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*Scientific Article*

# Particle film effects on the ecophysiological parameters of two arboreal species under water restriction

# Efeitos do filme de partículas nos parâmetros ecofisiológicos de duas espécies arbóreas sob restrição hídrica

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**ABSTRACT** - The objective of this study was to evaluate the effects of using particle film associated with two water regimes on the ecophysiological parameters of young plants of two species native to the Brazilian semiarid region (*Tabebuia aurea* and *Ziziphus joazeiro*). The experiments were conducted in randomized blocks in a 2 × 2 factorial design, with nine replications. The treatments used were the application of particle film (Surround® WP) at a concentration of 5% and without film or 0%, and two irrigation water regimes based on reference evapotranspiration (ETo), irrigated with 100% of ETo and not irrigated or 0% of ETo. Gas exchange determinations were performed at 0, 15, 30, and 45 days after treatments imposition, while the analyses of photosynthetic pigments were carried out only at the end of the experiment. The species *Tabebuia aurea* and *Ziziphus joazeiro* showed tolerance to water stress, demonstrated by their high water use efficiency. On the other hand, the application of particle film caused an increase in stomatal conductance, transpiration, and intrinsic water use efficiency and reductions in leaf temperature and instantaneous water use efficiency in plants of both species studied. The particle film was efficient in providing photoprotective properties verified by the increase in the content of photosynthetic pigments. However, the use of this film requires more in-depth investigations, which could allow a better understanding of its management in tree species in the Brazilian semiarid region.

**Keywords**: Caatinga. Thermal stress. Photosynthetic pigments. Photochemistry. Gas exchange.

**RESUMO** - O objetivo deste estudo foi avaliar os efeitos do uso do filme de partículas associado a dois regimes hídricos sobre os parâmetros ecofisiológicos de plantas jovens de duas espécies nativas do semiárido brasileiro (*Tabebuia aurea* e *Ziziphus joazeiro*). Os experimentos foram conduzidos em blocos casualizados em esquema fatorial 2 × 2, com nove repetições. Os tratamentos utilizados foram aplicação de filme de partículas (Surround® WP) na concentração de 5% e sem filme ou 0%, e dois regimes hídricos de irrigação baseados na evapotranspiração de referência (ETo), irrigado com 100% da ETo e não irrigado ou 0% da ETo. As determinações das trocas gasosas foram realizadas aos 0, 15, 30 e 45 dias após a aplicação dos tratamentos, enquanto as análises dos pigmentos fotossintéticos foram realizadas apenas ao final do experimento. As espécies *Tabebuia aurea* e *Ziziphus joazeiro* apresentaram tolerância ao estresse hídrico, demonstrada pela elevada eficiência no uso da água. Por outro lado, a aplicação de filme de partícula causou aumento na condutância estomática, transpiração e na eficiência intrínseca do uso da água e reduções na temperatura foliar e na eficiência instantânea do uso da água pelas plantas de ambas as espécies estudas. O filme de partículas foi eficiente em conferir propriedades fotoprotetoras verificadas pelo aumento no teor de pigmentos fotossintéticos. No entanto, a utilização desse filme requer investigações mais aprofundadas, que possam permitir um melhor entendimento de seu manejo em espécies arbóreas do semiárido brasileiro.

**Palavras-chave**: Caatinga. Estresse térmico. Pigmentos fotossintéticos. Fotoquímica. Troca gasosa.

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## INTRODUCTION

The increasing occurrence of seasonal droughts and the prospect of rainfall reductions and increased freshwater scarcity, especially in arid and semiarid regions, can compromise both plant growth and development (SANTOS et al., 2020; JARDIM et al., 2023a). Besides, intensification in the exploitation of natural resources has aggravated environmental degradation, especially forests and water sources. With climate change underway, the success of revitalizing degraded semiarid environments involves selecting native species with greater water use efficiency (WUE) and drought tolerance (SANTOS et al., 2023; JARDIM et al., 2023b).

In general, when plants are exposed to abiotic stresses (water and light), they accumulate excess energy, which, if not dissipated, can cause reduced growth and affect their physiological performance, for instance reducing the amount of photosynthetic pigments, stomatal closure, $CO_2$ assimilation and net photosynthesis rate (*A*) (SHERIN; ASWATHI; PUTHUR, 2022). Concomitantly, the initial stage of plant development is the most susceptible to these types of stress, a condition that compromises the survival rates of young plants. However, the use of species less susceptible to environmental stresses, associated with the use of technologies, such as simple hydrophilic polymers (SILVA et al., 2019d), mulching (ADHIKARI et al., 2016) and particle films (GLENN, 2016; SILVA et al., 2019a), can increase the adaptation of plants to environmental conditions, in addition to providing adequate levels of nutrients and water.

