

**RENATA RANIELLY PEDROZA CRUZ**

**PRODUCTION AND QUALITY OF *Capsicum chinense* and *Capsicum frutescens*  
CULTIVATED UNDER COLORED SHADE NETS**

Thesis submitted to the Plant Science Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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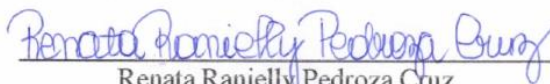
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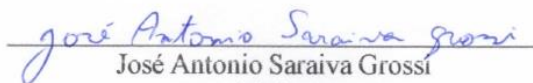
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*In memoriam to Lucidalva Pedroza da Costa.*

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*“Todo amanhã se cria num ontem, através de um hoje (...).  
Temos de saber o que fomos, para saber o que seremos.”*

**(Paulo Freire)**

## ABSTRACT

CRUZ, Renata Ranielly Pedroza, D.Sc., Universidade Federal de Viçosa, February, 2023. **Production and quality of ornamental peppers cultivated under colored shade nets.** Adviser: José Antonio Saraiva Grossi. Co-advisers: Ariana Mota Pereira, José Geraldo Barbosa, Luiz Alexandre Peternelli and Wellington Souto Ribeiro.

Temperature and intensity of solar radiation compromise the production, quality and photosynthetic efficiency, through leaf and fruit burns, photoinhibition, stomata closure, flowers and fruits abortion, among others. Colored shade nets were tested in order to identify their benefits production, quality and photosynthetic efficiency of *Capsicum chinense* and *C. frutescens*. This thesis has been divided into two papers that deal with the production and quality (paper 1), photosynthetic efficiency (paper 2) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. The experiment was developed from February to August 2021 in entirely randomized design. *C. chinense* and *C. frutescens* were cultivated under red, pearl and aluminet shade nets with 35% shading and without net. At 150 days, production, quality and photosynthetic efficiency variables were quantified. The red net reduced the maximum temperature by at 4.1°C and the pearl and aluminet nets reduced the minimum temperature by 3°C. The maximum and minimum relative humidity was increased by 2.6 and 8.5%, respectively, by the red net. The pearl net obtained the lowest percentage of solar radiation incidence. Plant height was greater in the red and pearl nets, and *C. frutescens*. The diameter and stem fresh matter did not differ statistically between treatments. Root length was greater in the red and aluminet nets. The longitudinal and transverse canopy ratio was higher in *C. chinense* cultivated under the aluminet net. The number of leaves and leaf fresh matter was higher in pearl and aluminet net, and in *C. frutescens*, but leaf dry matter was higher in *C. chinense*. The number of flower buds and flowers, and flower buds dry matter was higher in *C. chinense*. The root fresh matter and dry matter was greater in *C. chinense*. Leaf area, leaf area duration, leaf area ratio, specific leaf area and harvest index were higher in *C. frutescens* in comparison to *C. chinense* and leaf thickness opposite occurred.  $A$  and  $g_s$  were higher in *C. frutescens* cultivated under red net and *C. chinense* cultivated under aluminet net.  $E$  was higher in *C. chinense* cultivated under aluminet net and did not differ between the treatments applied to *C. frutescens*.  $WUE$  was higher in the red net and  $iWUE$  was higher in *C. frutescens*.  $F_o$  and  $F_m$  were higher in *C. frutescens* cultivated under red net.  $F_v/F_m$  was lower in *C. chinense* cultivated under red net and SPAD was higher in red net. LEF was lower in control. qL fraction

was higher in control and pearl net and in *C. frutescens*. RdF was lower in *C. chinense* cultivated under red net.  $\Phi$ NPQ and NPQt were higher in *C. chinense* cultivated under red net. The aluminet net in association with *C. chinense* are recommended considering the compactness of height, pot coverage, greater number, shape and arrangement of fruits. On the other hand, this one did not achieve efficient photosynthetic efficiency. *C. frutescens* cultivated under red net obtained a higher photosynthetic efficiency. On the other hand, *C. chinense* cultivated under red net had an inverse response, due to each specie having different responses under the same growing environment.

Keywords: Shading. Productivity. Photosynthetic efficiency.

## RESUMO

CRUZ, Renata Ranielly Pedroza, D.Sc., Universidade Federal de Viçosa, fevereiro de 2023. **Produção e qualidade de pimenteiras ornamentais cultivadas sob telas fotosseletivas.** Orientador: José Antonio Saraiva Grossi. Coorientadores: Ariana Mota Pereira, José Geraldo Barbosa, Luiz Alexandre Peternelli e Wellington Souto Ribeiro.

A temperatura e intensidade da radiação solar comprometem a produção, qualidade e eficiência fotossintética, através de queimaduras de folhas e frutos, fotoinibição, fechamento estomático, abortamento de flores e frutos, entre outros problemas. Telas fotosseletivas foram testadas a fim de identificar os benefícios na produção, qualidade e eficiência fotossintética de *Capsicum chinense* e *C. frutescens*. Esta tese foi dividida em dois artigos que abordam a produção e qualidade (artigo 1) e a eficiência fotossintética (artigo 2) de *C. chinense* e *C. frutescens* cultivadas sob telas fotosseletivas. O experimento foi desenvolvido de fevereiro a agosto de 2021 em delineamento inteiramente casualizado. *C. chinense* e *C. frutescens* foram cultivadas sob telas fotosseletivas nas cores vermelha, pérola e aluminet com 35% de sombreamento e sem telas. Aos 150 dias, foram quantificadas variáveis de produção, qualidade e eficiência fotossintética. A tela vermelha reduziu a temperatura máxima em 4,1°C e as redes de pérola e aluminet reduziram a temperatura mínima em 3°C. A umidade relativa máxima e mínima foi aumentada em 2,6 e 8,5%, respectivamente, pela tela vermelha. A tela pérolas obteve a menor percentagem de incidência de radiação solar. A altura das plantas foi maior nas telas vermelha e pérola, e *C. frutescens*. O diâmetro e a matéria fresca do caule não diferiram estatisticamente entre os tratamentos. O comprimento da raiz foi maior nas telas vermelha e aluminet. A razão longitudinal e transversal da copa foi maior em *C. chinense* cultivada sob a tela de aluminet. O número de folhas e de matéria fresca foliar foi maior em *C. chinense* e em *C. frutescens*, mas a matéria seca foliar foi maior em *C. chinense*. O número de botões de flores e de flores, e a matéria seca das flores foi maior elevada em *C. chinense*. A matéria fresca de raiz e a matéria seca foi maior em *C. chinense*. A área foliar, duração da área foliar, relação de área foliar, área foliar específica e índice de colheita foram mais elevados em *C. frutescens* em comparação com *C. chinense* e a quanto a espessura foliar ocorreu o inverso. *A* e *gs* foram elevados em *C. frutescens* cultivada sob tela vermelha e *C. chinense* cultivada sob tela aluminet. *E* foi maior em *C. chinense* cultivada sob tela de aluminet e não diferiu entre os tratamentos aplicados a *C. frutescens*. *WUE* foi maior na tela vermelha e *iWUE* em *C. frutescens*.  $F_o$  e  $F_m$  foram maiores em *C. frutescens* cultivada sob tela vermelha.  $F_v/F_m$  foi menor em *C. chinense* cultivada sob

tela vermelha e SPAD foi maior na tela vermelha. LEF foi menor no controle. qL foi maior no controle e tela pérola e em *C. frutescens*. RdF foi menor em *C. chinense* cultivada sob tela vermelha.  $\Phi$ NPQ e NPQt foram maiores *C. chinense* cultivada sob tela vermelha. A tela aluminet em associação com *C. chinense* são recomendadas tendo em conta a compactação da altura, cobertura de vaso, maior número, forma e disposição dos frutos. Por outro lado, esta não obteve eficiência fotossintética eficiente. *C. frutescens* cultivadas sob tela vermelha obteve eficiência fotossintética eficiente. Por outro lado, a *C. chinense* cultivada sob tela vermelha teve uma resposta inversa, devido a cada espécie apresentar respostas diferentes sob o mesmo ambiente de cultivo.

Palavras-chave: Sombreamento. Produtividade. Eficiência fotossintética.

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## 1. GENERAL INTRODUCTION

The *Capsicum* genus has about thirty-seven species native to Central and South America, where Brazil is the center of wild species and Peru and Bolívia are the center of domesticated species (Van Zonneveld et al., 2015), such as *C. annum*, *C. baccatum*, *C. chinense*, *C. frutescens* and *C. pubescens* with more than 200 varieties (Hassan et al., 2019).

Peppers have extensive participation in the ornamental plant market due to their aesthetic or quality characteristics, such as variegated foliage, dwarf size, coloration, fruit shape and position, leaf density, plant architecture, and durability of their fruits and leaves (Neitzke et al., 2016; Fortunato et al., 2019; Costa et al., 2020). Besides these, the ability to grow as perennial potted plants and with limited amount of substrate are indispensable for ornamental purposes (Pinto et al., 2010; Morais et al., 2020).

Among the ornamental pepper plants, *C. chinense* cv. Biquinho and *C. frutescens* cv. Etna stand out because the former has a branched, erect stem, lanceolate, green and shiny leaves with well-defined veins. The flowers are purplish white and the fruit is a spherical to pyriform berry with a tapered tip (Isla Sementes, 2022). *C. frutescens* cv. Etna, on the other hand, has compact dark green foliage, and red, spicy fruits arranged in clusters (Isla Sementes, 2022). Its fruits can vary in shape, size, color, flavor, and chemical composition due to the growing environment, changes in physiology and biochemistry throughout cultivation and storage (Zimmer et al., 2012; Bhandari et al., 2013; Koeda et al., 2014).

On the other hand, the cultivation of pepper plants is compromised in conditions with high temperature and incidence of solar radiation, due to compromised production through photoinhibition, stomatal closure, reduced photosynthesis; and cessation of cell division, leaf expansion, and reproduction (Ilić & Fallik, 2017). As well as, this can compromise the quality of these pepper plants, through burns on leaves and fruits, and absence of flowers and fruits caused by abortion. These characteristics are essential in consumer purchasing decisions (Neitzke et al., 2016).

Colored shade nets are increasingly widespread and used in crop production for temperature and incidence solar radiation control in the growing environment. These nets contain in light scattering and reflection aid pigments that improve the yield, quality and phytochemical composition of plants and fruits (Carvalho et al., 2016; Zare et al., 2019; Gao et al., 2021), and these results are evident during pre and postharvest. In addition to these uses, these nets are used in crop protection against pests, insects, and physical damage, as they also have easy handling and low cost (Stamps, 2009; Selahle et al., 2014; Cruz, et al., 2020).

Initially, colored shade nets were white, black or Aluminet® type (Ganelevin, 2006; Li et al., 2017), due to the good results obtained in crop production, in the year 1996, colored shade nets such as red, yellow, blue and pearl (ChromatiNet®) were produced to disperse and change the wavelength and amount of light, thanks to a partnership between the Israel Agricultural Research Organization, Volcani Center and *Polysack Plastics Industries* (Ganelevin, 2006; Manja & Aoun, 2019).

These benefits of these nets come from the coloration as observed in the literature, for example, red and yellow nets contribute to plant growth, blue nets cause dwarfism, and pearl net increase fruit size, yield, and postharvest quality (Ilić & Fallik, 2017). In red bell pepper cultivation, red net decreases postharvest losses due to elevation of antioxidant activity and carotenoid content reducing fruit spoilage (Alkalai-Tuvia et al., 2014).

