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Physiological performance of *Coffea arabica* cultivated in different shadings in the Brazilian semi-arid region

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A B S T R A C T

Coffee is one of the most consumed drinks in the world and its production comes from the work of approximately 100 million coffee farmers across the planet. For its cultivation in semi -arid regions, management is necessary to help mitigate possible abiotic and biotic stresses. An alternative to produce in these environments is the use of shading, as shading helps to reduce radiation damage and contributes to mitigating harmful effects. in photosynthesis generated by light saturation. In this context, the objective of this study was to determine the influence of different shading on the photosynthetic characteristics of young coffee plants, under Brazilian semi-arid conditions. The experiment was carried out following a randomized block design, with 4 treatments and 8 replications, totaling 32 experimental units. The four treatments were: 1- Full sun; 2- 50% shading, 3- 70% shading and 4- 80% shading. The physiological variables evaluated were: net photosynthesis, transpiration, stomatal conductance and internal CO_2 concentration, using the infrared gas analyzer (IRGA-Ci340). Furthermore, carboxylation efficiency values were obtained; water use efficiency and intrinsic water use efficiency. The results showed that coffee shaded with 50 and 70% showed an increase in photosynthetic rate. Cultivation conditions in full sun and 80% shade specifically reduced the photosynthesis of *Coffea arabica* plants, var. Red *catuai*. Water use efficiency, carboxylation efficiency and intrinsic water use efficiency were not significantly influenced by shading. Relatively, the 50% shading condition favored greater water use efficiency and greater intrinsic water use efficiency.

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R E S U M O

O café é uma das bebidas mais consumidas no mundo e sua produção é oriunda do trabalho de aproximadamente 100 milhões de cafeicultores em todo o planeta. Para seu cultivo em regiões semiáridas é necessário manejos que ajudem a mitigar possíveis estresses bióticos e abióticos, uma alternativa para se produzir nesses ambientes é a utilização de sombrites, pois, o sombreamento ajuda a reduzir os danos pela radiação e contribui na mitigação dos efeitos deletérios na fotossíntese gerados pela saturação por luz. Neste contexto, o objetivo deste estudo foi determinar a influência de diferentes sombreamentos nas características fotossintéticas de plantas jovens de café arábicas, sob condições de semiárido brasileiro. O experimento foi realizado seguindo o delineamento em blocos casualizados, com 4 tratamentos e 8 repetições, totalizando 32 unidades experimentais. Os quatro tratamentos foram: 1 - Pleno sol; 2- 50% de sombreamento, 3- 70% de sombreamento e 4- 80% de sombreamento. As variáveis fisiológicas avaliadas foram: fotossíntese líquida, transpiração, condutância estomática e concentração de CO_2 interna, utilizando o analisador de gás por infravermelho (IRGA-Ci340). Além disso, foram obtidos os valores de eficiência da carboxilação; eficiência de uso da água e a eficiência intrínseca do uso da água. Os resultados mostraram que o café sombreado com 50 e 70 % apresentou aumento na taxa fotossintética. As condições de cultivo a pleno sol e a 80% de sombreamento reduziram de forma específica a fotossíntese das plantas de café arábica, var. Catuaí vermelho. A eficiência do uso da água, a eficiência de carboxilação e a eficiência intrínseca do uso da água não sofreram influência significativa dos sombreamentos. De forma relativa, a condição de 50% de sombreamento favoreceu a maior eficiência do uso de água e a maior eficiência intrínseca do uso de água.

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Introduction

Coffee is one of the most consumed beverages in the world and its production comes from the work of approximately 100 million coffee farmers around the planet (Davis *et al.*, 2019). Due to climate change, coffee producing areas have had to adapt to different growing environments (Venancio *et al.*, 2020), and the environmental pressure of monoculture in the Brazilian coffee system (Matta *et al.*, 2019).

Coffea arabica, as an understory species, originates from mountainous forests of Ethiopia (Bez *et al.*, 2022; Hu *et al.*, 2022). At altitudes above 1,500 meters, characterized by an average annual temperature of 20°C Charrier and Berthaud, (1985), it normally requires greater care, especially in producing areas located in arid and semi-arid environments.