Particle films (PF) like kaolin have been an efficient technology indicated to increase the adaptation of plants to adverse conditions (GLENN, 2016). Different types of PF are effective in reducing leaf temperature in *Juglans regia* (L.) and *Lycopersicum esculentum* (Mill.) (SILVA et al., 2019c), in improving the WUE in coffee plants (SILVA et al., 2019b) and in improving the performance of photosynthesis energy metabolism in grapevines (SILVA et al., 2019a). PF also worked to reduce sun damage in apples (GLENN, 2016) and increase tolerance to salinity in tomatoes (BOARI et al., 2015). In plants, the efficiency of kaolin-based PF is related to the reflective nature of the chemically inert clay mineral particles (GLENN, 2016).

Among the native plant species found in the semiarid region of Northeast Brazil, *Tabebuia aurea* (Manso) Benth. & Hook., from the Bignoniaceae family, and *Ziziphus joazeiro* (Mart.), from the Rhamnaceae family, are naturally occurring endemic species in the Caatinga biome. These species have multiple uses in civil construction, landscaping, and traditional medicine (CUNHA et al., 2022), in addition to being indicated for reforestation work in areas with low rainfall (SILVA et al., 2019d).

The use of particle films can potentially improve the initial establishment of Caatinga tree species, promoting improvements in their physiological processes. Nonetheless, the use of particle films from calcium materials is still recent and needs more investigation. In fact, there is no information about the use of calcium-based particle films in Caatinga tree species. Therefore, the objective of this study was to evaluate the effects of using particle film associated with two water regimes on the ecophysiological parameters of young plants of two species native to the Brazilian semiarid region (*Tabebuia aurea* and *Ziziphus joazeiro*).

## MATERIAL AND METHODS

### Climatic and soil characteristics of the experimental area

The study was carried out at the arboretum experimental area of the Reference Center for Recovery of Degraded Areas, at the Federal University of Alagoas (UFAL), Campus of Arapiraca, Alagoas, Brazil (9º41'54.32" S, 36º41'10.85" W, 318 m). According to the Köppen-Geiger climate classification, the climate of the study region falls under the BSh type, characterized as dry and hot, with an annual average temperature around 27.0 ºC and evaporation of 1800 mm, dry summer and average annual rainfall of 600 to 900 mm (ALVARES et al., 2013). The averages of air temperature, relative humidity and solar radiation were 28.2 ºC, 69.9% and 22.3 MJ $m^{-2}$ $day^{-1}$, respectively, and a total rainfall of 9 mm was recorded over the experimental period. The area's soil was classified as *Latossolo Vermelho-Amarelo* (Oxisol) (SANTOS et al., 2018), and its physical-chemical characterization is shown in Table 1.

**Table 1**. Characterization of the soil of the study area in the profile of 0.0-0.20 m.

| Particle-size composition % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Clay | | | Silt | | Coarse sand | | Fine sand | | |
| 28.7 | | | 6.2 | | 42.7 | | 22.4 | | |
| Chemical composition | | | | | | | | | |
| pH ($H_2O$) | $Ca^{2+}$ | $Mg^{2+}$ | H+Al | $Na^+$ | P | $K^+$ | CEC | V | OM |
| | --------- ($cmol_c$ $dm^{-3}$) --------- | | | --------------- (mg $kg^{-1}$) --------------- | | | ---------------- (%)---------------- | | |
| 5.8 | 3.2 | 1.8 | 1.9 | 40 | 12 | 178 | 5.63 | 74.8 | 2.72 |

CEC - Cation exchange capacity; V - Base saturation; OM - Organic matter.

### Crop management, irrigation and application of particle films

Seeds of *Tabebuia aurea* and *Ziziphus joazeiro* were germinated in a greenhouse in plastic bags. Each container contained sand, soil, and charred rice husk in a ratio of 2:2:1. After germination and establishment of the seedlings, they were kept in a nursery. When the seedlings completed six months after emergence, they were selected and standardized by size and health status. They were later transplanted to the field in June 2017 (rainy season), with a spacing of 3.0 m between rows and 3.0 m between plants.

The plants were kept under daily irrigation, always in the late afternoon, until the beginning of the field experiment on October 21, 2017. It is important to point out that the plants of both species came from seeds of a single parent plant, in order to reduce the effects of genetic variability within the experiment.

The water depth (mm) was determined based on the difference between reference evapotranspiration (ETo, mm) and rainfall (mm), disregarding the contribution of the water table. Each irrigation event was carried out in the afternoon, using a surface drip system, with drip tubes (online type) with a flow rate of 2.0 L $h^{-1}$. ETo was estimated using the FAO Penman-Monteith method (ALLEN et al., 1998), with data from the automatic meteorological station located 100 meters away from the experimental area.

The particle film based on processed kaolin (Surround® WP) was weighed on a semi analytical balance and diluted in water to a concentration of 5% (w/v). The particle film solution application was carried out on all the leaves of plants subjected to this treatment, using an SG-11-PLUS high-pressure manual spray pump (Stihl, Brazil), with a flow rate of 600 $cm^3$ $min^{-1}$ and a working pressure of 3 bar. Spraying was carried out at a distance of 20 cm from the plants for an average of 20 seconds until reaching uniform distribution. For this purpose, four applications were performed throughout the experimental period, seven days before the gas exchange evaluations, to reconstitute the film layer. Adjacent control plants were carefully protected by a plastic film during kaolin application.