In ornamental plants, red and yellow net promoted vegetative growth rate and vigor, blue nets caused dwarfism, and pearl nets intensified branching in cut flowers (Nissim-Levi et al., 2008). Marigold and violet plants obtained higher vegetative growth, carotenoids, Brix°, chlorophyll content when cultivated with yellow net (Zare et al., 2019).

Furthermore, the shading percentage of the colored shade nets should be chose cautiously based on the expected morphological and physiological performances (Salazar-Canales et al., 2021; Oliveira et al., 2021), because these nets create an internal microclimate capable of altering gas exchange and chlorophyll fluorescence. Studying such changes is important because they allow for a deeper understanding of these photosynthetic processes through the interactions of the growing environment with the crop plants (Kuhlgert et al., 2016).

Bell pepper cultivated under colored shade net, for example, had reduced net photosynthesis, transpiration, stomatal conductance, water use efficiency, and internal CO<sub>2</sub>, but PSII efficiency was elevated (Díaz-Pérez, 2013). On the other hand, lemon trees cultivated under colored shade nets had reduced transpiration and increased water use efficiency, i. e., less water stress than unshaded lemon trees (Alarcon et al., 2006).

Given the above, understanding the effects of colored shade nets on the production and quality of *C. chinense* e *C. frutescens* is important because it provides the scientific basis for recommending these materials for cultivation in order to mitigate high temperature and solar radiation incidence. The general objective of this thesis was to (I) evaluate the production and quality and (II) photosynthetic efficiency of *C. chinense* and *C. frutescens* cultivated under colored shade nets.

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## **Paper 1: PRODUCTION AND QUALITY OF ORNAMENTAL PEPPERS CULTIVATED UNDER COLORED SHADE NETS\***

\* Approved to *Comunicata Scientia*.

**Abstract:** The cultivation of ornamental peppers in places with high temperature and incidence of solar radiation limits the production and quality of plants and fruits. The colored shade nets were introduced and adopted, because they reduce the temperature and intensity of solar radiation, as well as, low cost and simple to handle. The aimed was to evaluate the production and quality of *C. chinense* and *C. frutescens* cultivated under colored shade nets. The experiment was developed in the Floriculture Sector of the Agronomy Department of the Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil from February to August 2021 in entirely randomized design. *C. chinense* and *C. frutescens* were cultivated under red, pearl and aluminet shade nets with 35% shading and without net. At 150 days, production variables were quantified. The red net reduced the maximum temperature by at 4.1°C and the pearl and aluminet nets reduced the minimum temperature by 3°C. The maximum and minimum relative humidity was increased by 2.6 and 8.5%, respectively, by the red net. The pearl net obtained the lowest percentage of solar radiation incidence. Plant height was greater in the red and pearl nets, and *C. frutescens*. The diameter and stem fresh matter did not differ statistically between treatments. Root length was greater in the red and aluminet nets. The longitudinal and transverse canopy ratio was higher in *C. chinense* cultivated under the aluminet net. The number of leaves and leaf fresh matter was higher in pearl and aluminet net, and in *C. frutescens*, but leaf dry matter was higher in *C. chinense*. The number of flower buds and flowers, and flower buds dry matter was higher in *C. chinense*. The root fresh matter and dry matter was greater in *C. chinense*. The aluminet net in association with *C. chinense* are recommended considering the compactness of height, pot coverage, greater number, shape and arrangement of fruits.

**Key-words:** *Capsicum* spp., floriculture, potential ornamental, shading.

### **1. INTRODUCTION**

The *Capsicum* genus consists of vegetables are widely produced and consumed (Olatunji & Afolayan, 2019), due to they have multiple marketable aptitudes such as use in food (Antonious, 2017), pesticide (Valková et al., 2021), pharmaceutical (Olatunji & Afolayan, 2019), nanotechnology (Velsankar et al., 2021) and ornamental (Lee et al., 2016) industries.

In recent years, the growth of the ornamental sector has occurred due to consumers being attracted to various species of the *Capsicum* genus due to the following characteristics that

confer ornamental quality such as compact architecture; number, shape and position of fruits; coloration, shape and density of leaves and fruits, ease of cultivation, durability of leaves and fruits and continuous fruit production (Neitzke et al., 2016)

Among the species cultivated as ornamental pepper, *C. chinense* and *C. frutescens* gain notoriety, due to *C. chinense* having height between 50 to 100 cm, oval leaves and slightly wrinkled surface, white flowers and arranged in up 3 per node and elongated fruits with 5 to 7 cm long with 2.5 to 3.0 cm in diameter and coloration between light green to orange (Sarwa et al., 2012). *C. frutescens* has a height of up to 1.2 m, smooth and simple leaves, while to yellowish flowers and small, pungent, erect and slightly pointed fruits (Jaiswal et al., 2021).

The cultivation of ornamental pepper plants in locations with high temperature and incidence of solar radiation limits the production and quality of plants and fruits (Lekala et al., 2019), because CO<sub>2</sub> assimilation of most C<sub>3</sub> species saturates at low irradiance (600-900  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and excess of solar radiation causes heat stress, stomata closure, and reduced net photosynthesis (Ilić & Fallik, 2017). In addition, temperatures above 35 °C impair cell division, leaf expansion and the abortion of buds, flowers and fruits; as well as, burns on leaves and fruits (Flashman et al., 2015), compromising their availability and commercialization in the market.

Among the available technologies in plant production, the colored shade nets have been introduced and adopted because they reduce the temperature and intensity of solar radiation, as well as the attacks of pests and strong winds. Furthermore, they are low cost and simple to handle (Angmo et al., 2022). These nets transmit modified light spectrum from the sunlight that touches their wires, which, is spread over their canopy increasing production, quality and post-harvest (Ilić & Fallik, 2017; Mohawesh et al., 2022; Zha et al, 2022) through positive morphological and physiological responses, as reported in peppers grown under pearl net (Ilić et al, 2017), tomato grown under pearl and red net (Ilić et al., 2015), fresh herbs grown under red and pearl net (Buthelezi et al., 2016), lettuce grown under pearl and black net (Ntsoane et al., 2015), marigold and violet in red and yellow net (Zhare et al., 2019).

Linked to this, the choice of shading percentage should be made carefully, because excessive shading compromises the growth and development of crops, as it does not allow them to maintain effective photosynthesis during cultivation and subsequently compromises the production and quality of the final product (Martinez-Luscher et al., 2017). In view of the above, the use of colored shade nets in ornamental pepper plants needs to be studied to identify materials that reduce temperature and incidence of solar radiation conferring production and

quality throughout cultivation. The aimed was to evaluate the production and quality of *C. chinense* and *C. frutescens* cultivated under colored shade nets.

## 2. MATERIAL AND METHODS

### *Experimental Design*

The experiment was conducted in a 2x4 factorial scheme (varieties x colored shade nets), resulting in 8 treatments distributed in an entirely randomized design with five repetitions.

### *Localization and Experimental Conduct*

The experiment was developed in the Floriculture Sector of the Agronomy Department of the Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil from February to August 2021.

According to the Köppen climate classification, mapped in Brazil by Alvares et al. (2013), the climate in the region varies between the Cwa and Cwb types. The climate types correspond to Cwa: tropical humid zone with dry winter and with hot summer; and Cwb: tropical humid zone with dry winter and with temperate summer.

Seedlings of *C. chinense* cv. Biquinho Iracema and *C. frutescens* cv. Etna were purchased from Isla Sementes<sup>®</sup> (São Paulo, Brazil). These were grown in rigid polypropylene trays filled with Tropstrato<sup>®</sup> commercial substrate in a greenhouse, and when the seedlings presented two to three pairs of true leaves, they were transplanted into number 16 pots filled with the same substrate to roofs covered with red, pearl, and aluminet shade nets with 35% shading, purchased from Ginegar (São Paulo, Brazil) and without net.

These wooden structures had of 0.50x 0.50 x 0.70 m (width x length x height) arranged in the open air 2.0 m apart in the rows and 3.0 m between rows so that there was no shading from one to the other. The ornamental peppers were fertilized with 2 g of NPK 10-10-10 fertilizer, once a week, irrigation until the substrate reached field capacity and weeds were removed as necessary.

### *Environment data*

Maximum and minimum temperature and relative humidity were recorded every 1 min in each shed using an AKSO AK-174 datalogger with a thermometer and hygrometer. Temperature was expressed in °C and relative humidity in %. Wavelength and solar radiation intensity intercepted by the colored nets were quantified by optical absorption using a spectrometer model USB4000, Ocean Optics. The spectra were processed using SpectraSuite

software. The wavelength was expressed in nanometers (nm) and the intensity in percentage (%).

#### *Production and quality variables*

The following variables were quantified at 150 days after sowing:

Plant height: was measured from the lower base of the pot to the last fully expanded leaf with the aid of a tape measure and the results were expressed in centimeters (cm).

Stem diameter: was determined with the aid of a pachymeter and the results were expressed millimeters (mm).

Root length: the plants were removed from the pots and the substrate adhered to the roots was removed with the aid of weak jets of water. The roots were dried and the measurements taken with the aid of a ruler, starting at the neck of the plant and the results were expressed in cm.

Longitudinal and transverse canopy ratio: was the quotient between the longitudinal and transverse canopy diameters. The results were expressed in millimeters (mm).

Number of leaves, flower buds, flowers and fruits: were obtained at the end of the experiment based on their respective counts.

Production: was obtained by weighing the total number of fruits on each plant and expressed in grams (g).

Fruits length and diameter: four sampled fruits from each batch for spectral collection and reference analyses were measured, with the length being determined in cm. The mean of three measurements performed with the aid of a caliper in the peduncle region, central and at the apex of the fruit, was determined, and the diameter was obtained in mm.

Stem, leaves, flower buds, flowers and root fresh matter: a cut close to the neck of the plant was made with the objective of separating the aerial part from the roots. The stem, leaves, flowers buds, flowers and were separated. The root system was carefully removed from the pot and crushed manually with the aid of weak water jets. Then they were weighed. The results were obtained from weighing on a semi-analytical balance (Mark S2) with precision of  $\pm 0.005$ g and were expressed in percentage (%).

Stem, leaves, flowers, buds and root dry matter: were placed, separately, in 5kg Kraft paper bags, and placed in the oven at 70 °C until they reached constant weight. The results were expressed in g.

### Statistical Analysis

The data obtained were subjected to normality (Shapiro-Wilk) and homogeneity (Bartlett) test of variances, analysis of variance (ANOVA) and test of means (Tukey at 5%) were performed in programming language R in version 3.6.3 (R Core Team, 2021). The graphs were made in the software Sigma Plot.

### 3. RESULTS AND DISCUSSIONS

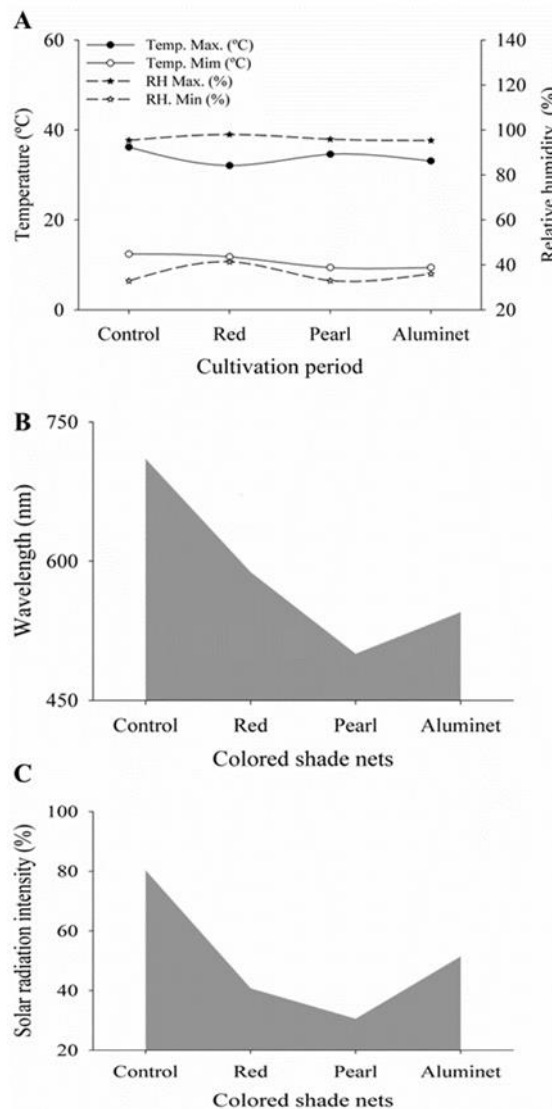


Figure 1. Temperature and relative humidity (A), wavelength (B) and solar radiation intensity (C) of the control, red, pearl and aluminet shade nets.

