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Physiological and productive performance of papaya plants irrigated in a semiarid environment

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Abstract

Papaya tree has great economic importance and potential of cultivation in semiarid environment. However, water scarcity in this region may reduce photosynthetic activity and limit the production of this crop, being necessary to use strategies of irrigation management that rationalize water and allow the production of the plants without affecting photosynthetic activity. In this sense, this study aimed to evaluate the physiological and productive performance of papaya "Calimosa" under different water replacement rates in semiarid environment. Papaya plants were irrigated with four water replacement rates (50, 75, 100 and 125% ETo) from 30 days after transplant of seedlings to the experimental area. At 10 months after transplant were realized evaluations of gas exchange and chlorophyll fluorescence, and at 12 months after transplant, it was started harvesting fruits to determine the yield. Water replacement rates significantly influenced the parameters of gas exchange of papaya with better results on rates of 125% ETo. However, application of water replacement rates of 100% ETo provide conditions adequate for the activity of gas exchange and better quantum efficiency of photosystem II, that contribute to fruit production in papaya. With rates less than 75% ETo occur drastic reductions in gas exchange, quantum efficiency of photosystem II, and fruit production of papaya, which impairs its cultivation in semiarid environments.

Keywords: *Carica papaya* L., plant physiology, chlorophyll fluorescence, production

Introduction

Papaya (*Carica papaya* L.) is a crop with economic and social importance, mainly by the possibility of increasing farmer's income and improve their socio-economic reality (Venturini et al., 2012; Godi et al., 2020). Brazil is an important producer of papaya with a production of 1.6 million tons that represent 17% of worldwide production (FAO, 2016). The Northeast region is the largest producer of papaya, and its cultivation is growing as an economic opportunity for farmers that diversify agricultural production. However, some environmental factors, such as water scarcity may limit the growth and production of papaya, especially when cultivated in semiarid regions, where the climate is characterized by low rainfall and relative humidity, and high temperatures (Cardoso et al., 2020), conditions that favor for a less water availability in soil (water deficit). In this sense, the use of irrigation can become an alternative advantageous that increase the water availability in soil, avoiding significant reductions in production.

Irrigation, when used consciously and efficiently, improves the physiological performance of plants and promotes increments in production and fruit quality (Nascimento et al., 2015). However, if used improperly, can affect aeration in the root zone and cause nutrient leaching in soil, which directly affects the growth and production of plants. Thus, optimize irrigation with efficient use of water is a necessary practice to have sustainable agriculture with a greater economic return (Dutra et al., 2018).

Soil water deficit, common in a semiarid region, promotes significant changes in the gas exchange and damages in the photosynthetic apparatus of plants (Suassuna et al., 2011; Melo et al., 2020). This effect is due to the limitation of stomatal conductance, which inhibits photosynthetic activity due to CO_2 influx limitation and

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water efflux from transpiration (Silva et al., 2015; Araújo et al., 2019), and also the changes in the activity of enzymes and metabolites, and inhibition of chloroplast activity (Lisar et al., 2012). Therefore, evaluate gas exchange well as efficiency of the photosystem II may help understand the responses of papaya to soil water deficit, in addition, to quantify it is acclimatization capacity to this condition to develop adequate management of irrigation for crop, optimizing fruit production, and water use.

In semiarid region, irrigation with low water volume (less than evapotranspiration) may be a tool to rationalize water. However, studies are necessary to measure the physiological responses of papaya and it is fruit production under different water rates of replacement. Hence, it is hypothesized that irrigation using water rates of replacement between 75 and 100% reference evapotranspiration maintains the efficiency of the photosynthetic system and yield of papaya. Therefore, this study aimed to evaluate physiological and productive performance of papaya "Calimosa" under different water replacement rates in semiarid environment.

