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Photo selective shade nets in vegetable crops: A review

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Abstract

Photo selective shade nets have emerged as an advanced protected cultivation technology for sustainable vegetable production under changing climatic conditions. Unlike conventional shade nets, Photo selective nets modify both light intensity and spectral quality, thereby influencing plant growth, physiology, productivity, and crop quality. These nets regulate microclimatic factors such as temperature, humidity, solar radiation, and evapotranspiration while also providing physical protection against excessive heat, ultraviolet radiation, wind, and insect pests. Different net colors, including red, blue, green, yellow, pearl, and black, selectively alter light wavelengths to induce specific physiological responses such as improved photosynthesis, Photo morphogenesis, flowering, fruiting, and stress tolerance. Red shade nets generally promote vegetative growth and fruit production, blue nets improve compact growth and chlorophyll synthesis, while green and pearl nets enhance overall crop performance through balanced spectral modification and light diffusion. Across diverse vegetable groups including solanaceous, cucurbitaceous, leafy, leguminous, and root vegetables, Photo selective shade nets have demonstrated significant improvements in growth, yield, fruit quality, nutritional composition, and water use efficiency. Additionally, yellow and UV-blocking nets contribute to integrated pest management by reducing insect populations and disease incidence. Crop responses vary depending on species, cultivar, climatic region, net color, and shading intensity, necessitating crop-specific optimization for commercial adoption. Overall, Photo selective shade net technology represents a climate-smart, economically viable, and environmentally sustainable approach for enhancing vegetable productivity, improving crop quality, and ensuring resilient horticultural production systems under adverse environmental conditions.

Keywords: Photo selective shade nets, protected cultivation, vegetable crops, light quality, microclimate modification, crop productivity, sustainable horticulture, climate resilience, spectral manipulation, vegetable yield

Introduction

Vegetable crops are highly sensitive to fluctuations in environmental conditions, particularly excessive solar radiation, high temperature, drought, salinity, water stress, and biotic pressures, all of which significantly influence crop productivity, quality, and profitability (Bray *et al.*, 2000; FAO, 2021; Medany *et al.*, 2009; Semida *et al.*, 2021) ^[20, 56, 74]. In tropical and subtropical regions, rising temperatures, erratic climatic conditions, and increased ultraviolet radiation associated with climate change have intensified production challenges in open-field vegetable cultivation (FAO, 2021; Shahak, 2014) ^[20, 76]. These constraints often result in reduced photosynthesis, flower drop, poor fruit set, sunscald, diminished marketable yield, and deterioration of nutritional quality. Consequently, protected cultivation technologies, including greenhouses, polyhouses, screenhouses, and shade net systems, have emerged as essential tools for sustainable vegetable production and climate adaptation (Castellano *et al.*, 2008; Kittas *et al.*, 2012; Tanny, 2013; Tzortzakos *et al.*, 2020) ^[12, 44, 91, 94].

Although climate change and extreme environmental fluctuations cannot be entirely controlled, vegetable production systems can be strategically adapted to protect crops and reduce their dependency on adverse external conditions. Modern horticulture increasingly focuses on safeguarding crop productivity through three major approaches: protected cultivation, development of resistant cultivars, and improved crop management practices. Protected cultivation systems such as shade nets, greenhouses, screenhouses, and polyhouses create

favorable microclimates that shield crops from excessive heat, radiation, wind, pests, and erratic weather. Concurrently, breeding programs aimed at developing stress-tolerant and resistant cultivars enhance the inherent capacity of crops to withstand environmental challenges. Complementary management practices, including optimized irrigation, mulching, nutrient management, and integrated pest management, further strengthen crop resilience under changing climatic scenarios (Tzortzakis *et al.*, 2020; Semida *et al.*, 2021) [94, 74]. Together, these strategies form the foundation of climate-resilient vegetable production.

Among these technologies, protected cultivation through shade net systems has gained substantial importance due to its relatively low cost, simplicity, and effectiveness in modifying the crop microclimate. Traditional black or green shade nets primarily reduce light intensity and temperature; however, they offer limited control over light spectral quality (Stamps, 2009) [87]. Recent advances in agricultural engineering have led to the development of Photo selective or colored shade nets, which not only reduce radiation intensity but also selectively modify the spectral composition of transmitted light to regulate plant physiological responses (Shahak *et al.*, 2004a; Shahak *et al.*, 2008) [77, 78].

Photo selective shade nets are manufactured using high-density polyethylene materials embedded with specific chromatic pigments, reflective additives, UV stabilizers, and lightdiffusing elements that alter the proportions of blue, red, far-red, and ultraviolet wavelengths reaching the plant canopy (Al-Helal *et al.*, 2012; Hemming *et al.*, 2008; Rajapakse and Shahak, 2007) [27, 3, 67] (Rajapakse and Shahak, 2007) [67]. Different net colors such as red, blue, pearl, yellow, and gray exert distinct effects on plant morphology, physiology, and productivity by influencing phytochrome- and cryptochrome-mediated processes including stem elongation, branching, chlorophyll synthesis, flowering, and fruit development (Oren-Shamir *et al.*, 2001; Shahak, 2008) [77, 65].

The principle behind Photo selective netting is based on spectral manipulation combined with physical crop protection. Red nets typically enhance vegetative growth and biomass accumulation through enrichment of red and far-red wavelengths, while blue nets often reduce stem elongation and improve compact growth by increasing blue light transmission. Pearl and reflective nets improve light diffusion, promoting better canopy penetration, photosynthetic efficiency, and uniform plant growth (Shahak *et al.*, 2009; Stamps and Chandler, 2008) [77, 88, 80, 6]. Yellow nets can interfere with insect behavior, thereby reducing pest infestation and virus transmission in several vegetable crops (Ben-Yakir *et al.*, 2008) [6].

Research across diverse vegetable species such as tomato, bell pepper, cucumber, sweet pepper, lettuce, spinach, and leafy greens has demonstrated that Photo selective shade nets can improve vegetative growth, physiological efficiency, yield parameters, fruit appearance, phytochemical composition, water use efficiency, and postharvest performance (Díaz-Pérez, 2014; Selahle *et al.*, 2015; Mashabela *et al.*, 2015; Ilić *et al.*, 2017; Fallik *et al.*, 2009; López-Marín *et al.*, 2012; Ambrózy *et al.*, 2016) [31, 53, 73, 33, 4, 19, 55] (Ilić *et al.*, 2017; Díaz-Pérez, 2014; Kabir *et al.*, 2020) [40]. For example, pearl and red nets have consistently shown positive effects on bell pepper productivity, while colored nets have also enhanced antioxidant compounds, carotenoids, vitamin C, and flavonoid accumulation in fruits and leafy vegetables (Ilić and Fallik, 2017) [31].