For its cultivation in semiarid regions, management is required to help mitigate possible abiotic and biotic stresses. Because these production environments often offer environmental conditions that are different from those of deep forests such as those in the centers of origin of coffee, these particularities make species shade-tolerant (Ayalew, 2018).

Thus, their seedlings are generally produced in nurseries with plastic mesh shades that block approximately 50 to 75% or more of the photosynthetically active radiation (PAR), reaching values between 400 and 700 µmol of photons $m^{-2}s^{-1}$, which corresponds to the light saturation point in coffee (Matiello *et al.*, 2010, Rakocevic *et al.*, 2021, León-Burgos *et al.*, 2022).

In general, light is one of the most important environmental factors for the commercial establishment of a crop, and its intensity can influence plant growth and development, as well as their foliar gas exchange and water use efficiency (Hatamian *et al.*, 2015; Thakur *et al.*, 2019). According to Moraes *et al.* (2010), seedlings in shaded conditions, compared to full sun, have larger and greener leaves, which may give a false impression of greater vigor. However, seedlings grown in the shade may present photooxidative damage when transplanted to the field, requiring acclimatization or a gradual reduction in the level of shade (Moraes *et al.*, 2010).

After transplantation, coffee seedlings are subjected to high air temperatures and high solar irradiation. This exposure can simultaneously cause leaf burns (Ulm and Jenkins, 2015; Santos *et al.*, 2016; Bernado *et al.*, 2021). Sunburn is expressed by symptoms of chlorosis and necrosis in one in several species (RACSKÓ *et al.*, 2010). In addition to these symptoms, sunburn can lead to reduced photosynthetic rates, decreased plant height, leaf area, shortening of the internode and the length of the coffee tree branches (Santos *et al.*, 2016).

Thus, shaded cultivation emerges as an alternative for crop production, as it helps to reduce radiation damage and contributes to mitigating deleterious effects on photosynthesis generated by light saturation, in addition to increasing water use efficiency, as leaves directly exposed to the sun have greater hydraulic conductance per unit of leaf area and consequently greater water demand (Carins Murphy *et al.*, 2012). As observed by Damatta (2004), due to light saturation, the plant needs greater transpiration to maintain low leaf temperature, resulting in greater water consumption.

Therefore, the objective of this study was to determine the influence of different shading on the photosynthetic characteristics of young *Coffea arabica* plants, under Brazilian semiarid conditions.