**Experimental design and treatments**

Two experiments were carried out, defined according to the plant species (*Tabebuia aurea* and *Ziziphus joazeiro*). Each experiment was carried out in randomized blocks in a 2 × 2 factorial design, with nine replications. The first factor was composed of two irrigation water regimes based on ETo (irrigated with 100% ETo and not irrigated or 0% ETo). The second factor was composed of two levels of particle film [with particle films (Surround® WP) at a concentration of 5% and without film or 0%]. Thus, the treatments were described as T1 - non-irrigated (NI)/without particle film (WPF); T2 - non-irrigated (NI)/with particle film (PF); T3 - irrigated (I)/ without particle film (WPF); and T4 - irrigated (I)/with particle film (PF). The model used for the block design was as follows: $Y_{ij} = \mu + \tau_i + b_j + e_{ij}$, where $Y_{ij}$ represents the value observed in the experimental plot that received the i-th treatment in the j-th block; $\mu$ is the overall mean; $\tau_i$ is the effect of the i-th treatment; $b_j$ is the effect of the j-th block; and $e_{ij}$ is the random experimental error associated with $Y_{ij}$.

**Leaf gas exchange**

Measurements of leaf temperature ($T_{leaf}$), stomatal conductance (*gs*), transpiration (*E*), net $CO_2$ assimilation rate (*A*), and vapor pressure deficit between leaf and air ($VPD_{leaf-air}$) were performed on selected leaves, corresponding to the second pair of fully expanded leaves. These assessments were made using a portable infrared photosynthesis analyzer system (IRGA, model Li-6400XT, Li-Cor Biosciences), with a variable external light source coupled to the sensor head of the clamp, with a leaf chamber of 6.0 $cm^2$.

The measurements were performed on four occasions (October 21st, November 5th, and 20th, and December 4th, 2017) every 15 days, between 8:00 am and 11:00 am. Photosynthetically active radiation (PAR) and $CO_2$ level were kept constant inside the chamber, with a photon flux intensity of 1,600 μmol $m^{-2}$ $s^{-1}$ and 400 μmol $CO_2$ mol $air^{-1}$, respectively. The system's airflow was adjusted to keep the $VPD_{leaf-air}$ readings relatively stable. Instantaneous (WUE) and intrinsic (iWUE) water use efficiency were estimated by the *A*/*E* and *A*/*gs* ratios, respectively.

**Total chlorophyll and carotenoid content**

Photosynthetic pigments in leaf tissues (chlorophyll *a*, chlorophyll *b*, total chlorophyll, and carotenoids) were determined at the end of the experiment on December 6, 2017, on the same leaves used in the gas exchange evaluations. For this, 3.0 mL of acetone (80%) was used as a solvent in a sample of 55 mg of fresh leaf material. In an environment with a green safety light, each sample was manually macerated, transferred to threaded test tubes wrapped in aluminum foil, and then stored in a refrigerator at 4 ºC for 24 hours, for complete pigment extraction. The samples in test tubes were vortexed and subsequently analyzed with a scanning spectrophotometer (UV-2001 PC, Shimadzu, Ouisburg, Germany) in an absorbance range of 350 to 900 nm. Contents of chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Chl *a* + Chl *b*), total carotenoids (xanthophylls + carotenes; $C_{x+c}$) were calculated according to the equations of Lichtenthaler (1987).

**Statistical analysis**

In both experiments, all collected data were checked for normality (Shapiro-Wilk test) and homoscedasticity (Bartlett test) and subsequently subjected to analysis of variance (ANOVA). When significant, the means were compared using the Tukey test ($p < 0.05$). The analyses were carried out using the R software.

## RESULTS AND DISCUSSION

**Gas exchange in Tabebuia aurea**

The results presented in the analysis of variance of the species *T. aurea* indicated that there were significant differences ($p < 0.05$) for the characteristics related to gas exchange variables caused by the individual effects of the irrigation (NI and I) and particle film (WPF and PF) factors. In the two species studied, significant differences in the parameters evaluated were observed after 15 days without irrigation (DWI), with more pronounced differences at 45 DWI (Figure 1).

Particle film application (Surround WP) was efficient in promoting artificial shading and reducing leaf temperature in plants of *T. aurea*. Similar thermal effects were observed in plants treated with kaolin particle films, as seen in grapevine, tomato, and Persian walnut (DINIS et al., 2016; SILVA et al., 2019c; BOARI et al., 2014). Reductions in leaf temperature are related to the protective layer on the leaf created by the PF and to the reflective and photoprotective mechanisms that reflect a greater fraction of the incident solar radiation (BOARI et al., 2014; SILVA et al., 2019a, SILVA et al., 2019b).