In addition to enhancing crop physiology, Photo selective nets contribute significantly to integrated pest management by

altering visual cues used by insects, reducing pest colonization, suppressing viral transmission, and in some cases minimizing fungal pathogen incidence (Ben-Yakir *et al.*, 2008; Ben-Yakir *et al.*, 2012; Arthurs and Stamps, 2009; Elad *et al.*, 2007) [6, 7, 17, 87, 5]. Studies have reported reduced populations of whiteflies, thrips, and aphids under yellow, pearl, and UVblocking nets, which subsequently lowers viral disease incidence (Ben-Yakir *et al.*, 2012) [7]. This ecological advantage reduces pesticide dependency and supports environmentally sustainable vegetable production systems.

Microclimate modification under Photo selective nets includes reductions in canopy temperature, solar load, evapotranspiration rates, and heat stress while increasing relative humidity, improving soil moisture conservation, and enhancing photosynthetic radiation use efficiency (Möller and Assouline, 2007; Tanny, 2013; Mahmood *et al.*, 2018; Gent, 2007) [54, 91, 24]. (Möller and Assouline, 2007) [59]. Such conditions are particularly advantageous in arid, semi-arid, and sodic environments where vegetable crops frequently encounter abiotic stress. By improving resource use efficiency, Photo selective net technology aligns with climate-resilient horticulture and sustainable intensification goals.

The increasing global demand for high-quality vegetables, coupled with shrinking arable land and environmental concerns, necessitates innovative cultivation approaches that maximize productivity while minimizing ecological impacts. Photo selective shade nets represent a multifunctional solution that integrates light management, climate moderation, pest suppression, and quality enhancement. Their role extends beyond simple shading to becoming a precision agriculture tool capable of tailoring crop responses through spectral engineering. Despite promising outcomes, crop responses to Photo selective nets vary depending on species, genotype, cultivar architecture, climatic region, shading intensity, net color, seasonal variation, and complementary management practices such as irrigation and nutrition (Mudau *et al.*, 2017; Son *et al.*, 2016; Midmore and Rank, 2002; Kumar *et al.*, 2020; Champaneri and Patel, 2022) [46, 13, 58, 85, 60]. Therefore, crop-specific and region-specific optimization remains essential for maximizing commercial adoption and sustainability. Therefore, region-specific optimization and further research are essential to develop crop-wise recommendations for commercial adoption.

This review focuses on the role of Photo selective shade nets in vegetable crop production, emphasizing their mechanisms of action, effects on growth and physiology, yield improvement, quality enhancement, pest and disease management, and their potential contribution to sustainable protected cultivation under changing climatic scenarios.

Type of Nets

Shade nets used in vegetable production are highly specialized agro-textile materials designed not only for shading but also for microclimate modification, spectral manipulation, crop protection, and durability under diverse environmental conditions. The performance of shade nets depends largely on their structural, radiometric, physical, and mechanical characteristics, which collectively determine their suitability for specific crops, climatic regions, and production objectives (Castellano *et al.*, 2008; Briassoulis *et al.*, 2007) [10, 12].

Major Commercial Types of Shade Nets

Selection of an appropriate shade net for vegetable cultivation requires careful evaluation of three major criteria: fabric material, density percentage, and Photo selective characteristics.

These factors determine the net's functional performance under varying environmental and crop production conditions.

Fabric Material

Shade nets are primarily classified based on manufacturing structure into knitted and woven nets.

Knitted shade nets are widely preferred in modern horticulture because of their flexibility, lightweight structure, superior tear resistance, and ability to resist unraveling when damaged. They are generally made from UV-stabilized HDPE monofilament or tape threads and are suitable for long-term protected cultivation due to enhanced durability and ease of installation (Briassoulis, 2006; Castellano *et al.*, 2008) ^[12, 9].

Woven shade nets are produced by interlacing flat tapes or fibers in a regular pattern. Although they often provide high tensile strength and uniform shading, woven nets are generally less flexible and may unravel when torn. Their application is more common in temporary or lower-cost installations (Papadakis *et al.*, 2000) ^[66].

Density Percentage (Shade Factor)

Shade nets are commercially available in a range of density percentages, typically including 15%, 35%, 40%, 50%, 75%, and 90%, depending on crop requirements and regional climatic conditions.

- 15-35% shade nets: Suitable for light shading in mild climates or for crops requiring high light intensity.
- 40-50% shade nets: Commonly used for most vegetable crops, balancing light reduction and photosynthesis.
- 75-90% shade nets: Used for nursery raising, highly sensitive crops, or extreme heat protection.

Higher density percentages reduce solar radiation and temperature more effectively but may also lower photosynthetic activity if excessive shading is applied (Stamps, 2009; Shahak, 2014) ^[76, 87]. Therefore, crop-specific optimization is essential.

Photo selective Shade Nets

Photo selective nets are further divided into

Colored and neutral nets

These include red, blue, yellow, pearl, gray, green, and black nets. Colored nets selectively alter spectral quality, while neutral nets mainly reduce overall radiation intensity without major spectral modification (Rajapakse and Shahak, 2007) ^[67].

Aluminate (reflective) shade nets

Aluminate or aluminized nets are manufactured with reflective metallic additives that improve solar reflection, reduce canopy temperature, enhance diffuse light distribution, and lower heat stress. These nets are particularly useful in hot arid climates and high-radiation environments (Al-Helal *et al.*, 2012) ^[3].

Structural Features of Shade Nets

The structural properties of shade nets include the type of material, thread dimensions, knitting pattern, mesh size, porosity, solidity, and net weight, all of which influence shading efficiency, airflow, longevity, and spectral behavior. Most commercial shade nets are manufactured from high-density polyethylene (HDPE) due to its lightweight nature, UV resistance, flexibility, and durability. HDPE nets are often treated with ultraviolet stabilizers and pigments to enhance lifespan and modify radiative properties (Castellano *et al.*, 2008; Briassoulis, 2006) ^[12, 9].

The type and dimensions of threads used in net fabrication

significantly affect net strength and shading percentage. Monofilament, tape, or fibrillated threads are commonly used, with thicker threads generally increasing durability but also influencing light interception and airflow (Kittas *et al.*, 2012) ^[44]. Knitted nets are preferred over woven nets in horticulture because of their flexibility, resistance to tearing, and better mechanical stability under wind loads (Papadakis *et al.*, 2000) ^[66].

Mesh size, expressed as the dimensions of openings between threads, determines insect exclusion capacity, ventilation rate, and light transmission. Fine mesh nets offer better pest protection but may reduce airflow and increase temperature, while larger mesh sizes improve ventilation but provide less insect exclusion (Teitel, 2007) ^[93]. Porosity or solidity, defined as the ratio of open to closed surface area, directly affects air exchange, humidity, and solar radiation penetration. Nets with higher porosity generally permit greater ventilation but lower shading intensity (Tanny *et al.*, 2009) ^[92].