The temperature was reduced with colored shade nets, the red shade net being the one that promoted the most significant reduction of the maximum temperature, at 4.1°C and the pearl and aluminet shade nets the ones that promoted the most significant reduction of the

minimum temperature at 3°C. Concerning the control, the maximum and minimum relative humidity increased with red shade net by 2.6 and 8.5%, respectively. The wavelength was concentrated between blue and far red (500-710 nm), and the intensity of solar radiation had an amplitude of 30.5 to 80.2% between treatments (Figure 1).

The optimal temperature for developing *C. chinense* and *C. frutescens* is around 21 to 33 °C (Lekala et al., 2019; Angmo et al., 2022). At temperatures higher than 35 °C, there is a reduction in cell division, leaf expansion, number of fruits, flower tip rot, and fruit burn (Mditshwa et al., 2017; Ilić & Fallik, 2017). Shading nets such as colored ones reduce the temperature by 1 to 5 °C, depending on shading level, coloring, and growing location (Angmo et al., 2022). In this study, the control showed plants with leaf burns due to the high monthly maximum temperature of 36.1°C. Although the temperature surpasses the optimal range of development of ornamental pepper (>33.1°C), the plants cultivated under the pearl and aluminet shade nets did not show burns on the leaves.

Colored shade nets can raise the relative humidity from 3.2 to 12.9% (Mditshwa et al., 2019). In this study, the interval between the colored shade nets was lower, ranging from 0.1 in control to 8.5% in red shade net. This variation occurs as a function of the interaction between temperature, relative humidity, and intensity of solar radiation (Zhou et al., 2018).

C3 plants, such as pepper plants, need low irradiance between 600-900  $\mu\text{mol m}^{-2}\text{s}^{-1}$  and this corresponds to 40% incidence of solar radiation throughout the day (Flaishman et al., 2015). Above that, as presented by the control, can cause photoinhibition, heat stress, and stomatal closure resulting in decreased photosynthesis and carbohydrate distribution, affecting plant growth and fruit formation (Flaishman et al., 2015; Ilić & Fallik, 2017). On the other hand, the red and pearl shade nets presented the ideal amount of 40.7 and 31.5% of incidence of solar radiation, respectively, for developing ornamental pepper, optimizing agronomic performance (Mditshwa et al., 2019).

The fraction of light passed through the holes of the colored shade nets has its quality unchanged, but the fraction of light reached by the wires is spectrally modified (Zare et al., 2019; Cruz et al., 2020). The red shade net transmits in red and far-red, while the pearl transmits in blue, yellow, green, red, and infrared (Ilić & Fallik, 2017).

The plant height was greater in the red and pearl nets compared to aluminet, but did not differ statistically from the control. Also, *C. frutescens* obtained greater height compared to *C. chinense* (Figure 2 A and B). Stem diameter did not differ statistically between treatments ( $x=11.74 \pm 1.55$  mm). Root length was greater in red and aluminet nets compared to the other

treatments (Figure 2 C). The longitudinal and transverse canopy ratio was higher in *C. chinense* grown under aluminet net compared to the control (Figure 2 D).

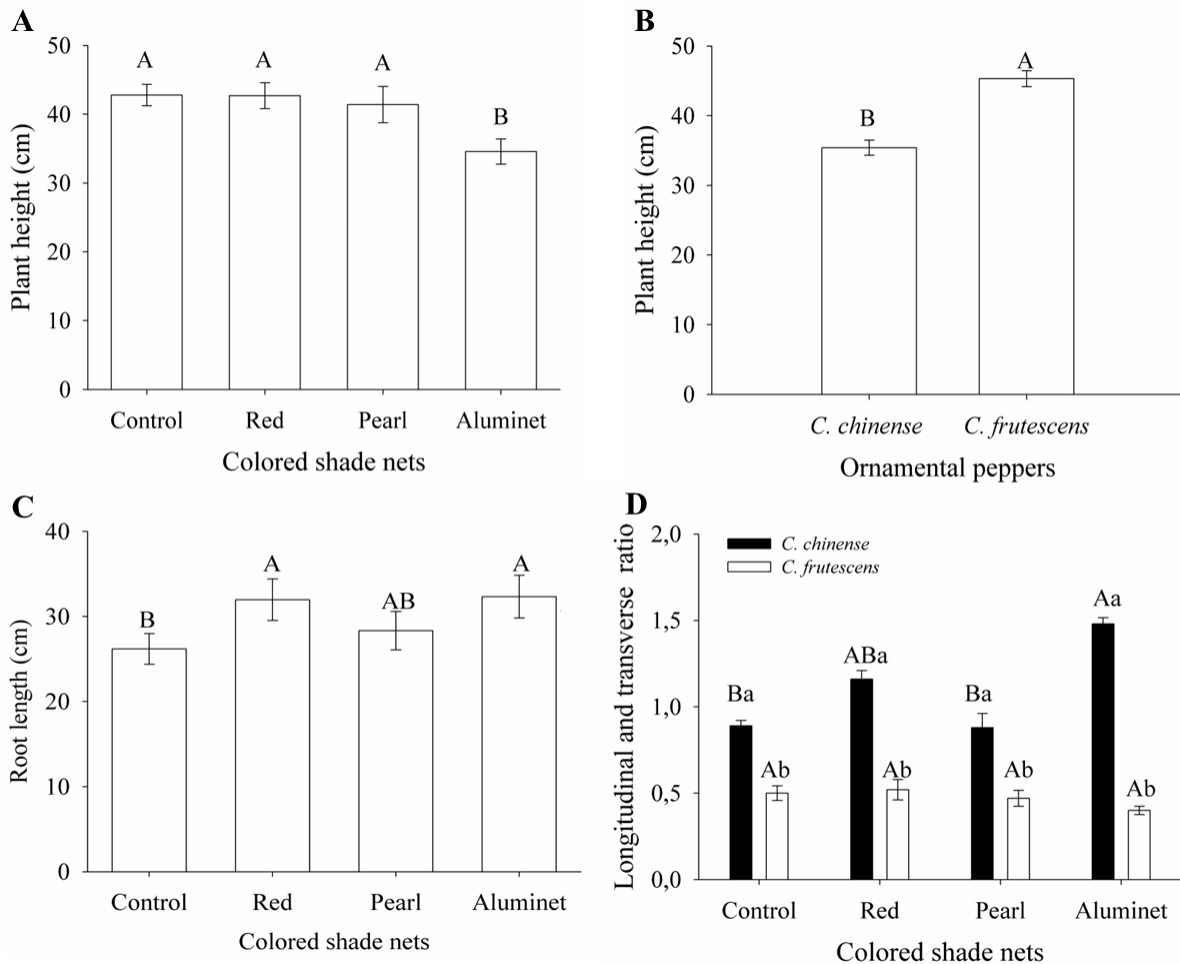


Figure 2. Plant height (A and B), root length (C) and longitudinal and transverse canopy ratio (D) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \*Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

Plant height was greater in red and pearl shade nets compared to aluminet, due to the balance in the ratio of red light (R): far red (FR), due to the light reaching the wires of these nets being filtered and transmitted as red light in greater proportion to far red, reducing plant compaction (Silva et al., 2016; Ilić & Fallik, 2017). This occurs, because stem elongation is associated with phytochrome being active by red light and deactivated by far red (Díaz-Pérez & John, 2019; Johnson et al., 2020). Plant height was higher in *C. frutescens*, because, morphologically, this pepper has greater height than *C. chinense* (Olatunji & Afolayan, 2018). In contrast, the height obtained in this study is shorter than that reported by Sarwa et al. (2012)

and Jaiswal et al. (2021), thus, these compact ornamental peppers are easily accepted by consumers due to the ease of growing them in pots, ease of displaying them in places with limited space, and durability compared to the medium and tall sizes intended for landscaping (Neitzke et al., 2016).

Generally, plants grown in full sun have their height reduced, due to the light temperatures and intensity of solar radiation causing damage to the photosynthetic organs causing the photoinhibition, closure of stomata, reduction of photosynthesis and distribution of carbohydrates for investment in growth (Silva et al., 2016; Ilić & Fallik, 2017). On the other hand, in the literature, there are reports of species in which the plant height in full sun and under colored shade nets did not differ as obtained in this study (Souza et al., 2014; Silva et al., 2016).

This occurs in species that are adapted to warm climate and cultivation in full sun as the pepper (Souza et al., 2014), however, these climatic conditions may affect the visual characteristics of the plant and the fruits causing them to burn as observed in this study in the control treatment that obtained a temperature of 36.2 °C and solar radiation intensity of 80.2%, and consequently, consumer repulsion (Souza et al., 2014). This repulsion is explained by the fact that the burns affect the surface texture, brightness and coloration of the leaves and fruits, which are characteristics observed in the purchase decision making of ornamental pepper plants (Neitzke et al., 2016).

Plants grown in full sun obtain a greater stem diameter in comparison with shaded plants, which have thin stems due to stretching (Silva et al., 2016). However, in this study, plants under all shade nets did not show such behavior because 35% shading did not compromise light interception as much as nets with shading higher than > 40% as observed in Díaz-Pérez & John (2019) and Souza et al. (2014).

On the other hand, the greatest root length was observed in both ornamental peppers shaded by the red and aluminet nets. In red net, the ratio of red light (R): far red (FR) was higher, consequently, phytochrome B (PHYB) is activated and induces root formation via auxin signaling (Chen et al., 2016; Rosado et al., 2021). The aluminet net, on the other hand, has lower red light (R): far red (FR) ratio, i.e., there is no PHYB actuation in root formation and growth (Rosado et al., 2021). On the other hand, the canopy of *C. frutescens* had the highest number of leaves and *C. chinense* had the highest longitudinal and transverse canopy ratio, contributing to light uptake under the canopy, production of photoassimilates and investment in root growth (Ribeiro et al., 2018).

The longitudinal and transverse canopy ration allows the evaluation of the equilibrium of the canopy of potted peppers in ornamental industry, which should have good coverage of the pot, swelling and firm stems with good support (Cruz et al., 2017). The longitudinal and transverse canopy ratio was higher in *C. chinense* cultivated on the aluminet shade net, because the oval leaves, although spaced apart, had greater pot coverage in the longitudinal direction compared to the other treatments (Sarwa et al., 2012). In addition, the aluminet net provided greater root length, ensuring effective support of the plant without tipping (Silva et al., 2016; Ribeiro et al., 2018).

The number of leaves was higher in the pearl and aluminet nets compared to the other treatments. Also, *C. frutescens* had more leaves compared to *C. chinense* (Figure 3 A and B). The number of flower buds and flowers was higher in *C. chinense* compared to *C. frutescens* (Figure 3 C and D).