Material and Methods

The experiment was conducted in experimental area of Paraíba State University in Catolé do Rocha, Paraíba, Brazil (6°20'38" S and 37°44'48" W at 250 m altitude) from August 2009 to November 2010. According to Köppen-Geiger climate classification, the region is characterized as semiarid with drought stress, average annual rainfall of 870 mm with greater volume of rain concentrated between February and April, and average air temperature of 27 °C (Dutra et al., 2015). Climatic data of temperature and relative humidity were recorded daily to compose the monthly average during the experimental period (Figure 1). The cumulative rainfall of the experimental period was 441.2 mm.

Soil of experimental area is classified as Neossolo Flúvico Eutrófico (Entisol) with sandy loam texture (Santos et al., 2018). The chemical and physical analysis of the soil 0 – 0.20 m layer showed the following result in Table 1.

The treatments were constituted to four water replacement rates, based on reference evapotranspiration (50, 75, 100, and 125% ETo), distributed in randomly block design with six replicates totaling 24 experimental units.

The soil was plowed and leveled with leveling harrow. Then, holes in soil on dimensions 0.40 x 0.40 x 0.40 m were opened for cattle manure application (2.0 L/hole) and 40 kg ha^{-1} of P_2O_5. Papaya seedlings hybrid UENF/Caliman 01 (Calimosa) were transplanted for holes in single rows the spacing 4 x 2 m, with 22 plants to row. Soil fertilization in topdressing was performed according to soil analysis and papaya nutritional requirement, with application of 80 kg ha^{-1} of N and 40 kg ha^{-1} of K_2O by fertigation every seven days (Sobral et al., 2007). NPK sources were urea, single superphosphate, and potassium chloride. The cultural practices were performed when necessary to keep the area free of weeds, diseases, and pests, providing favorable conditions for the development of the culture.

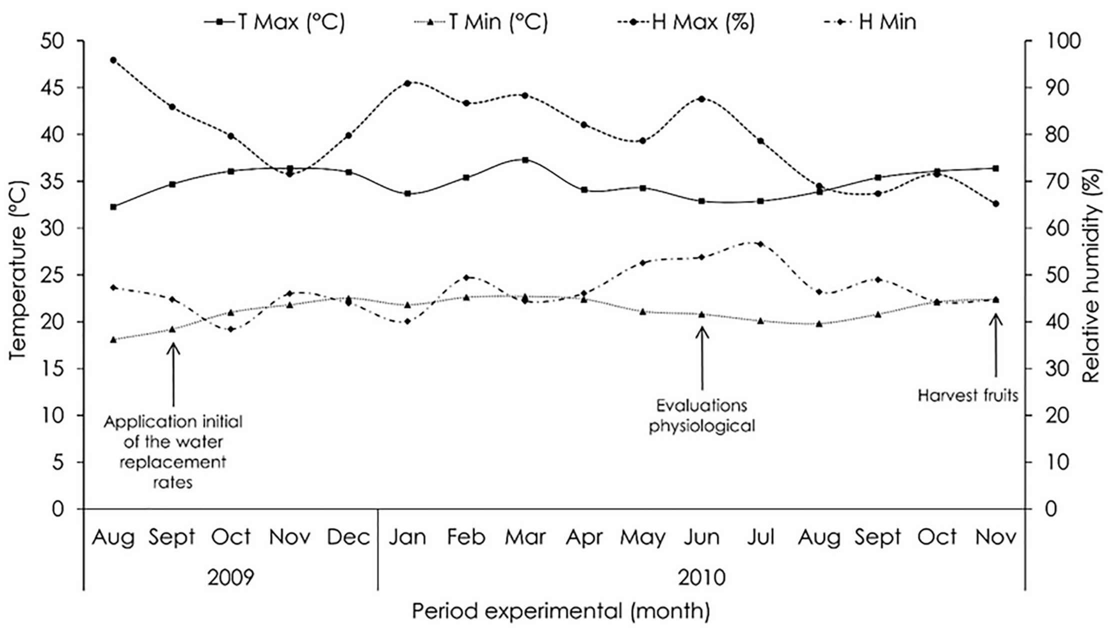

Figure 1. Maximum (T Max) and minimum air (T Min) temperatures, and maximum (H Max) and minimum (H min) relative humidity the experimental period.