Net weight, usually expressed in grams per square meter (g m^{-2}), reflects material density and structural robustness. Heavier nets tend to have improved mechanical resistance and longevity but may also increase installation costs and structural load requirements (Briassoulis *et al.*, 2007) ^[10].

Color Additives and Pigmentation in Shade Nets

The coloration and functional properties of shade nets are achieved through the incorporation of specific additives and pigments during polymer manufacturing. Black shade nets are typically produced by incorporating carbon black into polyethylene threads. Carbon black serves a dual role by providing black pigmentation while also functioning as an effective ultraviolet (UV) stabilizer. This significantly enhances the durability and lifespan of black-thread nets compared to transparent or lightly pigmented materials by protecting polymer chains from photodegradation (Briassoulis, 2006; Castellano *et al.*, 2008) ^[12, 9].

Commercially, carbon black is generally incorporated at concentrations below 1%, as excessive quantities may negatively affect the mechanical stability, flexibility, and tensile properties of the polymer threads (Scarascia-Mugnozza *et al.*, 2011) ^[72]. Thus, optimized additive concentration is essential to balance UV protection and structural integrity.

Other shade net colors are achieved through the use of specialized pigments and chromatic additives. For example, phthalocyanine-based pigments are commonly used to produce blue and green nets due to their excellent thermal stability, color persistence, and spectral selectivity. Metallic additives are used in aluminized nets to improve reflectivity, while red and yellow nets utilize distinct organic pigments for targeted spectral modification (Abdel-Ghany and Al-Helal, 2011) ^[2].

These pigmentation strategies not only determine visual appearance but also strongly influence radiometric behavior, crop microclimate and photomorphogenic responses.

The Three Dimensions of Light in Shade Net Technology

Light is a fundamental environmental factor governing plant growth, development, and productivity. Shade net technologies influence plant performance through modification of three principal dimensions of light:

Light Duration (Photoperiod)

Photoperiod refers to the daily duration of light exposure perceived by plants. It regulates flowering, tuberization, dormancy, and reproductive transitions through phytochrome-

mediated signaling pathways. While shade nets generally have limited direct influence on day length, they can indirectly modify photoperiodic responses by altering dawn/dusk light quality and extending diffuse light periods under protected structures (Rajapakse and Shahak, 2007) ^[67].

Light Quality (Spectral Distribution)

Light quality refers to the spectral composition or wavelength distribution of incident radiation. This is the most critical parameter manipulated by Photo selective shade nets. Different net colors selectively filter or enrich specific wavelengths such as red, blue, far-red, and UV radiation, thereby regulating plant architecture, photosynthesis, stomatal behavior, chlorophyll synthesis, flowering, and secondary metabolite production (Shahak *et al.*, 2004a; Oren-Shamir *et al.*, 2001) ^[65, 78].

For instance

- Red nets enhance vegetative vigor through modified red/far-red ratios.
- Blue nets improve compact growth and stomatal regulation.
- Pearl nets improve light diffusion and canopy penetration.
- Yellow nets may alter insect behavior

Light Quantity (Intensity)

Light quantity refers to total radiation intensity or photosynthetically active radiation (PAR) reaching the crop canopy. Shade nets reduce incident solar intensity based on their shading percentage, helping to prevent heat stress, photo inhibition, leaf scorching, and excessive evapotranspiration. However, excessive shading may reduce photosynthetic efficiency and yield if light becomes limiting (Stamps, 2009; Díaz-Pérez, 2014) ^[87].

Optimal net selection therefore requires balancing these three light dimensions to maximize crop productivity and quality.

Radiometric Properties of Shade Nets

Radiometric characteristics are among the most critical features of Photo selective nets, as they regulate both the quantity and quality of transmitted solar radiation. These properties include net color, transmissivity, reflectivity, absorptivity, and shading factor (Shahak *et al.*, 2004; Al-Helal *et al.*, 2012) ^[3, 78].

Color is a primary determinant of spectral selectivity. Black nets primarily absorb radiation and provide uniform shading, while colored nets such as red, blue, yellow, pearl, and gray selectively alter light spectra to induce specific physiological responses in crops (Shahak, 2014) ^[76]. Red nets enhance red/far-red light, stimulating vegetative growth; blue nets increase blue light, promoting compact morphology; pearl nets diffuse light, improving canopy penetration; and yellow nets can repel certain insect pests (Rajapakse and Shahak, 2007; Ben-Yakir *et al.*, 2008) ^[77, 67, 61].

Transmissivity refers to the proportion of solar radiation passing through the net, while reflectivity indicates the amount reflected away from the crop environment. These parameters influence photosynthetically active radiation (PAR), canopy temperature, and energy balance. Shade factor, usually expressed as a percentage, indicates the degree of radiation reduction and commonly ranges from 20% to 90% depending on crop and climatic requirements (Castellano *et al.*, 2008) ^[12].

Reflective and diffusive nets are increasingly used to optimize light distribution within plant canopies, enhancing photosynthesis and reducing sunburn damage in sensitive vegetable crops (Hemming *et al.*, 2008) ^[27].

Physical Properties of Shade Nets

Physical properties such as air permeability are essential for regulating greenhouse or screenhouse microclimate. Air permeability refers to the ability of air to pass through the net structure, influencing ventilation, temperature control, humidity management, and evapotranspiration (Tanny *et al.*, 2009) ^[92].

High air permeability is desirable in hot climates to prevent excessive heat buildup, while lower permeability may be useful in cooler regions for retaining warmth. However, excessively dense nets can restrict ventilation, potentially causing heat stress, elevated humidity, and disease incidence (Katsoulas *et al.*, 2012) ^[42]. Therefore, balancing shading and airflow is crucial for optimal crop performance.

Mechanical Characteristics of Shade Nets

Mechanical properties determine the structural stability and service life of shade nets under field conditions. Important parameters include tensile stress, tensile strength, elongation at break, tear resistance, and long-term durability under ultraviolet exposure and environmental wear (Briassoulis, 2006) ^[9].

Tensile strength refers to the maximum stress a net can withstand before failure, while elongation at break measures flexibility and deformation tolerance. Nets used in high-wind or storm-prone areas require superior mechanical properties to withstand external forces without tearing (Castellano *et al.*, 2008) ^[12]. UV degradation remains a major factor limiting net longevity; therefore, UV-stabilized polymers are essential for prolonged agricultural use (Briassoulis *et al.*, 2007) ^[10].