In *T. aurea* plants subjected to non-irrigated (NI) treatment, when compared to irrigated plants, the gas exchange variables were significantly reduced (Figure 1). Therefore, it is possible to observe that in NI treatment plants, compared to I treatment plants, the *gs* values decreased by 15.4, 29.5, and 50.6% at 15, 30, and 45 DWI, respectively. On the other hand, it appears that in the PF treatments, the *gs* values only differed significantly at 45 DWI, and the PF use promoted an increase of 23.1% in *gs*, in WPF plants (Figure 1a). It is possible to understand how these stomatal regulation mechanisms work in plants of *T. aurea*, when subjected to water restriction, as well as the use of PF as a strategy to minimize the negative effects of stress on plants.

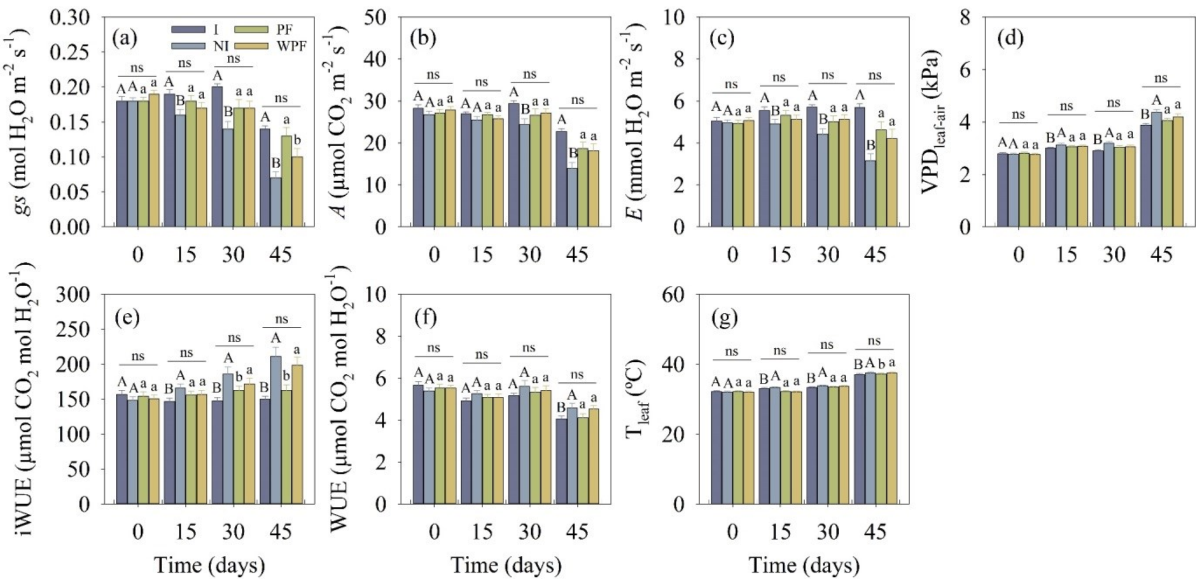


**Figure 1**. Stomatal conductance (*gs*; a), photosynthetic rate (*A*; b), leaf transpiration (*E*; c), vapor pressure deficit (VPD; d), intrinsic water use efficiency (iWUE; e), instantaneous water use efficiency (WUE; f) and leaf temperature ($T_{leaf}$; g) in young *T. aurea* plants subjected to two irrigation treatments and two particle film treatments for 45 days. Note: Statistical analysis was performed separately for the evaluation periods: 0, 15, 30 and 45 days. * - significant interaction between irrigation treatments and film treatments; ns - non-significant interaction, individual effect of film treatments and irrigation treatments. Equal letters do not differ between particle film treatments (lowercase) and irrigation treatments (uppercase) by Tukey's test at 5% probability level. Legend: irrigated (I), non-irrigated (NI), with particle film (PF) and without particle film (WPF). Error bars represent the standard error of the mean.

Plants with PF had the lowest WUE and iWUE. Such observations are in agreement with the work on grapevines of Shellie and King (2013), who reported that leaves subjected to PF application had lower WUE and iWUE values than WPF leaves, due to the reduction in leaf temperature and, consequently, increase in the values *gs* and *E*. According to Glenn (2010), when reflecting the incident light, PF application on leaf surface can improve the responses of plant's physiological variables.

PF action on these variables can vary according to the time of day, season, and changes in meteorological variables (BOARI et al., 2014). Air temperature values above 30 ºC and relative humidity below 40% observed throughout the experiment, resulting in an increase in $VPD_{leaf\text{-}air}$, were aggravated at 45 DWI by stress intensification.

As observed in the I treatment plants, the transpiration (*E*) of the NI plants responded in a similar way to *gs*, with reductions of 11.3, 22.6, and 44.6% at 15, 30, and 45 DWI, respectively (Figure 1c). However, concerning PF treatments, the *E* values did not differ significantly, although there were significant differences in the *gs* values at 45 DWI (Figures 1a and 1c). The $VPD_{leaf\text{-}air}$ values were high in NI plants, with average values ranging from 3.9 to 4.4 kPa (Figure 1d).

Compared to plants subjected to I treatment, the decline in *E* caused an increase in leaf temperature in plants subjected to NI. In comparison with PF plants, an opposite response was verified, a reduction in leaf temperature (-0.4 ºC) in WPF plants, at 45 DWI. On the other hand, over the evaluated times, leaf temperature increased by an average of 5.2 ºC (Figure 1g).