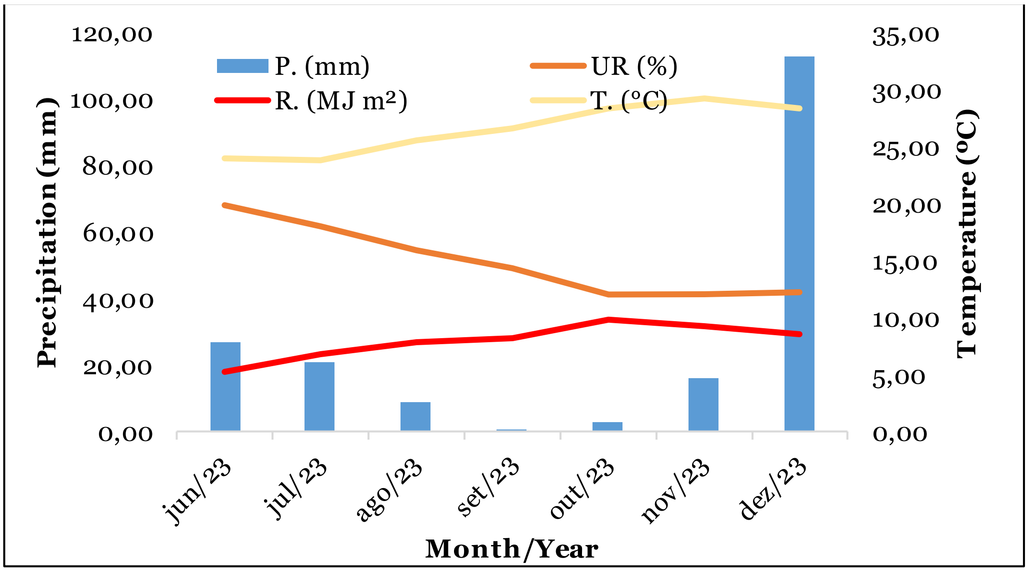
Materials and methods

Experiment location and plant material

The work was carried out from 06/18/2023 to 12/13/2023, in the experimental area of the Serra Talhada Academic Unit (UAST), linked to the Federal Rural University of Pernambuco (UFRPE), municipality of Serra Talhada, PE, Sertão do Pajeú microregion, located at the following geographic coordinates: Latitude: -7.95° 59' 7" South, Longitude: 38.29° 17' 34" West and Altitude of 499 m. Climatic conditions during the study are presented in Table 1.

Figure 1.

Average monthly values of Precipitation (P, mm); Relative Humidity (RH, %); Global Solar Radiation (R, MJ m-2) and Temperature (T, °C), from June to December 2023. Serra Talhada, PE. 2023.



Source: INMET, 2023.

Seeds of *Coffea arabica* (variation Red *catuai*) were sown in plastic trays on 09/15/2022, approximately 65 days after sowing, when seedlings had expanded cotyledonary leaves. They were transplanted into a 2 kg plastic bag where they remained until 06/18/23, when they were transferred to the soil, following a spacing of 2 x 1 m, in a population of 10 thousand plants per hectare. The chemical characteristics of the soil used in the study are shown in Table 1. After transplanting, the seedlings were separated into four groups corresponding to the shading levels. Each shade cloth was placed at a height of 1 m above the ground so as not to overlap the neighboring seedlings of each shaded experimental unit.

Table 1.

Chemical characteristics of the surface layer of the soil used in the experiment. Serra Talhada –PE, 2023.

Layer (cm)	P	pH	Ca	Mg	Na	K	Al	H
	mg dm^{-3}	(H_2O)	---------------------cmolc dm^{-3}--------------------					
0-40	252	6,4	4	1,5	0,03	0,7	0	0

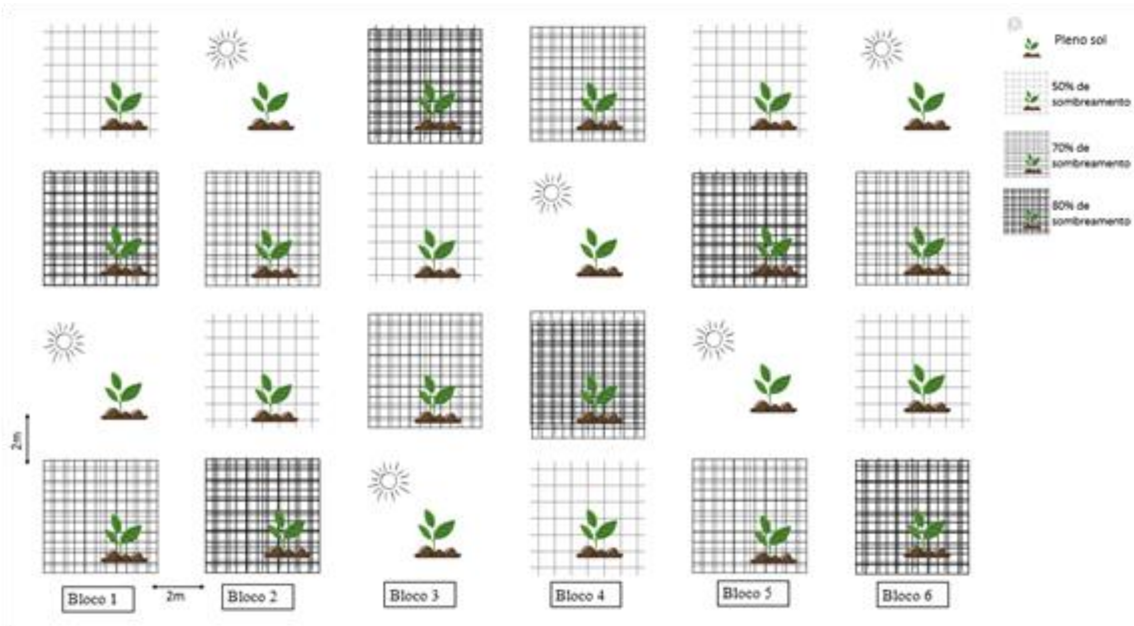
Source: IPA laboratory.