Durability is influenced by polymer composition, environmental exposure, maintenance practices, and manufacturing quality. Modern Photo selective nets are engineered to maintain optical and mechanical performance over multiple growing seasons, improving cost-effectiveness for commercial vegetable production (Shahak *et al.*, 2008) ^[77].

Factors That Impact the Physiology of Plants Under Photo selective Shade Nets

Photo selective shade nets influence plant physiological performance by modifying environmental parameters such as light spectrum, intensity, temperature, and humidity. These alterations significantly affect major physiological processes including Photo morphogenesis, photosynthesis, respiration, and transpiration, which collectively determine crop growth, productivity, and quality.

Photo morphogenesis

Photo morphogenesis refers to the regulation of plant growth and developmental patterns in response to light signals. It is primarily controlled by photoreceptors such as phytochromes, cryptochromes, and phototropins that perceive variations in light quality, quantity, direction, and duration. Photo selective shade nets modify spectral composition, particularly red, blue, and farred wavelengths, thereby influencing stem elongation, branching, leaf expansion, flowering, chlorophyll synthesis, and biomass partitioning (Smith, 2000; Taiz and Zeiger, 2015) ^[89, 83]. Red nets generally increase vegetative growth and shoot elongation by altering red to farred light ratios, whereas blue nets promote compact growth, thicker leaves, and enhanced stomatal development. Pearl nets improve light diffusion and canopy penetration, supporting uniform growth patterns (Oren-Shamir *et al.*, 2001; Shahak, 2014) ^[76, 65]. Through these mechanisms, Photo selective nets act as practical tools for manipulating crop architecture and developmental responses.

Photosynthesis

Photosynthesis is one of the most directly affected physiological processes under shade net cultivation. Shade nets regulate photosynthetically active radiation (PAR), light distribution, and leaf temperature, thereby influencing carbon assimilation efficiency. Moderate shading can improve photosynthetic performance by reducing photo inhibition, heat stress, and excessive radiation damage, particularly under high-temperature environments (Díaz-Pérez, 2014; Hemming *et al.*, 2006) ^[26].

Diffused light under pearl or reflective nets enhances deeper canopy penetration, improving whole-plant photosynthetic efficiency. Blue and red spectral manipulations can further optimize chlorophyll activity and stomatal function, promoting higher biomass accumulation and yield. However, excessive shading may reduce PAR below optimal thresholds, limiting photosynthesis and productivity (López and Runkle, 2008) ^[52].

Respiration

Respiration is strongly influenced by temperature and metabolic activity, both of which are modified by shade net environments. Elevated temperatures generally increase respiration rates, potentially leading to excessive carbohydrate depletion and reduced growth efficiency. By lowering canopy and ambient temperatures, shade nets reduce maintenance respiration demands and improve net carbon gain (Tanny, 2013) ^[91].

Reduced heat stress under Photo selective nets supports better energy balance, enzyme stability, and mitochondrial efficiency. This is particularly beneficial in vegetable crops exposed to high summer temperatures, where moderated respiration contributes to improved biomass retention and fruit development (Semida *et al.*, 2021) ^[74].

Transpiration

Transpiration, the process of water vapor loss through stomata, is closely linked to radiation intensity, vapor pressure deficit, temperature, and wind speed. Shade nets significantly reduce transpiration rates by lowering solar radiation, canopy temperature, and wind velocity while increasing relative humidity (Möller and Assouline, 2007) ^[59].

This improved microclimate enhances plant water use efficiency, reduces irrigation requirements, and minimizes drought stress. In hot climates, reduced transpiration under shade nets can prevent wilting, improve stomatal regulation, and support sustained physiological activity (Mahmood *et al.*, 2018) ^[54]. However, excessive humidity under poorly ventilated nets may increase disease risk, emphasizing the need for balanced net design.

Spectral Regions of Light and Their Physiological Effects on Vegetable Crops

Light spectrum plays a critical role in regulating plant growth, development, metabolism, and reproductive behavior. Different wavelengths of light influence distinct physiological and biochemical processes through specialized photoreceptors, including phytochromes, cryptochromes, phototropins, and UV receptors. Photo selective shade nets manipulate these spectral regions to optimize crop responses under protected cultivation.

Ultraviolet Light (UV: 10-400 nm)

Ultraviolet radiation is divided into UV-C (100-280 nm), UV-B (280-315 nm), and UV-A (315-400 nm). Excessive UV-B and UV-C exposure can cause DNA damage, oxidative stress, protein degradation, reduced photosynthetic rate, impaired chloroplast function, disruption of flowering and pollination, and

poor seed development (Jansen *et al.*, 1998; Hideg *et al.*, 2013) ^[28, 34]. However, moderate UV-A exposure can influence Photo morphogenesis and often promotes stem elongation and adaptive responses in certain species.

UV-blocking or UV-selective nets are commonly used to protect vegetable crops from harmful ultraviolet radiation while maintaining productivity and reducing stress-induced physiological damage.

Blue Light (430-450 nm)

Blue light is highly influential in regulating photosynthesis, chlorophyll synthesis, stomatal opening, phototropism, and seedling morphology. It enhances vegetative growth, leaf expansion, chloroplast development, and photosynthetic efficiency in young plants while reducing excessive stem elongation (Hogewoning *et al.*, 2010) ^[29].

Blue-enriched environments generally produce compact plants with thicker leaves, improved stomatal regulation, and stronger structural development, making blue Photo selective nets useful for nursery production and high-quality seedling establishment.

Green Light (500-550 nm)

Although green light is less efficiently absorbed by chlorophyll compared to red and blue wavelengths, it penetrates deeper into plant canopies and contributes significantly to photosynthesis in lower leaf layers. Green wavelengths support chlorophyll formation, canopy photosynthesis, and overall energy balance (Smith *et al.*, 2017) ^[84].

Green light also interacts with blue and red signaling pathways, influencing plant morphology and adaptive responses under shaded or diffused light environments.

Red Light (600-700 nm)

Red light is a major driver of photosynthesis and phytochrome-mediated developmental regulation. Phytochromes are highly sensitive to red wavelengths, which influence flowering, fruiting, stem diameter, branching, seed germination, and photoperiodic responses (Franklin and Quail, 2010) ^[22].

Red light can induce flowering in long-day plants and suppress flowering in short-day plants depending on photoperiodic context. Red-enriched Photo selective nets often enhance biomass accumulation, reproductive growth, and fruit yield in vegetable crops.

Far-Red Light (700-800 nm)

Far-red light strongly influences shade avoidance responses, stem elongation, flowering induction, and internode expansion through phytochrome signaling. Increased far-red exposure often promotes elongation growth and can trigger flowering in long-day plants (Casal, 2013) ^[11].

Manipulation of red to far-red ratios under Photo selective nets is critical for controlling crop architecture, flowering time, and biomass partitioning.