Water deficit intensification reduced net $CO_2$ assimilation rate (*A*), with significant differences observed only after 30 DWI, with reductions of 16.7 and 38.5%, at 30 and 45 DWI, respectively (Figure 1b). Regarding PF treatments, there was no significant difference ($p > 0.05$). Under water restriction conditions, stomatal closure is the primary response and the control mechanism among species.

Although tolerance levels vary depending on species, and as a result of reductions in *gs*, there is a reduction in *E* and $CO_2$ concentration in the mesophyll (SILVA et al., 2019b; SANTOS et al., 2017). Transpiration is the main route of leaf heat transfer and, due to the water deficit, stomatal closure induces an increase in the leaf/canopy temperature and decreases the photosynthetic assimilation of $CO_2$ (GLENN, 2010).

Simultaneous *gs* reductions in WPF and NI treatment plants led to greater intrinsic water use efficiency (iWUE), with increasing values over 45 DWI, compared to plants in PF and I treatments, which showed apparently static values (iWUE) (Figure 1e). On the other hand, the opposite behavior is observed in iWUE, which showed a marked reduction in all treatments at 45 DWI (Figure 1f), aggravated by the increase in $VPD_{leaf\text{-}air}$. In WPF and NI treatment plants, a strong reduction in *E* values at 45 DWI promoted a greater WUE, with the PF and I treatment plants (Figure 2f).

In this work, a reduction in $VPD_{leaf\text{-}air}$ values was observed in the PF treatments, indicating that the PF protective layer on the leaves favored the increase of *gs* and *E* (GHARAGHANI; JAVARZARI; VAHDATI, 2018; SILVA et al., 2019b). The results found for *gs* are consistent with the reduction in the canopy temperature of tomato plants. This canopy temperature variable had an inversely proportional response with the increase in PF concentrations, which indicates the potential of PF to reflect excess light and thus promote leaf temperature reduction (SILVA et al., 2019c).

In these circumstances, increases in *gs* and *E* may indicate changes in the stomatal mechanism, resulting in lower WUE and higher water consumption by the plant (SANTOS et al., 2017). Although the increase in *gs* and *E* can be beneficial in irrigated plants, for optimizing carbon assimilation, the opposite occurs, that is, stomatal closure occurs and reduces $CO_2$ access to RuBisCO carboxylation sites.

**Photosynthetic pigments in T. aurea**

A significant interaction was observed between the irrigation (NI and I) and particle film (WPF and PF) factors in *T. aurea* plants for the characteristics related to photosynthetic pigments. For the Chl *a* values, the PF factor had no significant influence ($p > 0.05$) on this species. The total chlorophyll content in *T. aurea* plants subjected to NI treatment decreased significantly. The average reduction compared to plants subjected to the treatment I was 13.44 and 11.58% in the interaction with the treatments WPF and PF, respectively. Therefore, the highest total chlorophyll content was found in plants of the I/PF treatment (Table 2).

Throughout the experimental period, the contents of chlorophyll *a*, chlorophyll *b*, and total chlorophyll decreased in the leaves of *T. aurea* and *Z. joazeiro* plants subjected to water restriction. The levels of these leaf pigments had a similar response to the *A*, *gs*, and *E* values. The decrease in chlorophyll contents was due to the degradation of photosynthetic pigments as a response caused by drought stress (GENC et al., 2013; GHARAGHANI; JAVARZARI; VAHDATI, 2018).

**Table 2**. Contents of total chlorophyll ($Chl_{total}$), chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), chlorophyll *a*/chlorophyll *b* (Chl *a*/Chl *b*) and carotenoids ($C_{x+c}$) in leaves of young *T. aurea* plants.

| | $Chl_{total}$ (µg $mL^{-1}$) | | Chl *b* (µg $mL^{-1}$) | |
|---|---|---|---|---|
| Treatment | Irrigated | Non-irrigated | Irrigated | Non-irrigated |
| With film | 23.13 ± 0.38 aA | 19.95 ± 0.93 bA | 6.12 ± 0.10 aA | 4.41 ± 0.33 bA |
| Without film | 20.45 ± 0.03 aB | 17.27 ± 0.27 bB | 5.25 ± 0.01 aB | 3.88 ± 0.33 bB |
| | Chl *a*/Chl *b* | | $C_{x+c}$ (µg $mL^{-1}$) | |
| Treatment | Irrigated | Non-irrigated | Irrigated | Non-irrigated |
| With film | 2.46 ± 0.01 bB | 2.57 ± 0.03 aA | 1.90 ± 0.09 aA | 1.56 ± 0.03 bB |
| Without film | 2.68 ± 0.01 aA | 2.48 ± 0.05 bB | 2.13 ± 0.01 aA | 2.09 ± 0.11 aA |
| | Chl *a* (µg $mL^{-1}$) | | | |
| Treatment | Irrigated | Non-irrigated | With film | Without film |
| | 14.56 ± 0.29 a | 10.34 ± 0.33 b | 12.48 ± 0.95 a | 12.42 ± 0.56 a |

Equal letters do not differ between irrigation treatments (lowercase) and particle film treatments (uppercase) by Tukey's test at 5% probability level. Mean ± standard error.

