAR: 6 μmol m^{-2} s^{-1}	Apple tree	Increased activity of the parasitoid *Mastrus ridens*, a biological control agent for *Cydia pomonella*	Yáñez *et al*., 2021
	Shading: 18-35% Mechanism: light reflection	Cucumber	10% reduction in the incidence of cucumber mosaic virus (CMV)	Shahak *et al*., 2008
	Shading: 18-35% Mechanism: light reflection	Potato	Decrease in the incidence of potato virus Y (PVY)	Shahak *et al*., 2008
Green	Shading: 30%	Tomato	Greater fruit length, diameter, wall thickness, and number of locules	Zakher and Abdrabbo, 2014
Yellow	Shading: 25% UV blocking	Turmeric	Increase in leaf area, primary rhizome production, and dry matter accumulation	Harish *et al*., 2022
	Shading: 25% UV blocking	Cucumber	Higher incidence of whiteflies (50%) and cucumber mosaic virus (CMV)	Harish *et al*., 2022
	Shading: 48.6% Dispersion: 44.1%	Eustoma Widow's flower Star of Bethlehem Sunflower	Increase in stem length	Ovadia *et al*., 2009; Shahak *et al*., 2009

Continued

Continued Table 2. Physiological effects of photo-selective nets on different crops.

Color	Nets specifications	Crop	Effects on crops	Authors
Yellow	Shading: 50% PAR: 705 μmol m^{-2} s^{-}	Marigold Violet	Increased growth. Higher carotenoid, chlorophyll, and BRIX° content	Abbasnia *et al*., 2019
	Shading: 40% PAR: 851.81 μmol m^{-2} s^{-}	Tomato	Lower synthesis of aromatic compounds and lycopene	Tinyane *et al*., 2013
	R/FR Ratio: 0.36 PAR transmission: 21%	Pepper	Greater synthesis of aromatic compounds, lycopene, and flavonoids. Reduction in photosynthetic rate and stomatal conductance	Mashabela *et al*., 2015
	R/FR Ratio: 1.039 Shading PAR: 21.1%	Grape	Increased antioxidant concentration and reduces fungal diseases	Shahak *et al*., 2016
	Shading: 30%	Vegetables	Lower incidence of aphids and whiteflies	Ben-Yakir *et al*., 2012
Grey	PAR: shading: 50.8% Indirect light: 22.1%	Pittosporum	Increased branching and foliage density Reduces leaf size and variegation	Oren-Shamir *et al*., 2001

PAR: photosynthetically active radiation; R: red; FR: far-red; R/FR: ratio red/ far-red; B: blue; G: green; Y: yellow.

PHOTOELECTRONIC COVERS

The spectrum of incident light is modified through fluorescence towards longer wavelengths, facilitated by the presence of light-emitting fluorescent compounds embedded in a matrix. The most used photo-selective covers with spectral shifting are those containing dyes (Pandey *et al*., 2023).

Photoelectronic covers have improved flower yield and fruit number, and positive effects have also been reported on the growth, antioxidant capacity, and biomass of lettuce and arugula (Tab. 3). It is important to note that this review included only a limited amount of information on photoelectronic technology, as our focus was on plastic films and shade nets. Photoelectronic technology is less commonly used by

Table 3. Physiological effects of photoelectronic films on different crops.

Photoelectronic				
Color	Specifications	Crop	Effects on crops	Authors
Red	Unspecified	Carnation	Increase in stem yield	Magnani *et al*., 2008
	Unspecified	Rose	Longer and thicker stems, larger shoots	Mascarini *et al*., 2013
	Fluorescence: 600-690 nm, Transmittance PAR: 57.3%, R/FR ratio: 1.17	Strawberry	Slightly brighter fruits	Hemming *et al*., 2006
Blue	Fluorescence: 410-490 nm, Transmittance PAR: 83.1%, R/FR Ratio: 1.08	Strawberry	Increase in the accumulated number of fruits by 8 to 12%	Hemming *et al*., 2006
Orange Magenta	Unspecified	Cucumber	Greater vegetative growth	González *et al*., 2003
Magenta	Unspecified	Strawberry Cucumber	Reduction in the incidence of thrips	González *et al*., 2003
Yellow	Transmittance PAR: 76.6%	Lettuce Arugula	Greater antioxidant capacity and increased dry matter percentage	Magnani *et al*., 2008

PAR: photosynthetically active radiation; R: red; FR: far-red; R/FR: ratio red/ far-red.

small farmers; however, we acknowledge its potential to optimize light spectrum use and suggest that future research could further explore its applications.

LIGHT, INSECTS, VOLATILE COMPOUNDS, AND THEIR RELATIONSHIP

According to Shimoda *et al*. (2013), insects can see ultraviolet (UV) radiation. Nocturnal insects are often attracted to light sources that emit large amounts of UV radiation, leading to the development of devices that exploit this behavior, such as light traps for monitoring pest incidence and electric insect killers. On the other hand, some diurnal species are attracted to yellow; yellow traps are used for studying pest incidence, and yellow adhesive plates are employed for pest control. Lamps that emit yellow light have been effectively used to control the activity of nocturnal moths, thereby reducing damage to fruits, vegetables, and flowers. Covering cultivation facilities with films that filter radiation near UV rays reduces the invasion of pests like whiteflies and thrips in the facilities, thereby reducing damage. Reflective material placed on cultivated soil can control the approach of flying insects such as aphids. It is anticipated that future developments in light sources, such as light-emitting diodes, will be used to promote integrated pest management.