Optical Properties of Shade Nets: Absorption and Transmission Characteristics

The effectiveness of shade nets depends largely on their optical behavior, particularly their capacity to absorb, transmit, reflect, and diffuse solar radiation. Different net colors and materials selectively influence light interception, thereby modifying crop microclimate and physiological responses.

Net Color and Optical Behavior

The optical behavior of shade nets varies significantly according

to net color, pigment composition, and material structure, all of which determine their capacity to absorb, transmit, reflect, and diffuse solar radiation (Table 1). Black shade nets are widely used due to their strong absorption of photosynthetically active radiation (PAR), ultraviolet (UV), and infrared wavelengths, thereby effectively reducing total light intensity and lowering solar load. Their black coloration is primarily achieved through carbon black additives, which also provide excellent UV stabilization and enhanced durability.

Red shade nets selectively modify spectral quality by transmitting greater proportions of red and far-red wavelengths while absorbing substantial portions of blue and green light (Table 1). This spectral enrichment often promotes vegetative growth, stem development, and flowering responses through phytochrome-mediated pathways. In contrast, blue shade nets increase transmission of blue wavelengths while reducing red/far-red radiation, thereby encouraging compact plant growth, enhanced stomatal function, and improved chlorophyll synthesis. Green nets provide moderate and relatively balanced spectral filtering, allowing partial transmission of green wavelengths while offering general shading benefits (Table 1). Although less Photo selective than red or blue nets, green nets

are often used for conventional microclimate management.

Pearl or white nets function differently by reflecting and diffusing incoming radiation rather than strongly absorbing it (Table 1). This improves light distribution within plant canopies, enhances penetration to lower leaves, reduces canopy temperature, and minimizes sunscald damage. Such diffused light environments often improve whole-canopy photosynthetic efficiency.

Yellow nets selectively alter light quality in ways that can influence insect behavior, making them useful for integrated pest management in addition to crop protection. Aluminized or reflective nets contain metallic additives that significantly increase solar reflectance, particularly for infrared radiation, thereby reducing heat buildup, lowering plant stress, and improving environmental cooling under high-radiation conditions (Table 1). Overall, net color and optical behavior are critical determinants of crop physiological responses, influencing photosynthesis, plant architecture, flowering, fruit quality, pest interactions, and abiotic stress tolerance. Therefore, selecting appropriate net color is essential for optimizing protected vegetable production according to crop-specific and climatic requirements.

Table 1: General Absorption and Transmission Characteristics of Common Shade Nets

Type of Shade Net	Major Absorption Characteristics	Major Transmission Characteristics	Key References
Black Net	High absorption of PAR, UV, and infrared radiation	Low total light transmission; neutral spectral reduction	Briassoulis (2006) ^[9] ; Abdel-Ghany & Al-Helal (2013)
Red Net	Absorbs blue and green wavelengths	Enhanced red and far-red transmission	Shahak <i>et al.</i> (2016); Rajapakse & Shahak (2007) ^[67]
Blue Net	Absorbs portions of red/far-red spectra	Increased blue light transmission	Stamps & Chandler (2009) ^[87] ; Shahak (2008) ^[77, 79]
Green Net	Moderate absorption across visible spectrum	Partial green wavelength transmission	Vox <i>et al.</i> (2017) ^[95]
Pearl/White Net	Lower absorption; high reflectance and diffusion	Broad-spectrum diffused light transmission	Hemming <i>et al.</i> (2008) ^[27] ; Shahak <i>et al.</i> (2016)
Yellow Net	Absorbs blue wavelengths	Enhanced yellow spectrum; insect behavioral modification	Ben-Yakir <i>et al.</i> (2008) ^[6] ; Stamps (2009) ^[87]
Aluminized Net	Reflects infrared and excess solar radiation	Moderate diffused visible light transmission	Al-Helal (2006); Abdel-Ghany & Al-Helal (2013)

Vegetable Crops Growing Under Shade Net Conditions

Vegetable crops are highly sensitive to environmental fluctuations, particularly excessive solar radiation, high temperature, drought, salinity, heavy rainfall, and pest incidence, all of which can significantly reduce crop productivity, quality, and profitability under open-field cultivation. In tropical and subtropical regions, these adverse climatic factors often lead to heat stress, sunscald, flower drop, poor fruit set, reduced photosynthesis, moisture loss, and physiological disorders, thereby limiting sustainable vegetable production. Protected cultivation through shade net systems has emerged as an effective climate-resilient technology to overcome these challenges by creating a modified microenvironment favorable for vegetable growth and development.

Shade nets regulate key environmental parameters such as light intensity, spectral quality, temperature, humidity, and wind velocity, thereby protecting crops from abiotic and biotic stresses. By reducing excessive solar radiation and canopy temperature, shade nets improve photosynthetic efficiency, chlorophyll retention, water use efficiency, nutrient uptake, and reproductive performance. Different shade net colours, including black, green, red, blue, white, and pearl, selectively modify light spectra and influence crop morphology, flowering, yield, and

quality in distinct ways. The effectiveness of shade net cultivation depends on crop species, shading intensity, climatic conditions, and net colour. Figure 1 illustrates how vegetable crops exhibit different responses to different shade net colours under protected cultivation conditions.

Under shade net conditions, vegetable crops generally exhibit improved vegetative growth, better canopy architecture, enhanced flowering, higher marketable yield, improved fruit quality, and reduced pest and disease pressure compared with open cultivation. Solanaceous crops such as tomato, capsicum, chilli, and brinjal benefit from reduced heat stress and improved fruit set; cucurbitaceous vegetables such as cucumber, bitter melon, bottle gourd, and snake gourd show better vine growth and fruit quality; leafy vegetables maintain tenderness and delayed bolting; leguminous crops improve pod setting; and root vegetables achieve better root enlargement and quality.

The adoption of shade net cultivation is increasingly recognized as a sustainable, resource-efficient, and economically viable approach for year-round vegetable production, particularly under climate change scenarios. Thus, shade net technology plays a crucial role in enhancing productivity, quality, and resilience of vegetable crops across diverse agro-climatic regions.