On the other hand, the Chl *a* content was significantly reduced in the NI treatment, with a reduction of 28.98% compared to plants subjected to I treatment (Table 1). A similar response was observed regarding the Chl *b* content, with reductions in the NI/PF and NI/WPF treatments of 27.90 and 26.03% compared to the I/PF and I/WPF treatments, respectively. In contrast, PF application promoted an increase in the Chl *b* content, with significant increases of 13.56 and 16.62% in plants subjected to NI and I treatments, respectively (Table 2).

The Chl *a*/Chl *b* ratio was significantly reduced ($p < 0.05$) in plants subjected to NI/WPF treatment, with a 3.83% reduction in NI/WPF plants. However, this behavior was mitigated in plants subjected to PF treatment (Table 2). Therefore, in I and NI treatments, PF application induced significant reductions in carotenoid content, equal to 10.44 and 25.33%, respectively (Table 2).

Therefore, the reduction in the levels of the photosynthetic pigment can be a typical indication of oxidative stress, probably resulting from photo-oxidation of leaf pigments. This degradation of chlorophyll molecules can also be associated with photochemical damage to the light-harvesting complex and to the photosystem II reaction centers (GENC et al., 2013; CAVALCANTE et al., 2018). Therefore, chlorophyll degradation may have negatively affected the *A* of both species, as observed in *Jatropha curcas* (CAVALCANTE et al., 2018). Therefore, chlorophylls have often been used to identify damage to the photosynthetic system of plants under stress conditions (SANTOS et al., 2017; CAVALCANTE et al., 2018).

**Gas exchange in Z. joazeiro**

Unlike what was observed in *T. aurea* plants with the characteristics related to gas exchange variables, in *Z. joazeiro* plants there was a significant interaction ($p < 0.05$) between the irrigation factor (NI and I) and the particle film factor (WPF and PF). The same was not verified for photosynthetic rates. The suspension of irrigation caused severe reductions in the *gs* values in WPF plants, which were equal to 39.7, 67.1 and 78.5%, at 15, 30 and 45 DWI, respectively. In PF plants, these reductions were 36.6, 49.8 and 46.3%, at 15, 30 and 45 DWI, respectively.

It is also observed that, in NI plants, the presence of PF increased the values of *gs* compared to WPF plants (Figure 2a). The *E* values showed similar behavior to the *gs* values. PF application in NI plants increased the *E* rates by 44.2 and 63.2% at 30 and 45 DWI, respectively (Figure 2c). However, PF application did not induce significant effects on *E* in the I treatment plants.