Table 1. Chemical and physical attributes of soil in the experimental area before the developing of the experiment.

Chemical Attributes	pH (H_2O)	7.10
	Organic matter (g kg^{-1})	9.54
	P Melinch-1(mg dm^{-3})	36.0
	K ($cmol_c$ dm^{-3})	0.83
	Ca ($cmol_c$ dm^{-3})	2.81
	Mg ($cmol_c$ dm^{-3})	0.70
	Na ($cmol_c$ dm^{-3})	0.16
	Al ($cmol_c$ dm^{-3})	1.70
	H + Al ($cmol_c$ dm^{-3})	2.20
	Sum of bases ($cmol_c$ dm^{-3})	4.50
	Capacity of cation exchange ($cmol_c$ dm^{-3})	6.20
	Saturation for bases (%)	72.6
Physical attributes	Soil bulk density (g cm^{-3})	1.51
	Total porosity (%)	47.0
	Clay (%)	5.8
	Silt (%)	16.8
	Sand (%)	77.4

At 30 days after transplant, after acclimatization of the seedlings, treatments corresponding to the water replacement rates were applied, where the values of rates were calculated by Penman-Monteith (Equation 1) (Allen et al., 1998). The gross water level, application intensity, and irrigation time were determined according to equations 2, 3, and 4, respectively, proposed by Mantovani et al. (2006). Irrigation was performed according to the respective ETo replacement rates through dripping tape, in each row, with emitters with flow rate of 1.3 L h^{-1} and set at every 0.3 m. Climatological data used to calculate ETo were obtained daily at the agrometeorological station located near the experimental area.

$$ETo = \frac{0{,}408\Delta(R_n - G) + \gamma\left(\frac{900U_2}{T+273}\right)(e_s - e_a)}{\Delta + \gamma(1 + 0{,}34U_2)} \quad (1)$$

where, ETo is reference evapotranspiration (mm d^{-1}), R_n is net radiation at crop surface (MJ m^{-2} d^{-1}), G is soil heat flow (MJ m^{-2} d^{-1}), Δ is slope of the vapor pressure curve versus air temperature (kPa.°C^{-1}), U_2 is wind speed measured 2.0 m height (m s^{-1}), T is temperature (°C), e_s is saturation vapor pressure of water (kPa), e_a is actual pressure of water vapor (kPa), and γ is psychrometric factor (MJ kg^{-1}).

$$GWL = \frac{ETo.Ks - Pe}{Ef} \quad (2)$$

where, GWL is the gross water level (mm d^{-1}), ETo is reference evapotranspiration according to Penman-Monteith (mm d^{-1}), Ks is the percentage of wetted area by emitter, Pe is precipitation during the period (mm), and Ef is irrigation efficiency of method.

$$AI = \frac{n \times v}{ec} \quad (3)$$

where, AI is application intensity (mm h^{-1}), n is number of emitters per plant, v is emitter flow (L h^{-1}), and ec is area occupied by papaya plants (m^2).

$$IT = \frac{GWL}{AI} \quad (4)$$

where, IT is irrigation time (h), GWL is the gross water level (mm d^{-1}), and AI is the application intensity (mm h^{-1}).

We measured the internal CO_2 concentration (μmol m^{-2} s^{-1}), stomatal conductance (mmol H_2O m^{-2} s^{-1}), photosynthesis rate (μmol CO_2 m^{-2} s^{-1}), and transpiration rate (mmol H_2O m^{-2} s^{-1}) in the ninth leaf from plant apex (Reis & Campostrini, 2008), to 10 months after transplant of the plants (at flowering stage), between 7 and 10 a.m, by an infrared gas analyzer (LC-PRO+, ADC Bioscientific Ltd, Herts, UK) with airflow of 300 μmol mim^{-1} and an attached light source of 1200 μmol m^{-2} s^{-1}. With these data were calculated water-use efficiency (*WUE*), relating the photosynthesis rate with transpiration rate (*A/T*), and the instantaneous carboxylation efficiency (*IcE*), relating the photosynthesis rate with internal CO_2 concentration (*A/Ic*) (Melo et al., 2014; Silva et al., 2015; Melo et al., 2020).