Treatments and experimental design

The experiment was carried out following a randomized block design, with 4 treatments and 6 replicates, totaling 24 experimental units. The four treatments were: 1-Full sun; 2- 50% shade, 3- 70% shade and 4- 80% shade. Before the start of data collection, seedlings were maintained from 06/18/23 to 12/13/23 at shade levels corresponding to each treatment, figure 2.

Figure 2.

Sketch of the experimental area, coffee plants subjected to each level of shading. Serra Talhada, PE. 2024.



Source: Own authorship, 2024.

Treatments with fertilizers and agricultural inputs

Planting and growth fertilizations were carried out according to the soil analysis, table 1 and based on the fertilization recommendation manual of the State of Pernambuco, as recommended for the crop (Cavalcanti, 2008).

Weed control was carried out manually whenever necessary. During the experiment, 2 applications of insecticide based on (METHOMIL) 600 mL ha^{-1} and fungicide based on (MANCONZEB) 1.5 kg ha^{-1} were made to control insect pests and diseases that commonly occur in cultivation areas.

Irrigation was used daily based on crop evapotranspiration, following the model proposed by Penman-Monteith FAO 56:

Etc = (Eto . Kc) - P

In this:

Etc= Crop evapotranspiration (mm dia^{-1});

ETo= Reference evapotranspiration (mm dia^{-1})

Kc= Cultivation coefficient

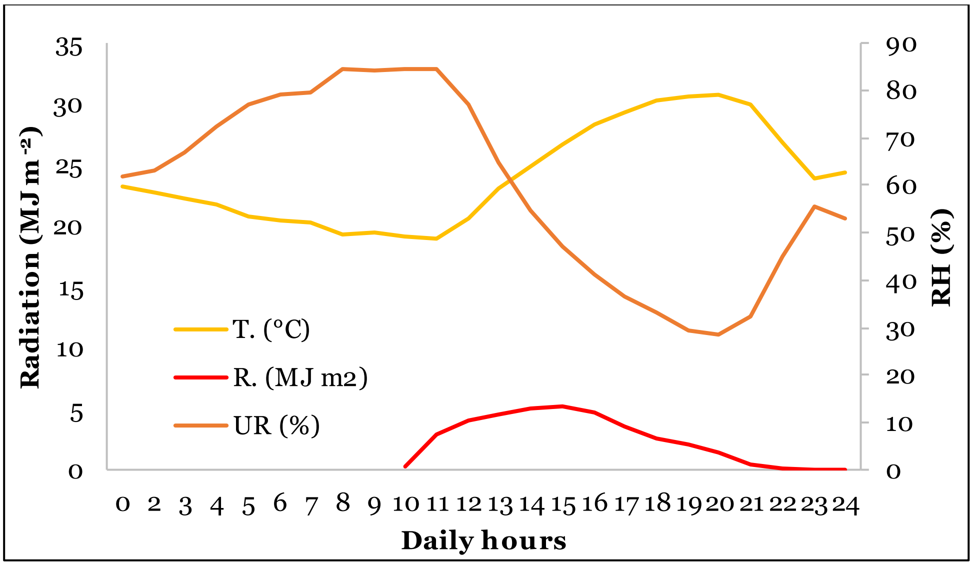
P=Precipitation (mm)

Measurements of gas exchange in young coffee plants

Measurements were carried out on December 13, 2023 between 10 and 11 am, on healthy leaves of the third plagiotropic branch, from the apex of each plant. The climatic conditions at the time of the measurements are shown in Figure 3, where measurements were carried out on six plants at each shading level, except for the two plants at the ends (borders). The physiological variables were: net photosynthesis (PN), transpiration (T), stomatal conductance (gs) and internal CO_2 concentration (Ci) using the infrared gas analyzer (IRGA-Ci340). In addition, the carboxylation efficiency (EC = Pn / Ci); water use efficiency (EUA = Pn / T) and intrinsic water use efficiency (EIUA = Pn / gs) were obtained.