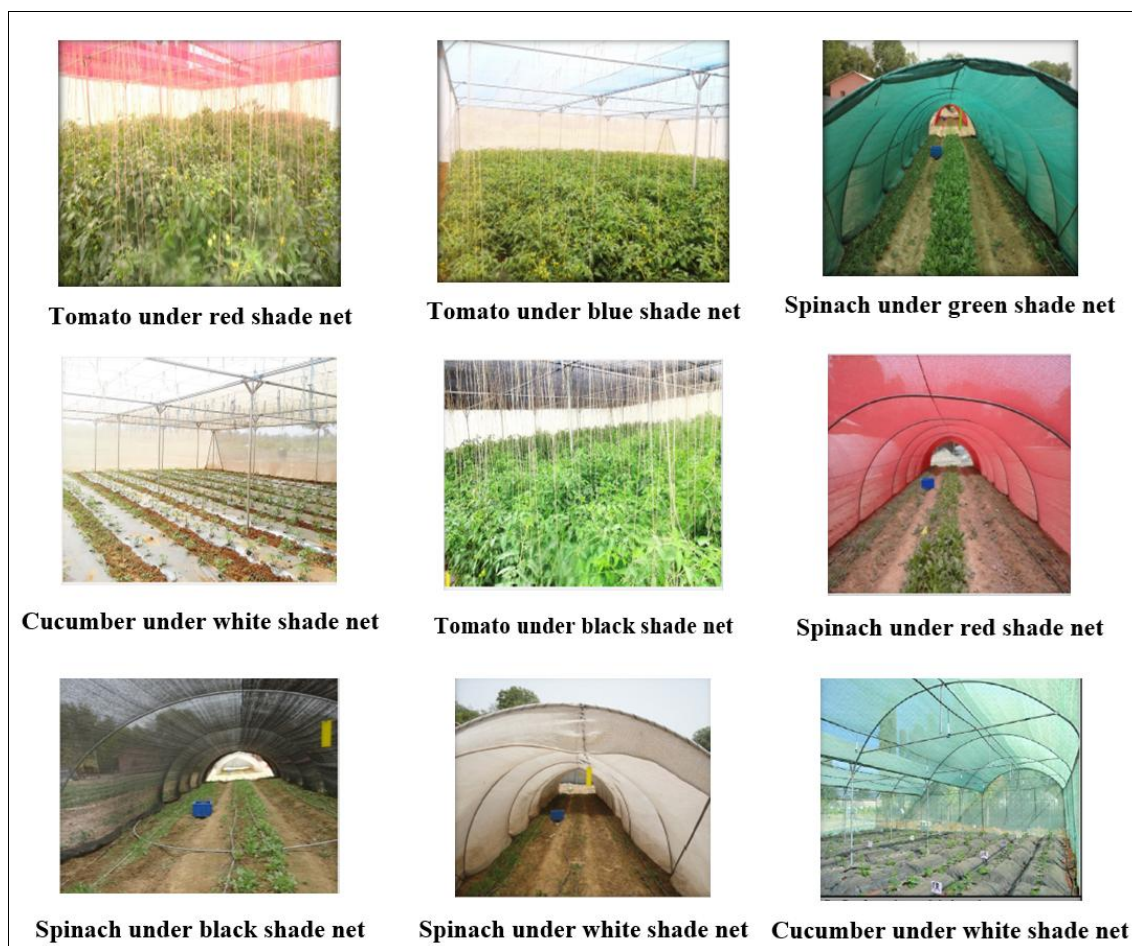


Fig 1: Vegetable crops exhibit different responses to different shade net colours under protected cultivation conditions.

Solanaceous Crops under Shade Net Cultivation

Solanaceous vegetable crops, including tomato (*Solanum lycopersicum*), sweet pepper/capsicum (*Capsicum annuum*), chilli (*Capsicum spp.*), and eggplant/brinjal (*Solanum melongena*), are among the most economically important vegetable groups cultivated worldwide. These crops are highly susceptible to excessive solar radiation, high temperatures, sunscald, blossom-end rot, flower abortion, poor fruit set, and other abiotic stress-related disorders under open-field conditions, particularly in tropical and subtropical climates. Shade net cultivation has emerged as an effective protected cultivation strategy for mitigating these stresses by optimizing light intensity, temperature, humidity, and spectral quality (Kabir *et al.*, 2024) ^[41].

Tomato: Tomato is highly responsive to shade net cultivation due to its vulnerability to heat stress, fruit cracking, blossom-end rot, poor pollination, and reduced lycopene synthesis under extreme summer conditions. Studies on tomato cv. Arka Rakshak demonstrated that different colors and intensities of shade nets significantly influence vegetative growth, flowering, yield, and fruit quality. Red shade nets, particularly at moderate to higher shade intensities, promoted earlier flowering, increased flower number, enhanced fruit set, and improved total fruit yield compared to unshaded controls. Colored nets such as red and pearl improved fruit quality by enhancing lycopene content, reducing fruit cracking, and minimizing sunscald incidence through favorable spectral modification and temperature regulation (Ilić *et al.*, 2012; Selahle *et al.*, 2015) ^[73, 33]. Moderate shading also improves water use efficiency, leaf chlorophyll concentration, and photosynthetic stability while

protecting tomato fruits from photooxidative damage. Consequently, shade net cultivation extends the productive season and improves marketable yield in hot environments.

Sweet Pepper (*Capsicum*): Sweet pepper is particularly prone to physiological disorders such as sunscald, blossom-end rot, fruit cracking, and poor fruit set under excessive radiation and heat stress. Shade net cultivation has shown substantial benefits in sweet pepper production by reducing canopy temperature, improving microclimate, and minimizing physiological disorders. Classic studies by Rylski and Spigelman (1986) ^[69] showed that moderate shading significantly reduced sunscald incidence while increasing the proportion of premium-quality fruits.

Photo selective nets such as red, pearl, and reflective nets further enhance pepper yield, fruit size, vitamin C concentration, and bioactive compounds while improving leaf gas exchange and calcium distribution. Shade levels between 20-35% are generally considered optimal for balancing photosynthesis and stress reduction in sweet pepper cultivation (Díaz-Pérez, 2014; López-Marín *et al.*, 2012) ^[53].

Chilli Pepper

Chilli peppers also benefit from shade net cultivation through improved vegetative growth, reduced transpiration losses, enhanced flowering, and improved fruit quality. Colored shade nets can reduce heat stress, increase chlorophyll content, and improve plant architecture, particularly in hot climates. Although excessive shading may delay fruit maturity, moderate shading generally supports higher marketable yield and fruit retention.

Eggplant (Brinjal): Eggplant is sensitive to intense radiation, heat, and water deficit, particularly during flowering and fruit development stages. Studies in semi-arid climates demonstrated that shade nets significantly improved plant growth, physiological efficiency, and fruit yield by protecting plants from excessive light stress and maintaining optimal daily light integral levels. A 21% shade net was reported as particularly suitable for eggplant production, enhancing plant height, leaf area, biomass accumulation, and fruit yield while minimizing environmental stress (Nguyen *et al.*, 2022) ^[61].

Shade net cultivation also reduces flower drop, improves fruit uniformity, and supports extended production under adverse climatic conditions.