The authors observed that the use of colored filters and their interaction between tomato plants (*Solanum lycopersicum*) and a key pest, like *Tuta absoluta* (Lepidoptera: Gelechiidae), results in effects that influence light quality. This interaction between light and plants generates an abiotic stress that induces the production of chemical substances in the tomato fruits. These substances, in turn, lead to differentiated behaviors in the larva's attack on the fruit.

This concept is validated by Miresmailli *et al.* (2014), who highlight that plants can convey information about attacking herbivores to the plant itself and the natural enemies of those insects through the emission of specific chemical signals. Plants can even respond chemically to herbivore oviposition before feeding damage occurs. They produce a wide spectrum of chemical substances in various aerial and underground tissues, which they use to defend themselves against biotic stressors (such as pathogen infection, insect feeding, and viruses) and abiotic stressors (such as drought, salinity, flooding, heavy metals, heat, ozone, among others).

According to Miresmailli *et al.* (2014), some chemical substances are induced after an attack. This author also reports that in some cases, the compounds directly affect the herbivore, while in others, they attract organisms from different trophic levels. Examples include the scent of flowers, phytotoxic root exudates, and stem latex, all of which modify interactions with other species.

Some of these volatile substances in tomatoes were studied by Pizzo *et al*. (2024), who found that they play a fundamental role in plant defense. These compounds, known as terpenes and terpenoids, represent a large family of hydrocarbon biomolecules and are present in many species, including plants, animals, and microorganisms. Recognized for their distinctive odors, these compounds play a crucial role in the chemical defense strategies of plants, acting as repellents or toxins against herbivores and pathogens, while simultaneously attracting natural predators. Terpenoids differ from terpenes in the rearrangement of oxidation states. In tomato plants, a wide range of terpenoids are produced, synthesized, and stored within specialized glands called trichomes located on the plant's surface. These trichomes serve as reservoirs for a variety of terpene compounds that can deter herbivores, attract predators, and influence interactions between plants and pollinators. The composition of terpenoids within tomato trichomes varies among different cultivated varieties and accessions. In particular, the terpene α-zingiberene is known for its repellency against whiteflies.

Meanwhile, Gong *et al.* (2023) describe the location and the characteristics where volatile compounds are released, specifically through stomata, which regulate the release of volatile organic compounds (VOCs) in addition to controlling the flow of CO_2 and H_2O. The production of VOCs in plants is also induced by mechanical damage. Although photosynthesis provides critical molecules to produce defense-related chemicals, inhibiting growth often leads to an increase in defenses, generating natural herbivore repellents as the primary anti-herbivore defense. These VOCs also function as informative compounds for plant-to-plant communication, influenced by changes in stomatal opening and closing. Some oxidized lipids are antimicrobial, and volatiles containing α, and β-unsaturated carbonyls are collectively referred to as reactive electrophilic antibacterial substances. Additionally, these authors determined that potassium is the second most abundant mineral nutrient in plants, regulating the activity of metabolic enzymes.

This element is essential for maintaining cell turgor, stomatal movements, and tropisms. The loss of K^+ from tissues affected by stress is caused by major abiotic and biotic phenomena, highlighting its role as an essential macronutrient and in the rectification of potassium channels in guard cells.

There are different characterization techniques to evaluate and quantify volatile chemical substances, as suggested by Katna *et al*. (2024), such as high-performance liquid chromatography (HPLC), liquid chromatography-tandem mass spectrometry (LC-MS/MS or LC/TQ), and gas chromatography-mass spectrometry (GC-MS/MS). Additionally, gas chromatography paired with an electron capture detector (GC-ECD) is detailed for tomato in this reference.

In general, agricultural production faces various challenges, with adverse climatic conditions resulting from climate change standing out. This phenomenon is altering environmental conditions, including light, which is a key factor in agriculture as it directly impacts the physiological processes of plants. To meet the growing demand for food, it is crucial to implement alternatives that optimize production systems. Understanding how different light spectra and intensities influence the growth, development, and yield of crops, as well as the production of bioactive compounds such as vitamins, antioxidants, and phytochemicals, will help develop more efficient and sustainable cultivation systems. These systems will not only be capable of meeting the food needs of a growing population but will also play a fundamental role in adapting agriculture to current challenges, while also adding value to production chains.

CONCLUSION

The above considerations lead to the conclusion that the photosynthetic efficiency of conventional cultivation with the use of photoselective cover can be indirectly improved. Additionally, the use of photoselective cover creates an interaction between plants and insect pests, where the plants produce chemicals that affect insect attack behavior. New light sources, such as LEDs, are expected to be developed and used in the future to support integrated pest management.

Understanding the specific responses of each crop could lead to the development of agronomic strategies that enhance efficiency and productivity.

Light quality also enhances the functional quality of agricultural products by improving the synthesis of organic compounds. This results in competitive market advantages and greater nutritional benefits for consumers.

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