Figure 3.

Average temperature (T, °C); Global solar radiation (R, MJ m-2) and relative humidity (RH, %) on the day of assessment. Serra talhada, Pernambuco. 2023.



Source: INMET, 2023.

Statistical analysis

Results obtained were subjected to the normality of distribution test using the Shapiro-Wilk test with a significance level of 5% ($p < 0.05$), subsequently, analysis of variance (ANOVA) was performed, using the F test ($p < 0.05$). When significant, the Tukey test was performed at 5% probability ($p < 0.05$), using the statistical software R version 4.1.3 (R Core Team, 2020). Then, principal component analysis (PCA) was applied in order to examine the interrelationships between the physiological variables of *Coffea arabica* var. Red *catuai* in different shadings. Significant principal components (PCs) were selected according to the Kaiser criterion (1960), considering only eigenvalues greater than 1.0 for the validity of the application of the (PCA) (Lamichhane *et al.*, 2021). Principal component analysis was performed using PAST 4.03 software (Hammer *et al.*, 2001).

Results

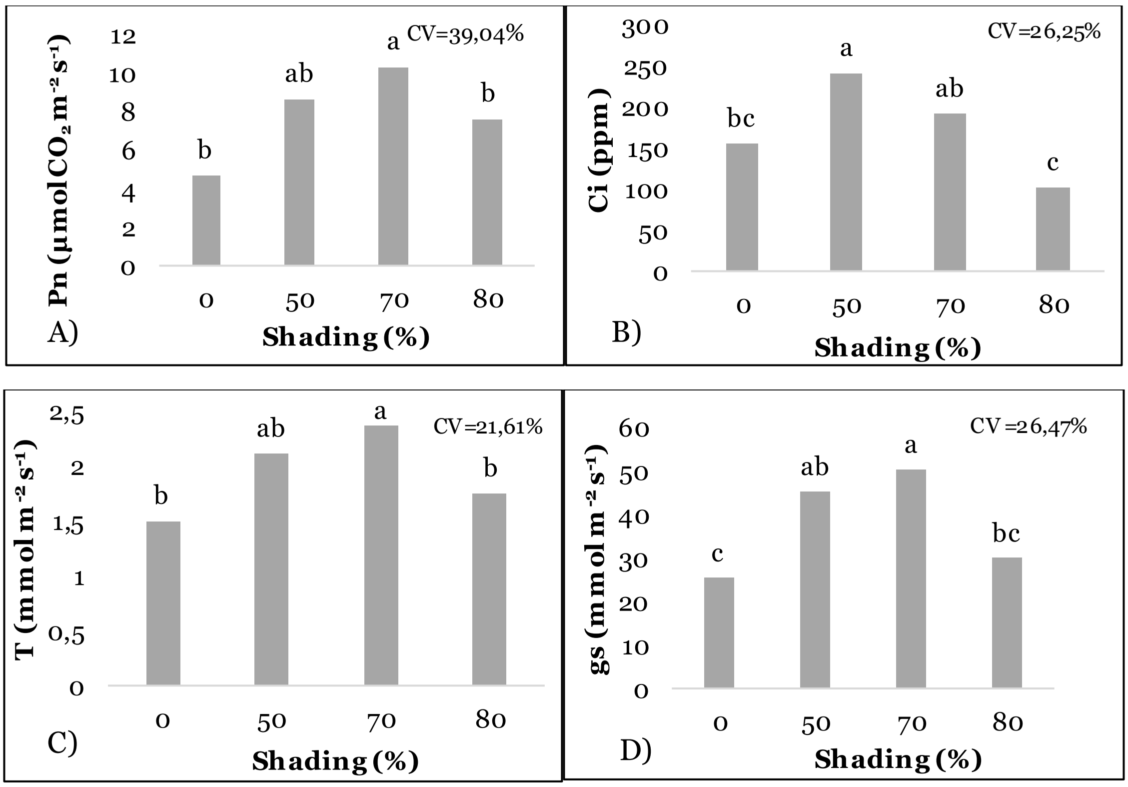
Results of net photosynthesis (Pn) were significantly influenced by different shading conditions, so that plants with 70% shading presented higher Pn values than when placed in full sun or 80% shade. In contrast, the full sun condition resulted in a reduction of more than 50% in net photosynthesis. These results suggest that young Catuí red coffee plants develop better in semiarid environments under shade between 50 and 70%. This suggestion is similar to the results found by (Tatagiba *et al.*, 2010, Córdova *et al.*, 2016), who observed better development in shade less than 60% compared to full sun.