At 10 months after transplant of seedlings, we proceeded to the determination of chlorophyll *a* fluorescence, assessing the initial fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv), and quantum efficiency of photosystem II (Fv/Fm) (Murchie & Lawson, 2013). Readings were taken five times along the day, at 8:00 a.m., 10:00 a.m., 12:00 a.m., 2:00 p.m., and 4:00 p.m. at ninth leaf from plants apex in each plot after being pre-adapted to the dark for 30 minutes, using a portable fluorometer (LI-1600, USA).

Harvest fruits took place weekly when they reached the maturation ripening stage I (less than 15% of the fruit surface yellow and 85% green light). Fruit mass (kg) was measured according to Morais et al. (2007). Fruit mass was obtained by digital precision scale (0.01g). Those measurements were made individually for each fruit. Yield (Mg ha^{-1}) was estimated based on the mass and number of fruits harvested during the first year (cycle) of production.

Data were submitted to variance analysis by 'F' test (α ≤ 0.05) and regression models were fitted according to the coefficient of determination (α ≤ 0.05), using the *Software* SAEG 9.1 and Table Curve 2D.

Results and Discussion

Water replacement rates significantly influenced the parameters of gas exchange of papaya, except for the transpiration rate that has not changed with the application of treatments. The internal CO_2 concentration (*Ic*) reduced with an increase of ETo replacement rates (Figure 2A), fact that is associated with the carbon metabolism process by plants, once carbon is the substrate for the photosynthetic process. With greater availability of water in the soil, the plant intensifies the gas exchange process that results in higher consumption of CO_2 by photosynthesis and, therefore, lower concentration of this substrate in the substomatal chamber (Farquhar & Sharkey, 1982). Thus, *Ic* reflects CO_2 concentration available to photosynthesis and may indicate if stomata closure affects this activity (Melo et al., 2009). In addition, the reduction loss of water by transpiration through stomata closure may impair CO_2 flux from the atmosphere to the substomatal chamber (Taiz et al., 2017), a fact not observed in this work.