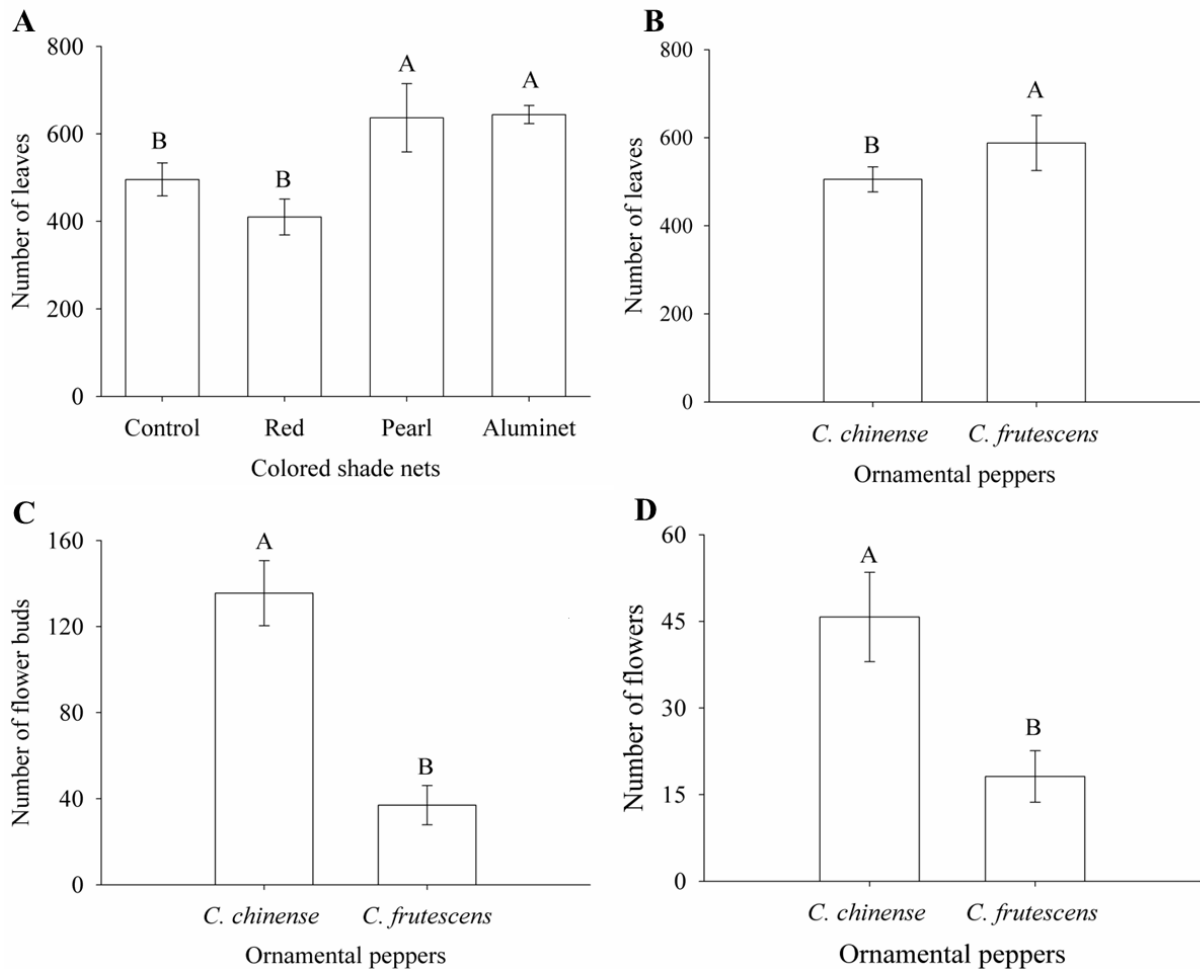


Figure 3. Number of leaves (A and B), flower buds (C) and flowers (D) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \*Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

The leaf fresh and stem matter was higher in *C. frutescens* compared to *C. chinense* (Figure 4 A and D). Root fresh matter was higher in *C. chinense* compared to *C. frutescens* (Figure 4 F). The stem fresh matter did not differ statistically among the treatments with the nets compared to the control (Figure 4 C). Leaf, stem, bud, and root dry matter was greater in *C. chinense* compared to *C. frutescens* (Figure 4 B, E, G and H).

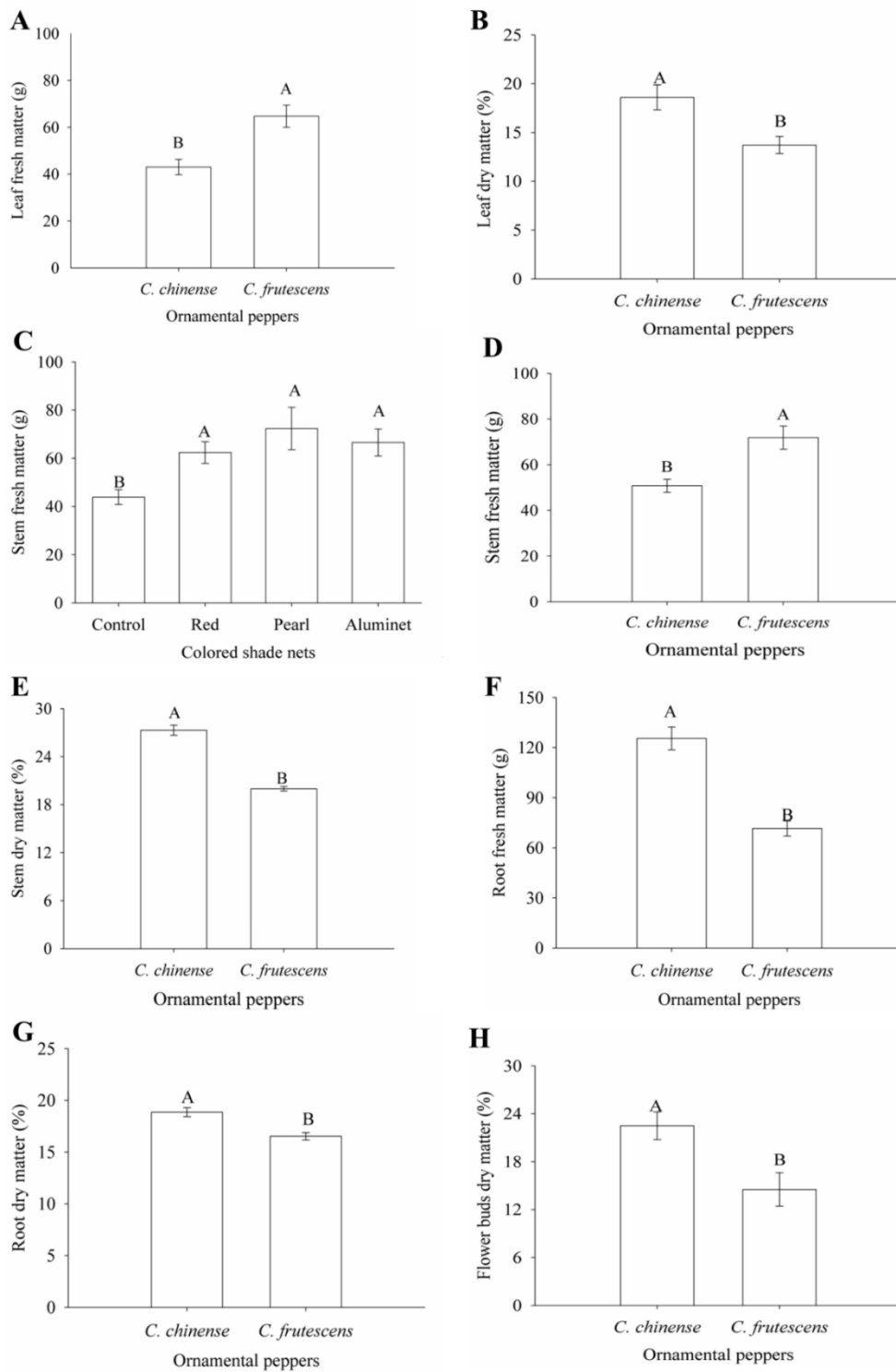


Figure 4. Leaf fresh (A), leaf dry (B), stem fresh (C and D), stem dry (E), root fresh (F), root dry (G) and flower buds dry matter (H) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \*Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

The number of leaves was higher in the pearl and aluminet nets, because plants shaded by nets tend to produce more leaves as a phenotypic adaptation to the reduction of light intensity as an alternative to the improvement of the capture of incident light in the canopy (Mathuer et al., 2018). Otherwise, ATP production would be insufficient for carbon fixation and biosynthesis, due to low ATPase activity, and Rubisco, thus reducing growth, development, and fruit formation (Shao et al., 2014; Mathuer et al., 2018).

The number of leaves and leaf fresh matter was higher in *C. frutescens*, because, it has a dense canopy with a greater number of leaves (Mditshwa et al., 2019). The dense canopy along with the coloration and brightness of this ornamental pepper allows contrast with the red of the fruits, which is highly appreciated in the ornamental sphere by consumers (Neitzke et al., 2016). Leaf dry matter was higher in *C. chinense* because the leaf area of this pepper is larger than that of *C. frutescens*, and the greater longitudinal and transverse canopy ratio promoted greater uptake of solar radiation, which increased the production of photoassimilates, which were converted into greater dry matter (Gao et al., 2021).

*C. chinense*, morphologically, has flower buds and flowers covered by leaves and the shading caused by the nets reduced the temperature (<35°C) promoting less buds and flowers abortion via heat stress (Mditshwa et al., 2017 and 2019; Ilić & Fallik, 2017). As well as, higher flower buds dry matter, due to lower of incidence of bud abortion and reduction in temperature (Ilić & Fallik, 2017).

The fresh matter of flowers and buds did not differ statistically between treatments, but was greater in treatment with pearl (x= 1.52 g) and aluminet (x=1.32 g) shade nets. The red shade net transmits the red and far-red spectrums, while the pearl net transmits in the blue, yellow, green, red and infrared spectrums and aluminet net absorbs in all spectra but does not transmit in any spectrum (Ilić & Fallik, 2017). In view of this, pearl and aluminet shade nets have lower ratio of the red light (R) to far red (FR) compared to red net (Mahmood et al., 2018; Zhou et al., 2018), thus, photoreversibility of phytochrome and higher flowering and flower bud formation occurred (Ilić & Fallik, 2017; Mditshwa et al., 2019).

*C. chinense* obtained greater longitudinal and transverse canopy ratio in all treatments compared to *C. frutescens*, but the latter showed shorter root length (x= 29.1 cm), there being the need to balance the area and roots, it showed a greater number of lateral roots to support the

weight of the canopy and consequently, greater fresh and dry root matter (Silva et al., 2016; Ribeiro et al., 2018).

The fresh and dry matter of the stem did not differ in the red, pearl and aluminet shade nets because these all plants cultivated under nets had greater height and root length in view of this, the dense stem was a phenotypic strategy to balance the aerial part with roots (Souza et al., 2014). As well as, *C. chinense* obtained greater dry matter of the stem, due to the greater longitudinal and transversal relationship of the canopy, being necessary, the balance between the support of the canopy and roots.

The number of fruits was higher in *C. chinense* cultivated under the aluminet net compared the other treatments (Figure 5 A). Production was higher in *C. chinense* em comparasion with *C. frutescens* (Figure 5 B). *C. frutescens* presented fruits with greater length and smaller diameter than *C. chinense*, which were not altered by the colored shade nets (Figure 5 C e D).