Still in this context, Ribeiro *et al.* (2019) obtained similar results, since according to these authors, light restriction (at adequate levels) improves the photosynthetic mechanism and gas exchange of the *Coffea arabica* plant during initial growth, mainly due to the photosynthetic capacity being reduced when overloaded by excess light (Mathur *et al.*, 2018).

Some authors emphasize that leaves developed in full sun compared to leaves in shaded conditions are generally thicker and have a thicker palisade parenchyma, have greater stomatal density, and, as a rule, a higher nitrogen concentration per unit of leaf area. However, they have less chlorophylls A and B in their leaf mass, in addition to presenting higher photosynthesis rates and an increase in the content of photoprotective pigments (Martins *et al.*, 2014; Assis *et al.*, 2019; Venâncio *et al.*, 2019; Pérez-Molina *et al.*, 2021). However, our results suggest that plants in full sun and 80% shaded conditions reduced their photosynthetic rates, stomatal conductance, transpiration, and internal CO2 concentration (Figures 4 (A; B; C and D), respectively).

Figures 4 (A; B; C e D).

Physiological parameters: A) Net photosynthesis (Pn); B) Internal carbon concentration (Ci); C) Transpiration (T) and D) Stomatal conductance (gs) in young plants of *Coffea arabica*, var. Red *Catuaí* subjected to four treatments: 1-Full sun; 2- 50% shading, 3- 70% shade and 4- 80% shading.



* Means followed by the same letter do not differ statistically from each other, according to the Tukey test at 5% probability ($p < 0.05$). CV = coefficient of variation.

In general, full sun and 80% shade treatments were statistically similar and resulted in the lowest rates of net photosynthesis, stomatal conductance, internal CO_2 concentration and transpiration. This fact was also observed by Zhu *et al.* (2017) who, studying the influence of light on pak-choi plants (*Brassica campestris* ssp. *Chinensis* Makino L. "ziyi"), found that the photosynthetic rate decreased significantly in plants subjected to low light (250 to 750 µmol photons $m^{-2}s^{-1}$) compared to normal light (1000 µmol photons $m^{-2}s^{-1}$), indicating that photosynthetic capacity is impaired in treatments with a certain level of shade.

Plants had higher transpiration values in the 50 and 70% shading treatments, while the lowest values were observed in the plants subjected to full sun and 80% shading. This may have occurred due to the weather conditions on the day of the measurements (Figure 3), where there was a large variation in relative humidity, with higher values in the early morning and decreasing throughout the day, generating an average below 50% RH. This condition, combined with the higher incidence of solar radiation, results in stresses capable of reducing transpiration, mainly due to stomatal closure (Figure 4B).

EC (Carboxylation efficiency), EUA (water use efficiency) and EIUA (intrinsic water use efficiency) values were not significantly influenced by the different shading levels (Figures 5A; B and C). However, higher relative values of carboxylation efficiency occurred due to coverage of 70 and 80%, respectively, showing that these shading levels promoted a favorable environment, reducing the stresses caused by radiation and temperature. According to Navarro *et al.* (2022), there are specific conditions for high carboxylation efficiency to occur, such as: availability of ATP and NADPH, amount of light, temperature level and CO2 concentrations to be made available in the mesophyll for carboxylation to occur (Nobre *et al.*, 2023).