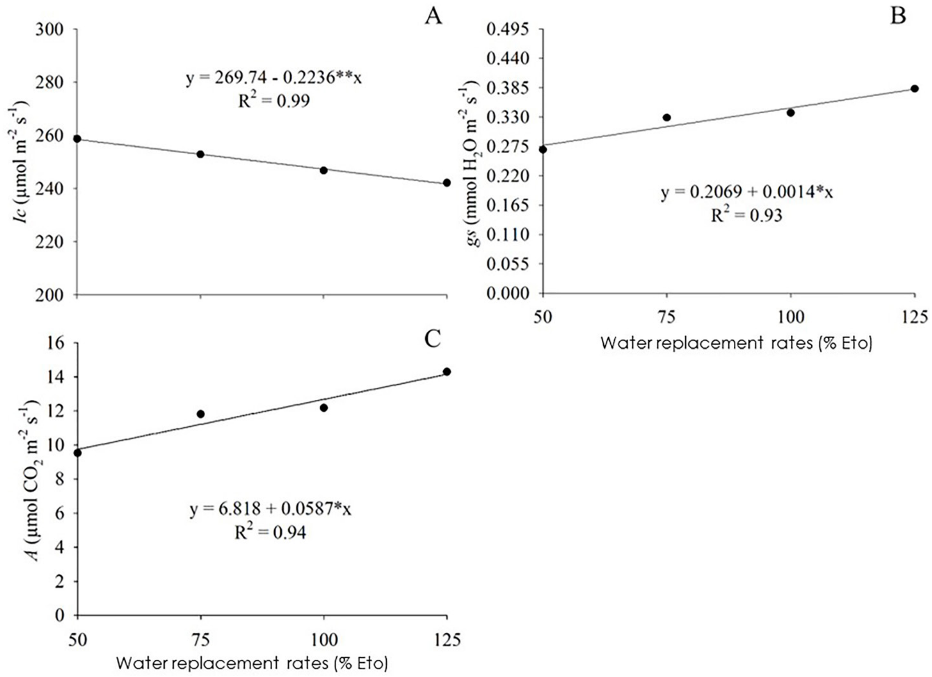

Figure 2. Internal CO_2 concentration - *Ic* (A), stomatal conductance - *gs* (B), and photosynthesis rate - *A* (C) of papaya "Calimosa" under water replacement rates.

The plants of papaya presented increment in the stomatal conductance (*gs*) when increased water replacement rates, occurring higher *gs* with irrigation of 125% ETo and lower values when applied 50% ETo (Figure 2B). Lower values of *gs* result in lower stomatal resistance to maintain the water potential of leaves, answer that is expected in plants subjected to water deficit, being regarded as the first strategy to prevent excessive water loss by plants (Lawson & Vialet-Chabrand, 2019). On the other hand, greater *gs* suggest greater water potential with a signaling effect for stomata opening and a consequent increase in the transpiration flow.

As reported by Melo et al. (2010), stomatal resistance decreases with the increase of water replacement rates in the soil, mainly in the period morning which brings about higher rates of stomatal conductance. Whenever plants close their stomata during hydric stress, they decrease their loss of water by transpiration, however, this behavior results in water loss and reduced turgor pressure on leaves cells, which characterizes stomata closure hydro passively (Tombesi et al., 2015). This condition also can happen through hydro active closure on which stomata close whenever leaves or roots show signs of dehydration (Taiz et al., 2017; Lawson & Vialet-Chabrand, 2019).

It is known that stomata are gas exchange regulators (Lawson & Vialet-Chabrand, 2019) and, according to *gs* behavior in response to soil water availability, it was possible to observe a direct relationship with CO_2 assimilation dynamics. Photosynthesis rate (*A*) in papaya plants increased with greater water replacement rates (Figure 2C), following the same trend as *gs*, which suggests that increasing *gs* imply higher CO_2 influx into leaves mesophyll and, therefore, higher rates of CO_2 assimilation. Thus, increasing CO_2 assimilation rate and stomatal conductance observed should be related to the increased soil water availability by ETo replacement rates, which enabled more stomata opening and, consequently, improvements in gas exchange with the environment. Amaral et al. (2006) reported that the most diffusive stomata resistance reduces photosynthesis, especially by gas transfer restriction in the leaves.

Carbon dioxide absorption from the external environment promotes water loss and the reduction of this loss restricts the CO_2 input throughout gas exchange (Lawson & Vialet-Chabrand, 2019). This interdependence expressed by the relationship between photosynthesis and transpiration shows water-use efficiency (*WUE*) in which observed values evidence the amount of carbon fixed by plants through the water amount lost on transpiration (Taiz et al., 2017). In this sense, the increase in soil water availability promoted an increase in *WUE*, with greater efficiency presented in papaya plants who received irrigation of 125% ETo (Figure 3A). Regarding *IcE* is observed an increase as a function of water replacement rates (Figure 3B). These results could be explained by greater CO_2 uptake when papaya were irrigated with higher water levels, resulting in greater efficiency of photosynthesis. This behavior is shown by low internal carbon accumulation in the leaves.