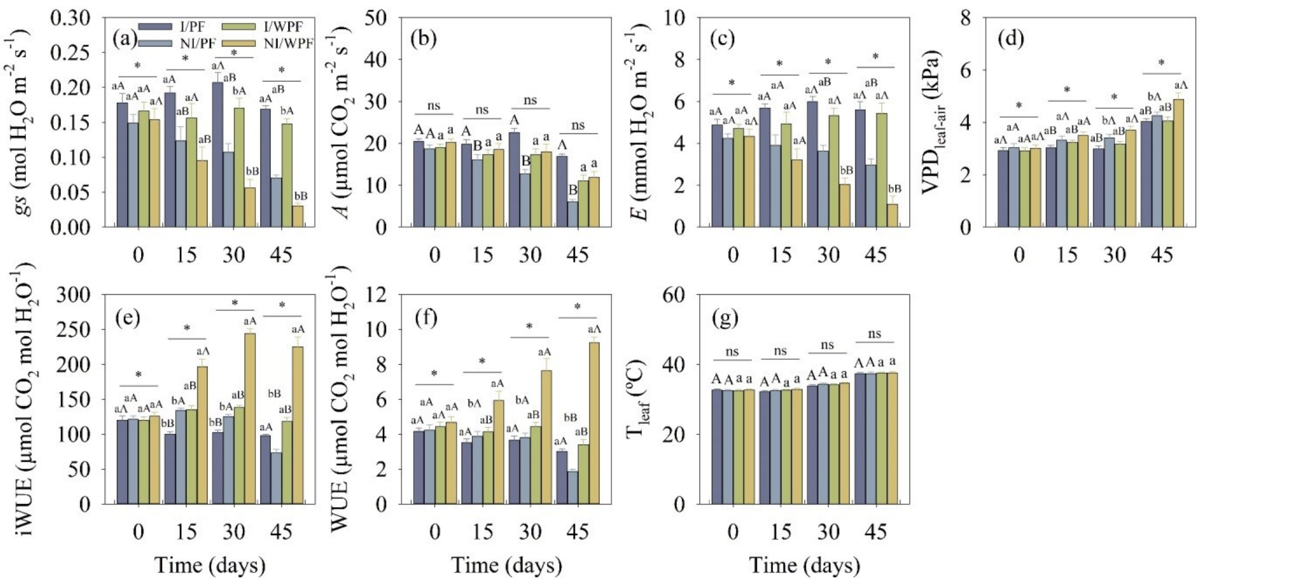


**Figure 2**. Stomatal conductance (*gs*; a), photosynthetic rate (*A*; b), leaf transpiration (*E*; c), vapor pressure deficit ($VPD_{leaf-air}$; d), intrinsic water use efficiency (iWUE; e), instantaneous water use efficiency (WUE; f) and leaf temperature ($T_{leaf}$; g) in young *Z. joazeiro* plants subjected to two irrigation treatments and two particle film treatments for 45 days. Note: Statistical analysis was performed separately for the evaluation periods: 0, 15, 30 and 45 days. * - significant interaction between irrigation treatments and film treatments; ns - non-significant interaction, individual effect of film treatments and irrigation treatments. Equal letters do not differ between particle film treatments (lowercase) and irrigation treatments (uppercase) by Tukey's test at 5% probability level. Legend: irrigated (I)/with particle film (PF), non-irrigated (NI)/with particle film (PF), irrigated (I)/without particle film (WPF) and non-irrigated (NI)/without particle film (WPF). Error bars represent the standard error of the mean.

The *A* values found in this work reveal that PF application did not influence the leaf net $CO_2$ assimilation rate of *T. aurea* and *Z. joazeiro*. However, there is a diversity of results, including positive effects (GHARAGHANI; JAVARZARI; VAHDATI, 2018; SILVA et al., 2019b, 2019a), negative effects (ROSATI et al., 2007; WÜNSCHE; LOMBARDINI; GREER, 2004), and even null effects of PF application on *A* (SHELLIE; GLENN 2008; GLENN, 2010). These differences can be explained by different climatic conditions, different species, equipment used and spraying mode, and even different gas exchange measurement times (BOARI et al., 2014; GHARAGHANI; JAVARZARI; VAHDATI, 2018).

In *Z. joazeiro* plants, over the evaluation periods, the *A* was severely affected in the NI treatment, with an intense decrease in values, with a response similar to that of *gs* and *E* (Figure 2b), whose initial values were on average 19.6 µmol $m^{-2}$ $s^{-1}$ and, at 45 DWI, the average was 6 µmol $m^{-2}$ $s^{-1}$. On the other hand, PF application did not influence the values of the plants ($p > 0.05$). When comparing the $VPD_{leaf-air}$ values as a function of the irrigation regime, an increase of this variable was observed in the NI treatment plants (PF and WPF) compared with I treatment plants. Therefore, PF application was able to reduce, in NI treatment plants, $VPD_{leaf-air}$ values by 4.9, 7.8 and 12.9%, at 15, 30, and 45 DWI, respectively. These results show that PF application can minimize the effect of damage to plants under conditions of water restriction, with the reduction of $VPD_{leaf-air}$ (Figure 2d).

The $VPD_{leaf-air}$ is one of the main environmental factors that influence stomatal control. In this study, *T. aurea* and *Z. joazeiro* plants showed an inverse correlation between $VPD_{leaf-air}$ and *gs*, *E*, and *A*, due to high temperatures, low relative humidity, and reduced soil water availability (SANTOS et al., 2017; ANDRADE et al., 2019; SILVA et al., 2019b). The sensitivity demonstrated in the *gs* values corroborates the hypothesis that an intense stomatal closure occurs in plants under water restriction, which allows them to reduce the *E*, avoiding water loss by the leaf (SANTOS et al., 2017).

Young *Z. joazeiro* plants were potentially less tolerant to water and light stress conditions compared to young *T. aurea* plants. The different responses to PF application between species in terms of gas exchange suggest that the effectiveness as a reflective antitranspirant for PF maybe influenced by genotype-dependent characteristics in response to drought (SHELLIE; GLENN, 2008; SHELLIE; KING, 2013). Denaxa et al. (2012) report that the application of kaolin is more efficient in reducing leaf temperature in broadleaf plants and improves photosynthetic performance under unfavorable temperature conditions and excessive solar radiation.

With the suspension of irrigation and water deficit intensification, the *gs*, *E*, and *A* values were reduced and caused increases in the WUE and iWUE values (Figures 2e and 2f). PF mitigated the water stress effects and caused smaller reductions in *gs* and *E*, keeping WUE and iWUE values higher than in stressed WPF plants.

Although PF minimizes the stressful effects of water lack, keeping leaf temperature lower, the results of this study show that PF does not completely reverse water stress effects on WUE and iWUE optimization. Consequently, plants subjected to NI and WPF treatment proved to be more water use efficient, compared to the other treatments, with significant increases ($p < 0.05$) throughout the evaluation periods and with the intensification of the water restriction (Figures 2e and 2f). It is worth mentioning that, for leaf temperature values, no significant difference was observed between the irrigation factor (NI and I) and particle film factor (WPF and PF) for *Z. joazeiro* (Figure 2g).