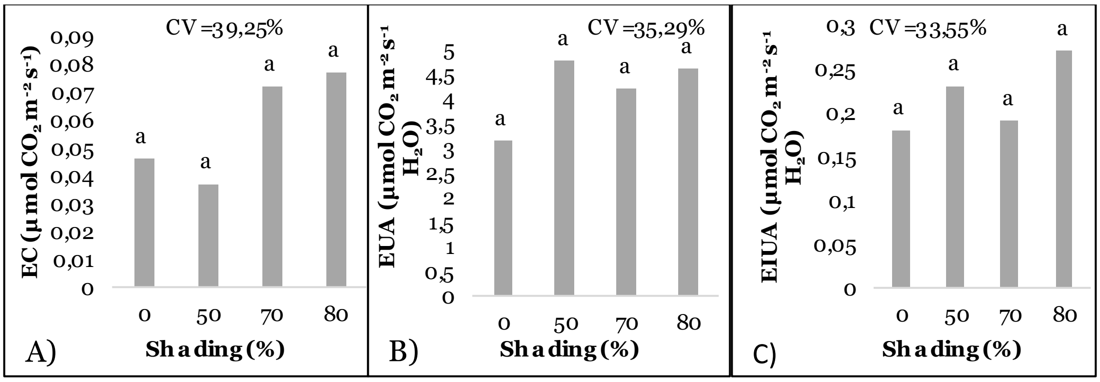
EUA refers to the amount of carbon fixed by the plant per water molecule and when plants have a net photosynthetic rate higher than the transpiration rate, there is a higher EUA (Chagas *et al.*, 2019).

These results suggest that in adequate shaded conditions, plants have greater agronomic efficiency, compared to those in full sun, which tend to have greater transpiration and, consequently, lower efficiency in water use, although no significant difference was observed in this study for this variable (Figure 5B).

It is worth observing, in particular, the behavior of coffee plants between treatments with 50% and 70% shade, although there was no significant difference between the treatments, it is important to highlight the greater efficiency of water use when in less shade (50%), ratifying the better environmental condition for better EC (Figures 5 A; B and C).

Figures 5 (A; B e C).

Physiological parameters: A) Carboxylation Efficiency (CE); B) Water Use Efficiency (WUE) and C) Intrinsic Water Use Efficiency (IWUE) of *Coffea arabica* var. Red *catuai* seedlings subjected to four treatments: 1-Full sun; 2- 50% shading, 3- 70% shading and 4- 80% shading.



* Means followed by the same letter do not differ statistically from each other, according to the Tukey test at 5% probability ($p < 0.05$). CV = coefficient of variation.