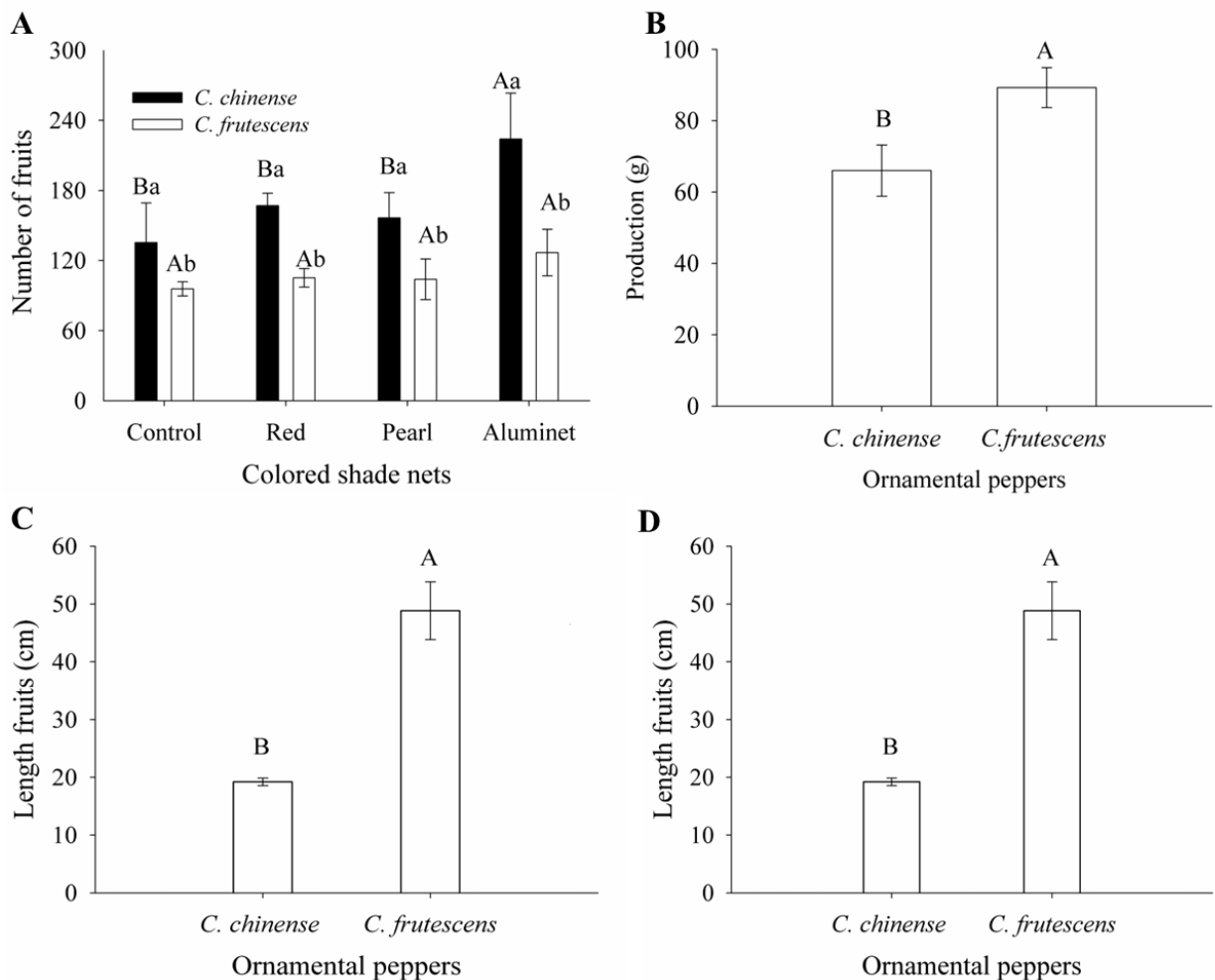


Figure 5. Number (A), production (B), length (C), and diameter fruits of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \*Capital letters refer to colored shade nets, and lowercase

letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

Aluminet net transmit smaller red-light (Mahmood et al., 2018; Zhou et al., 2018), promoting the photoreversibility of phytochrome and flowering swimsuits (Ilić & Fallik, 2017; Mditshwa et al., 2019), which led to higher fruit production. Despite *C. chinense* showed higher longitudinal and transverse canopy ratio, a more significant number of fruits occurred due to greater light penetration in the canopy allowing the direction of photoassimilates to the drains (Mditshwa et al., 2019). Ornamentally, consumers prefer pepper plants with a larger number of fruits, due to the contrast of these with the foliage, as well as for consumption or preparation of by-products, such as jams and jellies (Neitzke et al., 2016).

On the other hand, *C. frutescens* obtained higher fruit production, this may have occurred, due to the lower number of flowers of this pepper plant were not aborted, due to the temperature reduction obtained by the screens, these being reverted also in few fruits, which, obtained greater use in the photoassimilates distribution and consequently, higher weight gain (Mditshwa et al., 2017 and 2019; Ilić & Fallik, 2017).

Morphologically, the fruits of *C. chinense* have the shape of spherical berries, and the fruits of *C. frutescens* have an elongated shape, corroborating the result found (Nascimento et al., 2019). Spherical fruits like *C. chinense* are preferred by consumers for ornamentation of dishes and low pungency (Nascimento et al., 2019).

#### **4. CONCLUSION**

The aluminet net in association with *C. chinense* are recommended considering the compactness of height, pot coverage, greater number, shape and arrangement of fruits.

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#### **CONFLICT OF INTEREST**

The authors have no conflict of interest.

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## **Paper 2: PHOTOSYNTHETIC EFFICIENCY OF ORNAMENTAL PEPPERS CULTIVATED UNDER COLORED SHADE NETS**

**Abstract:** *Capsicum chinense* and *C. frutescens* exposed to high temperature and incidence of solar radiation have their photosynthetic efficiency compromised. Such conditions, reduce the cultivation schedule and its availability in the market. The colored shade nets were developed with purpose of decreasing the impact of high temperature and incidence of solar radiation on the plants. Therefore, the aimed to photosynthetic efficiency of *C. chinense* and *C. frutescens* cultivated under colored shade nets. The experiment was developed from February to August 2021 in entirely randomized design. *C. chinense* and *C. frutescens* were cultivated under red, pearl and aluminet with 35% shading by 150 days and without net. Leaf area, leaf area duration, leaf area ratio, specific leaf area and harvest index were higher in *C. frutescens* in comparison to *C. chinense* and leaf thickness opposite occurred.  $A$  and  $g_s$  were higher in *C. frutescens* cultivated under red net and *C. chinense* cultivated under aluminet net.  $E$  was higher in *C. chinense* cultivated under aluminet net and did not differ between the treatments applied to *C. frutescens*.  $WUE$  was higher in the red net and  $iWUE$  was higher in *C. frutescens*.  $F_o$  and  $F_m$  were higher in *C. frutescens* cultivated under red net.  $F_v/F_m$  was lower in *C. chinense* cultivated under red net and SPAD was higher in red net. LEF was lower in control.  $qL$  fraction was higher in control and pearl net and in *C. frutescens*.  $RdF$  was lower in *C. chinense* cultivated under red net.  $\Phi NPQ$  and  $NPQt$  were higher in *C. chinense* cultivated under red net. The shading provided by colored shade nets promoted morphological changes on the photosynthetic surface of *C. frutescens*. *C. frutescens* cultivated under red net obtained a higher photosynthetic efficiency. On the other hand, *C. chinense* cultivated under red net had an inverse reponse, due to each specie having different responses under the same growing environment.

**Key-words:** *C. chinense*; *C. frutescens*; gas exchanges; photosystem II; shading.

### **1. INTRODUCTION**

*Capsicum chinense* and *C. frutescens* are widely cultivated as ornamental potted plants (Peñuela et al., 2020; Valková et al., 2021), due to the diversity of their phenotic characteristics, mainly those related to the architecture, coloration and positioning of fruits and flowers (Zhang et al., 2019). Besides ornamental appeal, peppers plants have other aptitudes, such as their use as medicinal in the treatment of gastrointestinal (Xiang et al., 2021), respiratory (Dumitrache

et al., 2021), chronic (Shi et al., 2019) and depression (Xia et al., 2021) diseases. As well as pesticides in agriculture (Valková et al., 2021); in the food industry with the production of sweets and jellies; and in the cosmetics industry as pigments (Lee et al., 2016).

Pepper plants are C3 plants, which, have optimal growth at temperatures between 21 to 33°C (Lekala et al., 2019; Angmo et al., 2022). On the other hand, above 35°C, these showed reduce cell division and leaf area, burning and abortion of fruits, flowers and flower buds (Ilić & Fallik, 2017). Coupled with this, excesso incidente solar radiation causes heat stress, closure of stomata, and reduced photosynthesis through photoinhibition (Ilić & Fallik, 2017).

All these factors together compromise photosynthetic efficiency, i. e. conversion of light energy into usable biomass, reducing the production and availability of these plants in the market (Quin et al., 2016). This is because C3 plants have high complexity in the scope of photosynthetic and respiratory efficiency (Bräutigam & Gowik, 2016). This is, the solubility of CO<sub>2</sub> in water in the presence of heat is higher than that of O<sub>2</sub> resulting in lower CO<sub>2</sub> /O<sub>2</sub> ratio in the cell, decreasing the concentration of CO<sub>2</sub> in the carboxylation site of Rubisco, which favors oxygenase activity and consequently, photorespiration. Furthermore, increased heat affects the kinetic properties of Rubisco, stimulating oxygenase activity at the expense of carboxylase activity (Betti et al., 2016; Walker et al., 2016).

Therefore, within crop production, technologies are explored with the objective of reducing the impacts caused by temperature and solar radiation on photosynthetic efficiency in locations and seasons that are not favorable for plant development (Proietti et al., 2022). Among these, colored shade nets are designed in different colors, patterns, and shading density with the purpose of protecting plants against abiotic and biotic stresses such as high temperatures, solar radiation incidence, hail, wind, and pests through their physical barrier, microclimate modification, and spectral composition (Milenkovic et al., 2019).

The spectral composition of the sunlight filtered by the colored shade nets and received by plants is modified based on the ultraviolet, visible, or far-red spectral regions due to passage of sunlight through the net wires (Kotilainen et al., 2018). The incident radiation on the plants is reduced by means of the shading density of the nets based on the interweaving of the polyethylene or propylene wires (Kotilainen et al., 2018). It is necessary that the coloration and shading are chosen in such a way that they meet the expected objective (Kotilainen et al., 2018).

This is because coloration in association with shading modify chlorophyll fluorescence, growth, development, productivity and quality of vegetables, fruits and ornamental plants, as reported in several studies (Zhou et al., 2018; Mupambi et al., 2018), configuring efficient

against temperature fluctuations and solar radiation incidence throughout the crop (Mupambi et al., 2018; Manja & Aoun, 2019).

On the other hand, in the literature there is no information about how the photosynthetic efficiency of ornamental peppers is affected by the colored shade nets, being necessary to establish which changes occur by the coloration and shading imposed and then, indicate an efficient material for their cultivation. The aimed to evaluate photosynthetic efficiency of *C. chinense* and *C. frutescens* cultivated under colored shade nets.

## 2. MATERIAL AND METHODS

### *Experimental design*

The experiment was conducted in a 2x4 factorial scheme (varieties x colored shade nets), resulting in 8 treatments distributed in an entirely randomized design with five repetitions. The treatments were: control (no nets), red, pearl and aluminet shade nets.