**Photosynthetic pigments in Z. joazeiro**

The analysis of variance results of *Z. joazeiro* plants indicated that the levels of $Chl_{total}$, Chl *a*, Chl *b*, and the Chl *a*/Chl *b* ratio were significantly influenced by the individual effects of the irrigation factor. This fact showed that, in plants subjected to NI treatment, there was a greater degradation of these pigments, with reductions of 21.72%, 33.76%, and 25.33% in the contents of Chl *a*, Chl *b*, and $Chl_{total}$, respectively (Table 3), regardless of the PF application, which did not have a significant effect on these variables. The highest value of the Chl *a*/Chl *b* ratio was found in plants subjected to NI treatment, which showed an increase of 19.14% (Table 3).

**Table 3**. Contents of total chlorophyll ($Chl_{total}$), chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), chlorophyll *a*/chlorophyll *b* (Chl *a*/Chl *b*) and carotenoids ($C_{x+c}$) in leaves of young *Z. joazeiro* plants.

| | | | | |
|---|---|---|---|---|
| | | $Chl_{total}$ (µg mL$^{-1}$) | | |
| Treatment | Irrigated | Non-irrigated | With film | Without film |
| | 23.13 ± 0.95 a | 17.27 ± 0.55 b | 20.61 ± 0.64 a | 19.77 ± 0.82 a |
| | | Chl *a* (µg mL$^{-1}$) | | |
| Treatment | Irrigated | Non-irrigated | With film | Without film |
| | 16.20 ± 0.61 a | 12.68 ± 0.38 b | 14.51 ± 0.41 a | 14.35 ± 0.48 a |
| | | Chl *b* (µg mL$^{-1}$) | | |
| Treatment | Irrigated | Non-irrigated | With film | Without film |
| | 6.93 ± 0.36 a | 4.59 ± 0.19 b | 6.10 ± 0.08 a | 5.42 ± 0.05 a |
| | | Chl *a*/Chl *b* | | |
| Treatment | Irrigated | Non-irrigated | With film | Without film |
| | 2.35 ± 0.11 b | 2.80 ± 0.01 a | 2.81 ± 0.11 a | 2.52 ± 0.01 a |
| | | $C_{x+c}$ (µg mL$^{-1}$) | | |
| Treatment | Irrigated | | Non-irrigated | |
| With film | 2.41 ± 0.02 aA | | 2.02 ± 0.10 aA | |
| Without film | 0.83 ± 0.09 bB | | 1.58 ± 0.19 aB | |

Equal letters do not differ between irrigation treatments (lowercase) and particle film treatments (uppercase) by Tukey's test at 5% probability level. Mean ± standard error.

In *T. aurea* plants the treatments with PF caused an increase in the contents of Chl *b* and $Chl_{total}$ and reduction in the Chl *a*/Chl *b* ratio. Similar results were seen in walnut, basil, and olive trees (GHARAGHANI; JAVARZARI; VAHDATI, 2018; KHALIQ et al., 2015). The increase in the content of the photosynthetic pigment is due to the reduction of PAR below the PF protective layer (SILVA et al., 2019b). However, PF application did not interfere in the content of Chl *a*, Chl *b*, and $Chl_{total}$ in *Z. joazeiro* and *T. aurea*.

Regarding the carotenoid content, there was a significant interaction between the factors irrigation (NI and I) and particle film (WPF and PF). In WPF, the carotenoid content increased in NI plants, by 90% compared to plants subjected to I treatment. A similar response was found in plants subjected to PF treatments, with increases of 189.86 and 27.78% in plants subjected to the treatments I and NI, respectively (Table 3).

On the other hand, compared to the I/WPF treatment, *Z. joazeiro* plants subjected to NI/WPF treatment had increased carotenoid levels. Rojas et al. (2012), when studying *Gmelina arborea*, reported that such a response occurs as an attempt to minimize damage to the photosynthetic apparatus, due to the imposed stress, which may be a strategy for dissipating excess light energy in the face of water deficit conditions. However, under both water conditions, *Z. joazeiro* plants subjected to the application of particle film had an increase in carotenoid content. Wünsche, Lombardini and Greer (2004) reported that the increase in carotenoid levels may be related to a reduction in PAR below the PF layer.

## CONCLUSIONS

The use of particle film (Surround® WP) proved to be promising for promoting a reduction in leaf temperature, better water use efficiency (WUE) and photoprotection by increasing photosynthetic pigments. These benefits can be attributed to the particle film's ability to mitigate stress and regulate gas exchange in plants. However, young *T. aurea* and *Z. joazeiro* plants showed distinct responses to the use of particle film. Therefore, the use of this film on tree species native to the Brazilian semiarid region requires more in-depth investigations, which may allow a better understanding of their management and specificity for more effective use of the product.

Even under water stress conditions, young plants of *T. aurea* and *Z. joazeiro* managed to maintain the physiological activities associated with stable gas exchange, a condition demonstrated by the high WUE, which reveals the potential of these species for the recovery of degraded areas in semiarid environments.

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