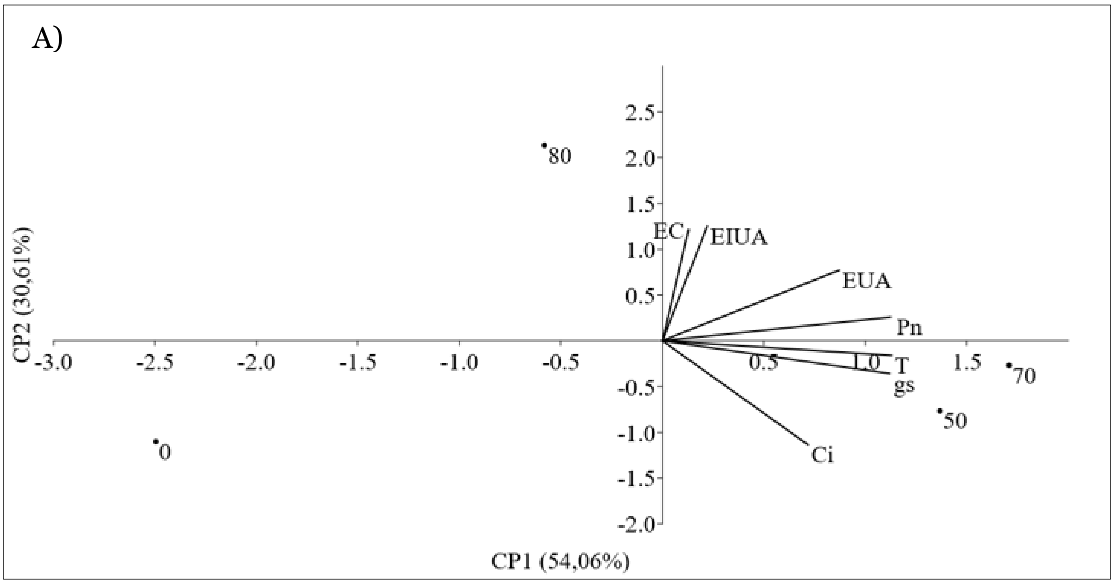
Figure 6 shows the principal component analysis (PCA) and the relationship between physiological variables of *Coffea arabica* var. Red *Catuaí* according to different shadings, suggesting that the two axes (CP1 and CP2) explain 84.67% of the data variation, with 54.06% explained by the first principal component (PC1) and 30.61% by the second principal component (PC2). The lines that connect the physiological variables to the center of origin of the graph are called vectors (Mirosavljevic *et al.*, 2018). Thus, angles formed between the vectors determine the relationship between shading levels, as well as between the physiological variables investigated and the shading levels. For example, variables that present an acute angle are positively correlated, while those that present obtuse angles are negatively correlated, and those that have a right angle (90°) between them are not correlated.

In this understanding, stomatal conductance (gs), transpiration (T) and liquid photosynthesis (Pn) are associated with the 70% coverage level, while internal carbon concentration revealed a better association with the 50% coverage treatment.

In Figure 6B, we observe variables that compose each principal component, with CP1 composed of variables with the highest loads, such as Pn (0.49634), T (0.49808), and gs (0.49486), while CP2 is composed of Ci (-0.50045) and EIUA (0.55178); finally, CP3 is composed of EC (-0.59059) and EUA (0.42387), respectively. Variable loads show that Pn, T, gs, EC, EUA, and EIUA are positively correlated, while Ci and EC are negatively correlated, evidencing that despite the high levels of internal CO_2, the plant ceased CO_2 assimilation due to the lower investment in proteins associated with Rubisco (Mendes *et al.*, 2017).

Figure 6 (A and B).

Principal component analysis (PCA) showing the relationship between physiological variables of *Coffea arabica* var. Red *Catuaí* subjected to four treatments: 1-Full sun; 2- 50% shading, 3- 70% shading and 4- 80% shading. A) Variable loadings on the first two axes and B) component matrix with loading factors for each variable on the first three PCs with eigenvalues greater than 1.0.



B)

CP.	Pn	Ci	T	gs	EC	EUA	EIUA
PC 1	0,49634	0,31641	0,49808	0,49486	0,05742	0,38438	0,09750
PC 2	0,11385	-0,50045	-0,0707	-0,15819	0,53506	0,34030	0,55178
PC 3	-0,19271	0,28053	-0,21665	-0,13494	-0,59059	0,42387	0,53904

Variables

-1 -0,333 0,333

* Pn= liquid photosynthesis; Ci= internal carbon concentration; T= Transpiration; gs= stomatal conductance; EC= Carboxylation efficiency; EUA= water use efficiency; EIUA= intrinsic water use efficiency; CP1= main component 1; CP2= main component 2; CP= main components.

Conclusions

Different shading conditions influenced the physiological characteristics of young plants of *Coffea arabica* var. Red *Catuaí*;

Young plants of coffee var. Red *Catuaí* subjected to treatments of 50 and 70% shading increased their photosynthetic rates;

Growing conditions in full sun and 80% shading reduced the photosynthesis of young plants of *Coffea arabica* var. Red *Catuaí*;

Water use efficiency, carboxylation efficiency and intrinsic water use efficiency were not significantly influenced by shading.

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