Cucurbitaceous Vegetables Under Shade Net Cultivation

Cucurbitaceous vegetable crops such as cucumber (*Cucumis sativus*), bitter gourd (*Momordica charantia*), bottle gourd (*Lagenaria siceraria*), muskmelon (*Cucumis melo*), watermelon (*Citrullus lanatus*), ridge gourd (*Luffa acutangula*), sponge gourd (*Luffa cylindrica*), and snake gourd (*Trichosanthes anguina*) are highly valued for their nutritional, medicinal, and economic importance (Kumar *et al.*, 2018; Tzortzakis *et al.*, 2020) ^[94, 46, 48]. These crops are generally sensitive to extreme temperatures, excessive solar radiation, moisture stress, and pest incidence, particularly during flowering and fruiting stages (Champaneri and Patel, 2022) ^[13]. Shade net cultivation provides an effective protected environment for cucurbits by moderating temperature, reducing radiation stress, improving humidity, and enhancing pollination efficiency, thereby significantly improving growth, yield, and fruit quality (Kumar *et al.*, 2018; Tzortzakis *et al.*, 2020) ^[94, 41].

Cucumber: Cucumber is one of the most extensively studied cucurbit crops under shade net systems. High temperatures and excessive radiation often reduce fruit set, increase bitterness, and impair vegetative growth. Moderate shading (30-50%) has been shown to improve vine growth, leaf area, chlorophyll content, and marketable fruit yield by reducing canopy temperature and photo inhibition (Ilić *et al.*, 2017) ^[31]. Blue, pearl, and neutral nets are particularly beneficial in improving fruit uniformity, reducing heat stress, and extending the harvest period (Elad *et al.*, 2007; Ilić *et al.*, 2017) ^[17] (Ilić *et al.*, 2017; Elad *et al.*, 2007). Shade net cultivation also improves water use efficiency and reduces transpiration losses, making it highly suitable for cucumber production in hot and semi-arid climates.

Bitter Gourd

Bitter gourd responds favorably to protected cultivation through improved vine growth, flowering, and fruit retention. Shade net structures reduce flower drop and improve female flower production under stressful summer conditions. Studies indicate that moderate shading can improve fruit yield, reduce sunburn, and enhance fruit quality characteristics such as color and marketability (Sarkar *et al.*, 2020) ^[71]. (Sarkar *et al.*, 2020).

Bottle Gourd and Ridge Gourd

Bottle gourd and ridge gourd cultivation under shade net systems has demonstrated improvements in vegetative growth, vine vigor, flowering behavior, and fruit quality (Jat *et al.*, 2017; Singh *et al.*, 2019) ^[81, 35]. Reduced heat stress and moderated microclimate improve pollination success, fruit elongation, and yield consistency. Shade net cultivation is especially useful in tropical climates where high temperatures often limit productivity.

Muskmelon and Watermelon

Muskmelon and watermelon benefit from shade net cultivation through improved fruit set, reduced sunscald, enhanced sugar accumulation, and better rind quality (Tzortzakis *et al.*, 2020) ^[94]. Reflective and pearl nets can improve canopy light distribution while lowering fruit surface temperatures. Protected cultivation also reduces pest pressure and improves fruit appearance, increasing marketable yield.

Snake Gourd and Other Gourds

Snake gourd, sponge gourd, and related gourds show enhanced vegetative growth and yield stability under shade net systems, particularly in sodic or heat-prone environments (Champaneri and Patel, 2022) ^[13]. Improved vine health, better flowering, and reduced abiotic stress contribute to superior performance under protected cultivation.

Leafy Vegetables Under Shade Net Cultivation

Leafy vegetables such as spinach (*Spinacia oleracea*), lettuce (*Lactuca sativa*), coriander (*Coriandrum sativum*), fenugreek (*Trigonella foenum-graecum*), amaranthus (*Amaranthus spp.*), kale, and other greens are highly responsive to microclimate modifications due to their short growth cycle, tender edible tissues, and sensitivity to excessive heat, solar radiation, and moisture stress (Soundy *et al.*, 2005; Olaniran, 2007; Semida *et al.*, 2020) ^[75, 64, 86]. Under open-field conditions, high temperatures and intense radiation often accelerate bolting, reduce leaf tenderness, impair chlorophyll accumulation, and lower marketable quality (Ntsoane *et al.*, 2016; Díaz-Pérez, 2013) ^[63]. Shade net cultivation offers an efficient protected production system for leafy vegetables by optimizing temperature, humidity, and light quality while improving physiological efficiency, leaf expansion, and nutritional value (Ilić *et al.*, 2018; Shahak *et al.*, 2008) ^[32, 77, 6].

Spinach

Spinach is particularly sensitive to elevated temperature and radiation stress, which can reduce leaf area, chlorophyll content, and biomass while promoting premature bolting. Microenvironment studies under different colored shade nets have demonstrated that shade net color significantly influences biophysical parameters, plant physiology, and yield performance in spinach (Kumar *et al.*, 2021) ^[47]. Blue, green, and pearl shade nets generally reduce canopy temperature, moderate solar radiation, and improve relative humidity compared with open conditions, creating a favorable environment for vegetative growth (Kumar *et al.*, 2021; Semida *et al.*, 2020) ^[75, 46].

Research indicates that colored shade nets improve plant height, leaf area index, chlorophyll concentration, stomatal conductance, and photosynthetic efficiency (Ilić *et al.*, 2018; Soundy *et al.*, 2005) ^[86, 32]. Blue nets often promote compact growth with darker green leaves due to enhanced chlorophyll synthesis, while pearl nets improve diffuse radiation and canopy penetration, leading to uniform leaf development and increased biomass accumulation. Moderate shading levels also reduce transpiration rates and improve water use efficiency, which is critical for leafy vegetable production in warm climates (Kumar *et al.*, 2021) ^[47].

Lettuce

Lettuce cultivation under shade nets has shown substantial benefits in reducing tip burn, bolting, leaf scorching, and bitterness caused by excessive sunlight (Ntsoane *et al.*, 2016) ^[63]. Photo selective nets enhance leaf tenderness, improve fresh

weight, and increase concentrations of antioxidants, phenolics, and vitamin C. Diffuse light environments created by pearl and white nets improve photosynthesis across the canopy while reducing thermal stress.

Coriander, Fenugreek and Amaranthus

Shade net cultivation in coriander, fenugreek, and amaranthus significantly improves leaf succulence, biomass yield, and market quality (Olasantan, 2007; Díaz-Pérez, 2013) ^[64]. Reduced radiation stress under shade structures enhances vegetative growth and extends harvest duration. Moderate shading is especially beneficial in summer cultivation where open-field production often suffers from moisture stress and reduced leaf quality.