### *Location and experimental conduct*

The experiment was developed in the Floriculture Sector, Agronomy, Department, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil in the months of February to August 2021. Seedlings of *C. chinense* cv. Biquinho Iracema and *C. frutescens* cv. Etna were purchased from Isla Sementes<sup>®</sup> (São Paulo, Brazil). These were grown in rigid polypropylene trays filled with Tropstrato<sup>®</sup> commercial substrate in a greenhouse, and when the seedlings presented two to three pairs of true leaves, they were transplanted into number 16 pots filled with the same substrate to roofs covered with red, pearl, and aluminet shade nets with 35% shading, purchased from Ginegar (São Paulo, Brazil) and without net.

These wooden structures had of 0.50x 0.50 x 0.70 m (width x length x height) arranged in the open air 2.0 m apart in the rows and 3.0 m between rows so that there was no shading from one to the other. The ornamental peppers were fertilized with 2 g of NPK 10-10-10 fertilizer, once a week, irrigation until the substrate reached field capacity and weeds were removed as necessary.

### *Environment data*

Presented in paper 1.

The following variables were quantified at 150 days after sowing:

### *Growth analysis*

Leaf area: was measured by the non-destructive method using a leaf area over time meter model AM350 and the results expressed in  $\text{cm}^2$ .

Leaf area duration: was measured by means of integral of leaf area over time and the results expressed in  $\text{cm}^2 \text{ dia}^{-1}$ .

Leaf area ratio: was measured by the ratio of leaf area index by leaf dry mass and the results expressed in  $\text{dm}^2 \text{ g}^{-1}$ .

Specific leaf area: was measured by the ratio of leaf area to leaf dry mass and the results expressed in  $\text{dm}^2 \text{ g}^{-1}$ .

Harvest index: was measured by the ratio between the dry mass of the fruits by the total dry mass of the plant.

#### *Gas exchange*

Gas exchange was measured infrared gas analyzer (IRGA – model LCPro, ADC BioScientific Ltd.), between 8 and 10 h. The net assimilation of  $\text{CO}_2$  ( $A = \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), stomatal conductance ( $g_s = \text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and transpiration ( $E = \text{mmol de H}_2\text{O m}^{-2} \text{ s}^{-1}$ ). Water use efficiency ( $WUE$ ) was calculated by dividing net assimilation of  $\text{CO}_2$  ( $A$ ) by transpiration ( $E$ ), and intrinsic water use efficiency ( $iWUE$ ) was calculated by dividing net assimilation of  $\text{CO}_2$  ( $A$ ) by stomatal conductance ( $g_s$ ).

#### *PhotosynQ measurements*

Spectroscopic measurements were performed on plant leaves using MultispeQ device (Ben-Jabeur et al., 2021), which is connected to the PhotosynQ platform00 (<http://www.photosynq.org>). The measurements were used to estimate leaf thickness, initial chlorophyll ( $F_0$ ), maximum chlorophyll ( $F_m$ ), relative chlorophyll content (SPAD), maximum quantum ( $F_v/F_m$ ), linear electron flux (LEF), PSII open centers fraction (qL), chlorophyll fluorescence rate decrease (RFd), non-photochemical extinction coefficient ( $\phi\text{NPQ}$ ), and non-photochemical dissipation of absorbed light energy (NPQ<sub>i</sub>).

#### *Statistical analysis*

The data obtained were subjected to normality (Shapiro-Wilk) and homogeneity (Bartlett) tests of variances, analysis of variance (ANOVA) and test of means (Tukey a 5% probability) were performed in the statistical software R version 3.6.3 (R Core Team, 2021). The graphs were prepared with Sigma Plot software.

### 3. RESULTS AND DISCUSSIONS

Leaf area, leaf area duration and leaf thickness did not differ between the colored shade nets treatments compared to control. (Figure 1 A, C and E). On the other hand, leaf area and leaf area duration were higher in *C. frutescens* compared to *C. chinense* (Figure 1 B and D), and for leaf thickness the opposite occurred (Figure 1 F).

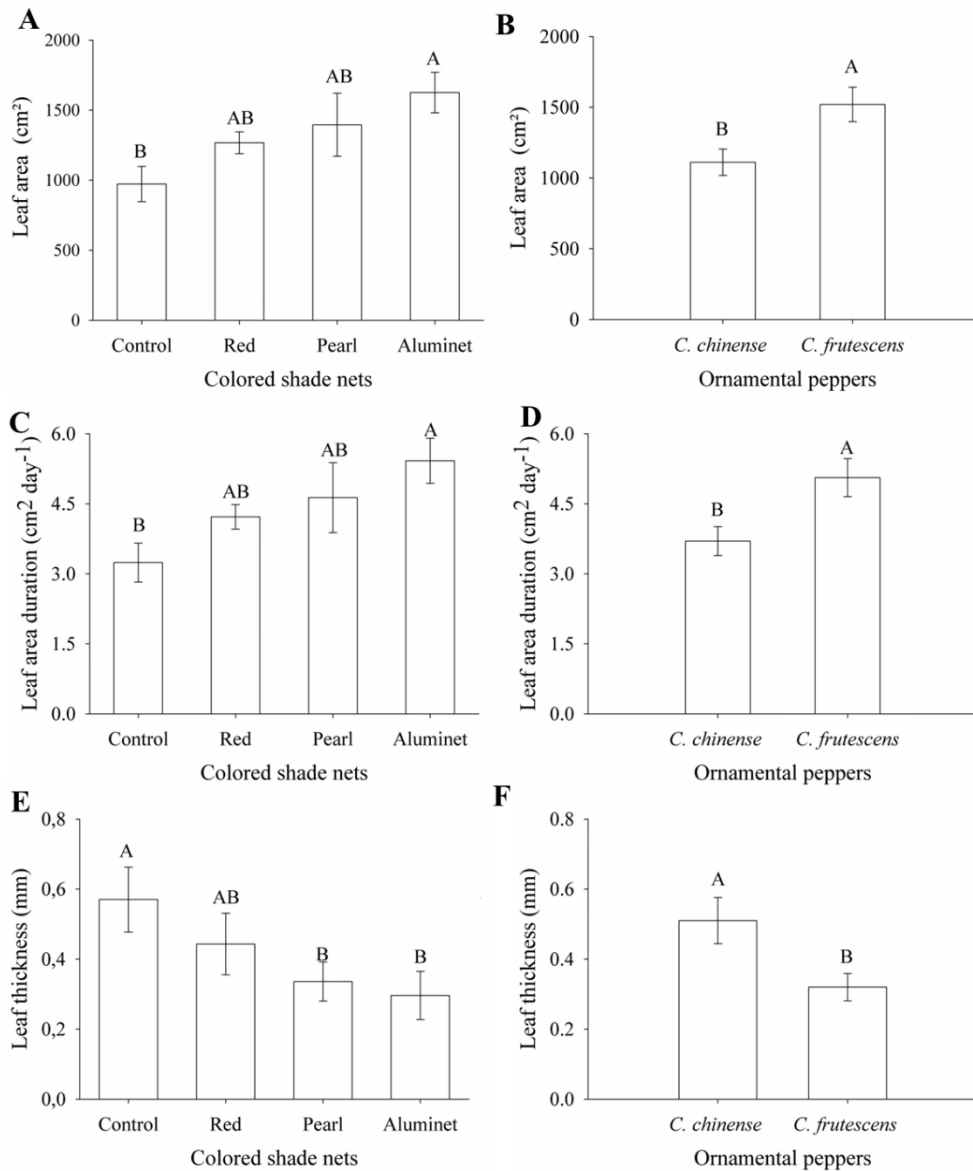


Figure 1. Leaf area (A and B), leaf area duration (C and D) and leaf thickness (E and F) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \*Different capital letters differ from each other by the Tukey test at 5%.

Colored shade nets did not differ in terms of leaf area, leaf area duration and leaf thickness, because they presented the same proportion of shading, temperature and humidity conditions as reported in paper 1. However, among the results presented, it is interesting to note

that the control treatment showed lower leaf area, leaf area duration and higher leaf thickness as a phenotypic adaptation to the conditions of high temperature and solar radiation even though it is a sun plant, enabling the use of colored shade nets as a strategy to reduce these (Martins et al., 2009).

An inverse condition was obtained in the aluminet net, due to the fact that plants under shading present adaptive strategies, which, allows optimization of light uptake in order to raise photosynthetic efficiency as observed in *C. frutescens* (Alexandre et al., 2018; Ilić et al., 2018), due to this being dependent on the dimensions of the photosynthesizing system (LA and LAD).

Thin leaves with larger area favor greater CO<sub>2</sub> diffusion por unidade de área, because the distance between stomata is reduced, due to thickness of the palisade and lacunate parenchyma, this being proven by the larger specific leaf area presented by *C. frutescens*, which allows the maximization of carbon gain unit leaf mass under shaded conditions (Gobbi et al., 2011). Furthermore, the shorter distance between the palisade and lacunate parenchyma promotes greater absorption of diffuse light from the shaded environment, as well as internal scattering between the chlorophylls of the chloroplasts (Gobbi et al., 2011). Coupled with this, less thickness leaves allow greater light diffusion to the lower leaves and thus increase photosynthetic efficiency, since these have light limitation due to self-shading (Gobbi et al., 2011). This type of phenotypic plasticity is observed in colored shade nets with shading starting at 30% (Ilić et al., 2018; Zare et al., 2019) such as those used in this study.

Moreover, these phenotypic strategies vary according to the species, in view, that in *C. chinense* obtained smaller leaf area, and greater leaf thickness (Ilić et al., 2018). Given this, it becomes important to know the development of leaf structure under the cultivation with colored shade nets (Martins et al., 2009).

Colored shade nets did not alter the leaf area ratio, specific leaf area and harvest index. However, they were greater in *C. frutescens* compared to *C. chinense* (Figure 2 A-C).

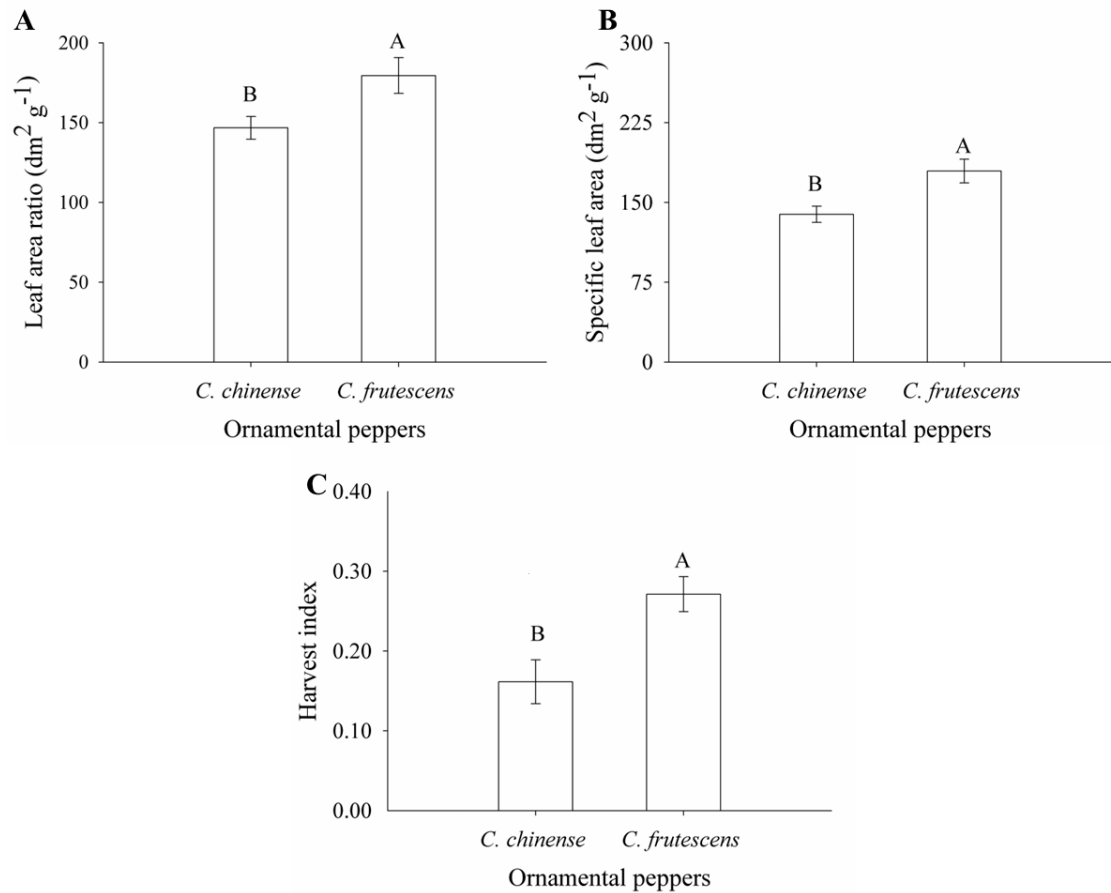


Figure 2. Leaf area ratio (A), specific leaf area (B) and harvest index (C) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \* Different capital letters differ from each other by the Tukey test at 5%.

*C. frutescens* showed higher leaf area ratio and specific leaf area, due to the greater investment of photoassimilates in increasing the leaf area to maximize the capture of light available for dry matter production (Gibbi et al., 2011), in this case, corroborated by the harvest index, which represents the conversion of synthesized products into material of economic importance (Martins et al., 2009), in this case the fruits. Among the results obtained, it is interesting to note that leaf area ratio decreases throughout the cultivation, due to the reduction in the leaf area duration, which does not occur in this study, due to the shading from the colored shade nets reducing physical and thermal damages (Milenkovic et al., 2019) to the photosynthetically active leaf surface.

Net  $\text{CO}_2$  assimilation ( $A$ ) were higher in *C. frutescens* cultivated under red net and *C. chinense* cultivated under aluminet net in comparison with the control (Figure 3 A). A stomatal conductance ( $g_s$ ) was higher in *C. frutescens* cultivated under red net and *C. chinense* cultivated under aluminet in comparison with the control (Figure 3 B). A transpiration ( $E$ ) was higher in *C. chinense* cultivated under aluminet net in comparison with the control and did not differ

among the treatments applied to *C. frutescens* (Figure 3 C). *WUE* was higher in the red net in comparison with the control (Figure 3 D) and *iWUE* was higher in *C. frutescens* compared to *C. chinense* (Figure 3 E).

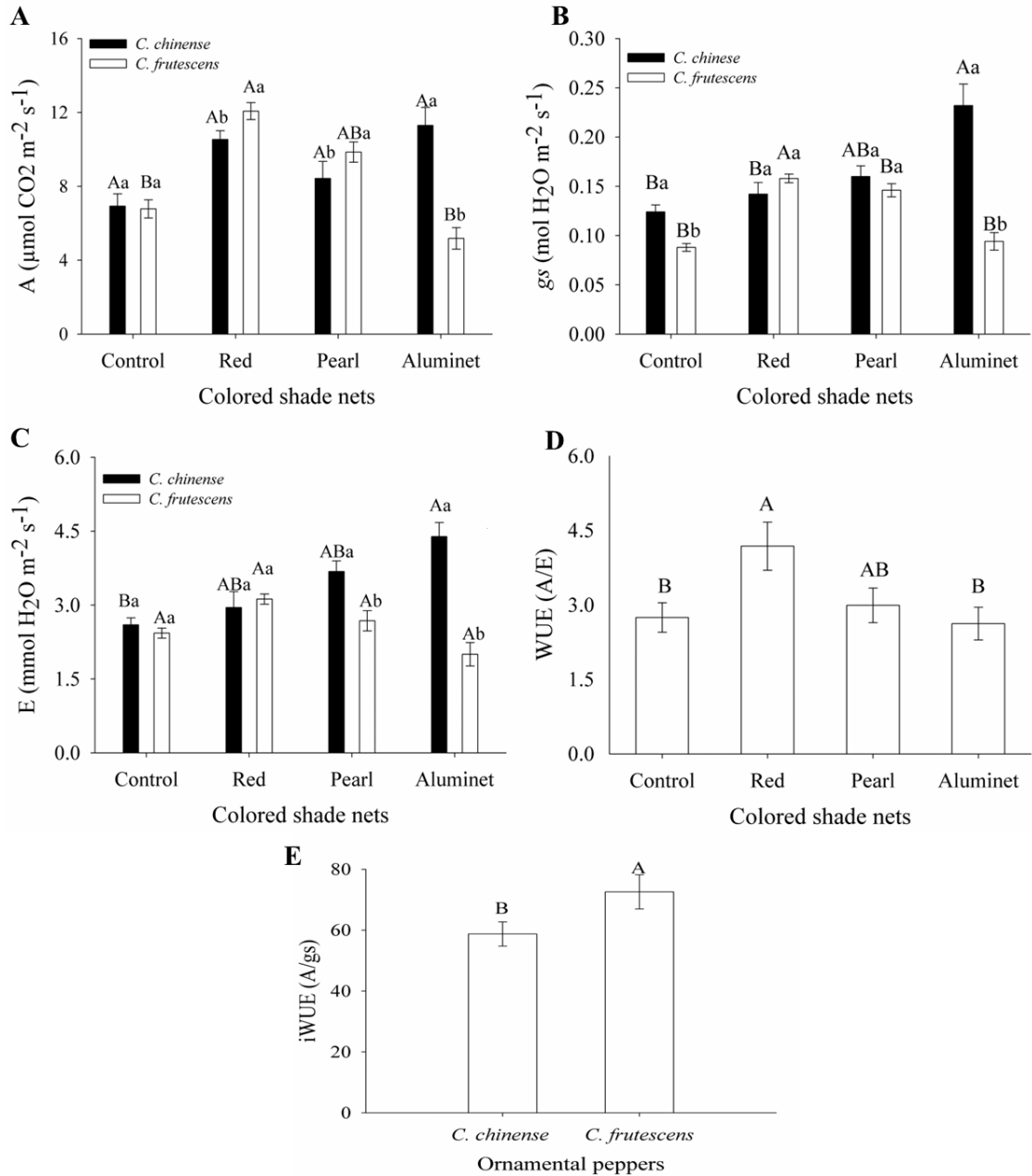


Figure 3. Net CO<sub>2</sub> assimilation - *A* (A), stomatal conductance- *gs* (B), transpiration - *E* (C), efficiency - *WUE* (D) and intrinsic water use efficiency - *iWUE* (E) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \* Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

Peppers plants are C3 plants with optimal growth at a 33 °C (Angmo et al., 2022; Ilić & Fallik, 2017), from this, net CO<sub>2</sub> assimilation was higher in *C. frutescens* cultivated under red

net due to the maximum temperature throughout the cultivation being 32.1°C (Angmo et al., 2022) and solar radiation incidence maintains by 40.7% (Mditshwa et al., 2019) compared to the other treatments. Among these, temperature is the main limiting factor to net CO<sub>2</sub> assimilation, given that its excess photorespiration (Betti et al., 2016). Therefore, this result is attributed to the higher concentration of carbon in the carboxylation sites, decreasing the photorespiration process (Gamage et al., 2018) and increasing dry matter production (O’Leary et al., 2015). This allowed greater production of carbon skeletons through respiration, glycolysis and electron transport chain for investment in growth and fruit formation, corroborating *C. frutescens* having higher leaf area ratio, specific leaf area and harvest index (García-Sánchez et al., 2015; Gao et al., 2021).

A lower *g<sub>s</sub>* is seen, when plants are subjected in conditions with high CO<sub>2</sub> concentration (Uddin et al., 2018), but *C. frutescens* cultivated under red net and *C. chinense* cultivated under aluminet net obtained elevated *A* and *g<sub>s</sub>*. Lahive et al. (2017) found similar result in cocoa plants in which the higher *g<sub>s</sub>* in face of high CO<sub>2</sub> was a reflection of the humid cultivation environment (Lahive et al., 2017) corroborating the result found in *C. frutescens* cultivated under red net, due to this net having had higher humidity compared to the other treatment. On the other hand, contrary to the previous hypothesis, Purcell et al. (2018) evidences that although rare, plants with higher *A* and *g<sub>s</sub>* at the same time, but in a less humid environment is evidence that these are adapted to hot and dry places, corroborating the result found in *C. chinense* cultivated under aluminet.

In presence of high concentration of CO<sub>2</sub>, transpiration is reduced, increasing the water content in the soil and consequently, occurring greater investment in the transformation of organic compounds into dry matter (Harrison et al., 2020; Fay et al., 2015). In conducting the experimente, the substrate was irrigated daily until it reached field capacity, which probably mitigated the effects of high transpiration allowing the highest *WUE* and *iWUE* in red net and *C. frutescens*, respectively. As well, probably what occurred was caused by the IRGA measuring the *g<sub>s</sub>* by the opening and closing of the stomas, and these may be partially open or closed, which is not identified by the device. Thus, the stomas may have allowed sufficient CO<sub>2</sub> to enter for photosynthesis and higher *iWUE*, due to the lower temperature in the red net and less need for cooling of the leaf by loss of latent heat via transpiration (Harrison et al., 2020).

The inverse presented by aluminet net and *C. chinense* is explained by even if the substrate reaches field capacity, the control of gas exchanges within the cultivation environment is complex and depends on the species and the type of experiment, I this case, the aluminet net,

whiche, despite presenting the optimum growing temperature of 33 °C and obtained lower relative humidity, consequently lower water use efficiency.

Initial ( $F_0$ ) and maximum chlorophyll ( $F_m$ ) was higher in *C. frutescens* cultivated under red net (Figure 4 A and B). Maximum quantum efficiency ( $F_v/F_m$ ) was lower in *C. chinense* cultivated under red net (Figure 4 C) and relative chlorophyll content (SPAD) was higher on red net compared to the others.