Leguminous Vegetables Under Shade Net Cultivation

Leguminous vegetable crops such as French bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), garden pea (*Pisum sativum*), cluster bean (*Cyamopsis tetragonoloba*), and lablab bean (*Lablab purpureus*) are important sources of plant protein, vitamins, minerals, and dietary fiber (Shivashankara *et al.*, 2023; Bezerra Neto *et al.*, 2018). These crops are highly sensitive to elevated temperatures, excessive radiation, moisture stress, and flower abscission, particularly during reproductive stages (Pandey and Singh, 2017; Mupambi *et al.*, 2018). High temperature and solar stress often reduce pollen viability, pod setting, seed development, and overall productivity (Shahak, 2014; Kumar *et al.*, 2020) ^[76, 46]. Shade net cultivation offers an effective strategy to improve the microenvironment for leguminous vegetables by moderating temperature, reducing radiation load, improving humidity, and enhancing reproductive efficiency (Shivashankara *et al.*, 2023).

French Bean: French bean is highly responsive to Photo selective shade net technology, particularly in warm climates where excessive temperature can severely impair flowering and pod development. Studies evaluating different colored shade nets have shown that Photo selective nets significantly influence vegetative growth, flowering behavior, pod yield, and quality (Nair *et al.*, 2021; Singh *et al.*, 2019) ^[81]. Red and pearl shade nets often improve plant height, branch number, chlorophyll content, and pod yield by optimizing spectral quality and reducing thermal stress (Nair *et al.*, 2021; Kumar *et al.*, 2020) ^[46].

Research on the effect of Photo selective shade nets on French bean yield demonstrated that moderate shading levels (typically 35-50%) enhanced flower retention, pod set, pod length, and marketable yield compared to open-field conditions (Nair *et al.*, 2021; Singh *et al.*, 2019) ^[81]. Colored nets improve photosynthetic performance by reducing photo inhibition while maintaining adequate light quality for reproductive development (Shahak, 2014; Mupambi *et al.*, 2018) ^[76]. In addition, shade nets reduce flower drop, improve pod uniformity, and enhance water use efficiency (Bezerra Neto *et al.*, 2018; Nair *et al.*, 2021) (Nair *et al.*, 2021).

Blue and pearl nets are often associated with improved canopy architecture and leaf development, while red nets may stimulate reproductive responses through modified phytochrome activity. Excessive shading, however, may delay flowering and reduce total productivity if light becomes limiting.

Cowpea and Garden Pea

Cowpea and garden pea also benefit from moderate shade net cultivation, particularly in regions with elevated summer

temperatures (Pandey and Singh, 2017; Shivashankara *et al.*, 2023). Protected cultivation improves vegetative growth, reduces flower abortion, enhances pod filling, and increases marketable yield (Pandey and Singh, 2017; Bezerra Neto *et al.*, 2018). Improved canopy temperature and moisture conservation contribute to better nitrogen fixation and sustained productivity.

Root Vegetables Under Shade Net Cultivation

Root vegetables such as beetroot (*Beta vulgaris L.*), carrot (*Daucus carota*), radish (*Raphanus sativus*), turnip (*Brassica rapa*), and other underground storage crops are important dietary sources of carbohydrates, minerals, antioxidants, and bioactive compounds (Olasantan, 2007; Tzortzakis *et al.*, 2020) ^[64, 94]. These crops are highly influenced by soil temperature, radiation intensity, and moisture availability, all of which directly affect root enlargement, pigment accumulation, texture, and market quality (Díaz-Pérez, 2013; Semida *et al.*, 2020) ^[75]. Excessive heat and solar radiation can impair root development, reduce biomass partitioning to storage organs, and lower nutritional quality (Ntsoane *et al.*, 2016; Shahak, 2014) ^[63, 76]. Shade net cultivation offers a valuable microclimate modification strategy for root vegetables by regulating temperature, light intensity, and evapotranspiration, thereby improving root growth and yield performance (Díaz-Pérez, 2013; Semida *et al.*, 2020).

Beetroot

Beetroot is particularly responsive to shading intensity and spectral manipulation due to its sensitivity to high temperatures and excessive radiation during root bulking stages. Studies on the effect of shading intensity manipulated through different shade net colours have demonstrated that colored nets significantly influence beetroot growth, physiological parameters, root yield, and quality traits (Reddy *et al.*, 2022; Kumar *et al.*, 2022). Moderate shading levels under colored nets such as green, red, blue, and pearl can improve leaf area, chlorophyll content, canopy temperature regulation, and root enlargement compared with open-field conditions (Reddy *et al.*, 2022; Kumar *et al.*, 2022) (Reddy *et al.*, 2022).

Green and pearl shade nets often create favorable microenvironments by reducing excessive radiation and maintaining balanced light diffusion, which supports improved photosynthesis and biomass accumulation. Red nets may enhance vegetative growth and carbohydrate partitioning, while blue nets improve chlorophyll synthesis and leaf compactness. Appropriate shading intensity improves root diameter, root weight, and total yield while reducing heat-induced growth suppression.

Research further indicates that optimized shade net color and intensity can improve betalain pigment concentration, antioxidant properties, and root quality characteristics such as color uniformity, tenderness, and total soluble solids (Kumar *et al.*, 2022). However, excessive shading may reduce photosynthetic efficiency and root biomass if light becomes limiting (Kumar *et al.*, 2022).

Carrot and Radish

Carrot and radish also benefit from moderate shading, particularly in regions experiencing high summer temperatures (Olasantan, 2007; Semida *et al.*, 2020) ^[75, 64]. Shade nets improve germination, leaf growth, root expansion, and root smoothness while reducing root cracking and bolting (Díaz-Pérez, 2013; Ntsoane *et al.*, 2016) ^[63]. Improved soil moisture conservation and moderated canopy temperature contribute to better root quality and marketable yield.

Conclusion

Photo selective shade nets have revolutionized protected vegetable cultivation by offering a multifunctional approach to climate-resilient crop production. By selectively modifying light quality, intensity, and microclimatic conditions, these nets significantly improve plant physiology, photosynthesis, growth, yield, and produce quality while reducing abiotic and biotic stresses. Different net colors provide crop-specific advantages, with green and red shade nets generally showing superior performance in enhancing vegetable productivity, while yellow nets contribute to effective pest management. Photo selective nets have proven beneficial across diverse vegetable groups including solanaceous, cucurbitaceous, leafy, leguminous, and root crops by optimizing environmental conditions, improving water use efficiency, and extending production periods under adverse climates. Although responses vary depending on crop species, cultivar, and regional conditions, proper selection of shade net color and shading intensity can maximize productivity and profitability. Overall, Photo selective shade net technology represents a sustainable, economically feasible, and climate-smart solution for future vegetable production systems.

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Consent for publication

All authors consent the publication of the current article.

Competing interests

The authors declare no competing interests.

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