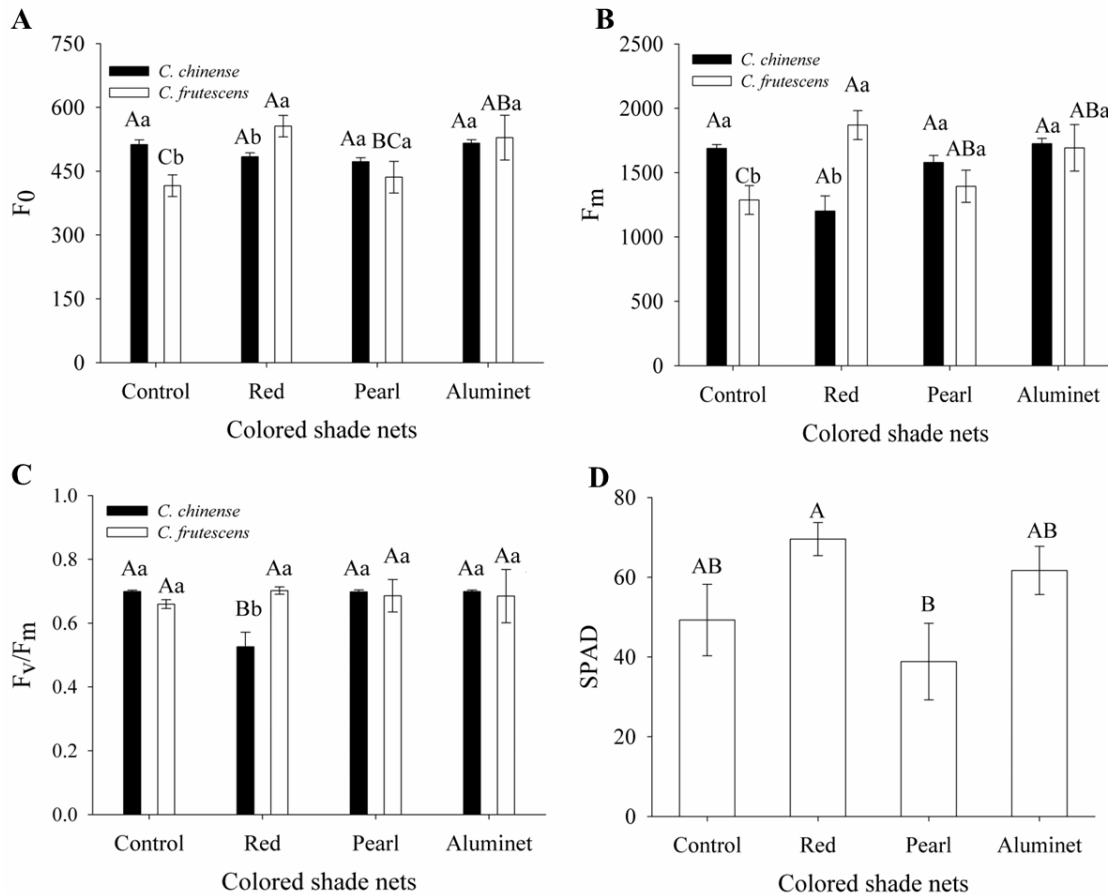


Figure 4. Initial chlorophyll -  $F_0$  (A), maximum chlorophyll -  $F_m$  (B), maximum quantum efficiency -  $F_v/F_m$  (C) and relative chlorophyll content - SPAD (D) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \* Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

Under shading conditions, *C. frutescens* exhibit leaf area and reduced leaf thickness, and probably greater number of chloroplasts in order to maximize the light uptake process via chlorophylls (Wang et al., 2018; Li & Mu, 2021). Whereas in *C. frutescens* cultivated under red net,  $F_0$  and  $F_m$  was higher by improving the process of absorption, transfer and utilization of energy through photosystem II (Yang et al., 2018).

SPAD was higher in *C. frutescens* cultivated under red net, because the reduced sun intensity and the supplementation of red light caused by the net coloration is captured and directed to chlorophyll synthesis (Chen et al., 2021). This occurs, due to the shaded leaves producing additional chlorophyll a and b capture diffuse light and use them for their dry matter production (Ilic & Fallik, 2017). In shaded tea plants supplement with red light, expression of the *CsPOR-2* gene encoding the enzyme protochlorophyllide oxidoreductase (*POR*) is induced in response to shading by catalyzing the reduction of prochlorophyllide oxidoreductase to chlorophyllide, from which, chlorophyll is derived (Wu et al., 2016; Liu et al., 2018; Chen et al., 2021).  $F_o$ ,  $F_m$  and SPAD directly contribute in increasing the net photosynthetic rate, corroborating the result found in *C. frutescens* cultivated under red shade net (Li & Mu, 2021).

$F_v/F_m$  is an indicator of plant adaptation to abiotic stress arising from high temperature and solar radiation (Zaman et al., 2022). Plants grown in full sun reduced values of  $F_v/F_m$ , that is, chlorophyll is reemitted via heat or the PSII reaction center malfunctions because it has suffered photoinhibition (Olivares-Souto & Bastías, 2018). In this study, the control treatment did not have this behavior because the temperature and solar radiation intensity did not cause photoinhibition in the plants (Wang et al., 2018; Yang et al., 2018). The maximum values of  $F_v/F_m$  are reached at temperatures between 36 to 39 °C as observed in the literature, corroborating the data present here in this study (Naschitz et al., 2015). However, there is a reduction in the values of  $F_v/F_m$  from 40 °C onwards (Naschitz et al., 2015), but *C. chinense* cultivated under red net obtained the lowest value with a maximum cultivation temperature of 32.1°C, this probably may be associated with the onset of photoinhibition, due to the lower value of  $E$  among the treatments with net. As well as, this is not adapted to hot and humid environments (Purcell, et al., 2018).

Linear electron flux (LEF) did not differ between net treatments *C. chinense*, but was lower in the control (Figure 5 A). In isolation, PSII open centers fraction (qL) was higher in control and pearl net compared to the others treatments and in *C. frutescens* (Figure 5 B and C). Decrease in chlorophyll fluorescence rate decrease (RdF) was lower in *C. chinense* cultivated under red net compared to the others treatments (Figure 5 D). Non-photochemical extinction coefficient ( $\Phi_{NPQ}$ ) and non-photochemical dissipation of absorbed light energy (NPQt) were higher in *C. chinense* cultivated under red net compared to the others treatments (Figure 5 E and F).

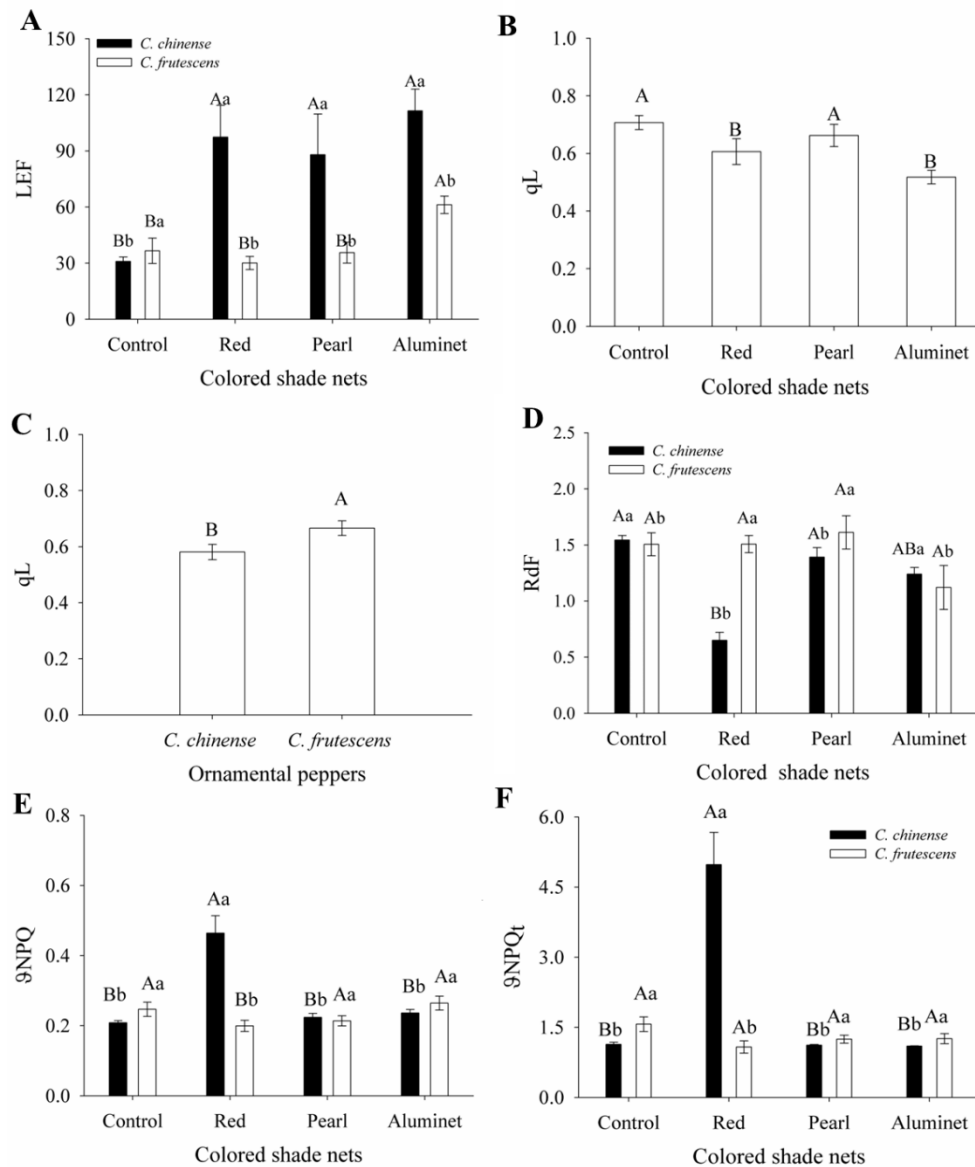


Figure 5. Linear electron flux - LEF (A), PSII open centers fraction - qL (B and C) chlorophyll fluorescence rate decrease - RFd (D), non-photochemical extinction coefficient –  $\Phi$ NPQ (E), and non-photochemical dissipation of absorbed light energy - NPQ<sub>t</sub> (F) of *C. chinense* and *C. frutescens* cultivated under colored shade nets. \* Capital letters refer to colored shade nets, and lowercase letters refer ornamental peppers. Different capital and lowercase letters differ from each other by the Tukey test at 5%.

Reduced LEF implies a decrease in intercellular CO<sub>2</sub> and ability to use the reducing power of NADPH and ATP in plants (Huang et al., 2012). This condition is an adjustment of the operational efficiency of PSII to couple the production of NADPH and ATP with the decreased assimilation of CO<sub>2</sub> (Huang et al., 2012; Ben-Jabeur et al., 2021), due to exposure to high temperature and solar radiation incidence.

The higher qL in the control and pearl net as in the *C. frutescens* species associated with reduced LEF occurred because the energy obtained by solar radiation under shaded conditions was enhanced and use by photosystem II (Yang et al., 2018). On the other hand, the control treatment even presenting high  $F_v/F_m$ , may have not at some time produced ROS by means of excess energy on the reaction centers (Jiang et al., 2018).

The lower RdF in *C. chinense* cultivated under red net associated with the lower qL and  $F_v/F_m$  implies the reduction of solar radiation energy on photosystem II, due to its reemission in the form of heat ( $\Phi$ NPQ and NPQt) (Murchie & Lawson, 2013), probably due to malfunction of the reaction centers or onset of photoinhibition (Olivares-Souto & Bastías, 2018). This is because, although  $E$  did not differ from the other treatments with net, it was lower, i. e., there was little reemission of latent heat, thus, reemission via  $\Phi$ NPQ and NPQt was a way to prevent the accumulation of ROS in the plant due to heat stress. (Ben-Jabeur et al., 2021).

#### 4. CONCLUSION

The shading provided by colored shade nets promoted morphological changes on the photosynthetic surface of *C. frutescens*. *C. frutescens* cultivated under red net obtained a higher photosynthetic efficiency. On the other hand, *C. chinense* cultivated under red net had an inverse response, due to each specie having different responses under the same growing environment.

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#### CONFLICT OF INTEREST

The authors have no conflict of interest.

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## 2. GENERAL CONCLUSION

The aluminet net in association with *C. chinense* are recommended considering the compactness of height, pot coverage, greater number, shape and arrangement of fruits. On the other hand, this one did not achieve efficient photosynthetic efficiency.

The shading provided by colored shade nets promoted morphological changes on the photosynthetic surface of *C. frutescens*. *C. frutescens* cultivated under red net obtained a higher photosynthetic efficiency. On the other hand, *C. chinense* cultivated under red net had an inverse response, due to each specie having different responses under the same growing environment.

Further studies with other colors and shading are needed to obtain new information about their behavior.