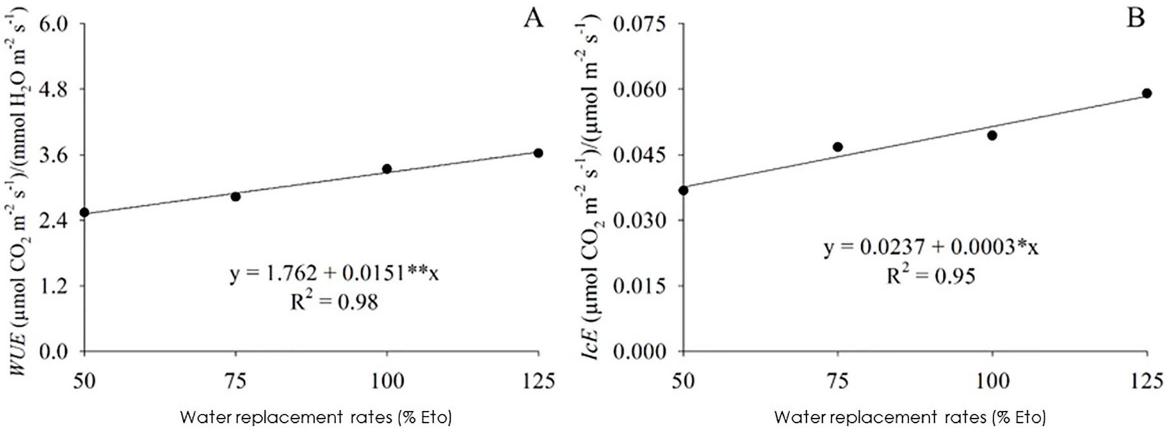

Figure 3. Instantaneous water-use efficiency - *WUE* (A), and instantaneous carboxylation efficiency -*IcE* (B) of papaya "Calimosa" under water replacement rates.

The parameters of chlorophyll *a* fluorescence were significantly affected by water replacement rates and evaluation period along the day, except for quantum efficiency of photosystem II (Fv/Fm) that was not influenced by the evaluation period. Initial fluorescence (Fo) increased gradually throughout the day, with maximum value (518.27) at 4:00 p.m. and an increase of 13.5% against fluorescence measured at 8:00 a.m. (Figure 4A). With the increase in air temperature throughout the day, mainly between 12:00 a.m. and 4:00 p.m., thermal stress is caused in plants, affecting the photosynthetic process because high temperatures cause stomatal closure and reduce intercellular of CO_2 concentration causes changes in the redox properties in acceptors of electrons in the PSII and reduces the efficiency of the electrons transport in both photosystems (Mathur et al., 2014).

Low water replacement rates promoted high values of initial fluorescence (Fo), mainly when an applied rate of 50% ETo (Figure 4B). However, the application of greater irrigation rates resulted in lower Fo and, therefore, less loss of energy captured. Fo represents part of energy captured by complex-antenna that was not absorbed by photosynthetic pigments, when it has high values, reveals damage in the reaction center of PSII (P680) or weakening in the transfer capacity of the energy of antenna complex to the reaction center (Murchie & Lawson, 2013). Thus, the increase in Fo may indicate the momentary occurrence of complex-antenna dissociation (LHC II) of PSII, inactivation of photochemical reactions in

PSII or a brief inhibition of electron flow due to the reduced transfer from quinone QA and QB (Mathur et al., 2014).

Maximum fluorescence (Fm) occurs more slowly than Fo and it refers to the state where the reactions centers of PSII are unable to increase photochemical reactions by reaching the peak of fluorescence (Murchie & Lawson, 2013), being the energy released or lost by electrons which, thrown out of their atoms, can reach the outside QA (Quinone, stable primary receptor belonging to PSII) (Baker, 2008). In the current study, Fm presented a growing performance between 08:00 a.m. and 4:00 p.m. (Figure 4C). Regarding water replacement rates, it was observed maximum value of Fm (2447.93) with estimated rate of 94% ETo, being higher than obtained in greater soil water availability (125% ETo) (Figure 4D). Fm indicates the maximum fluorescence intensity when the reaction centers FSII is unable of increasing the photochemical reactions and reaching their maximum capacity. Thus, it is suggested that papaya plants have the ability to increase their photochemical reactions when irrigated with 100% ETo. However, a reduction in photochemical reactions occurs when soil water availability is low.

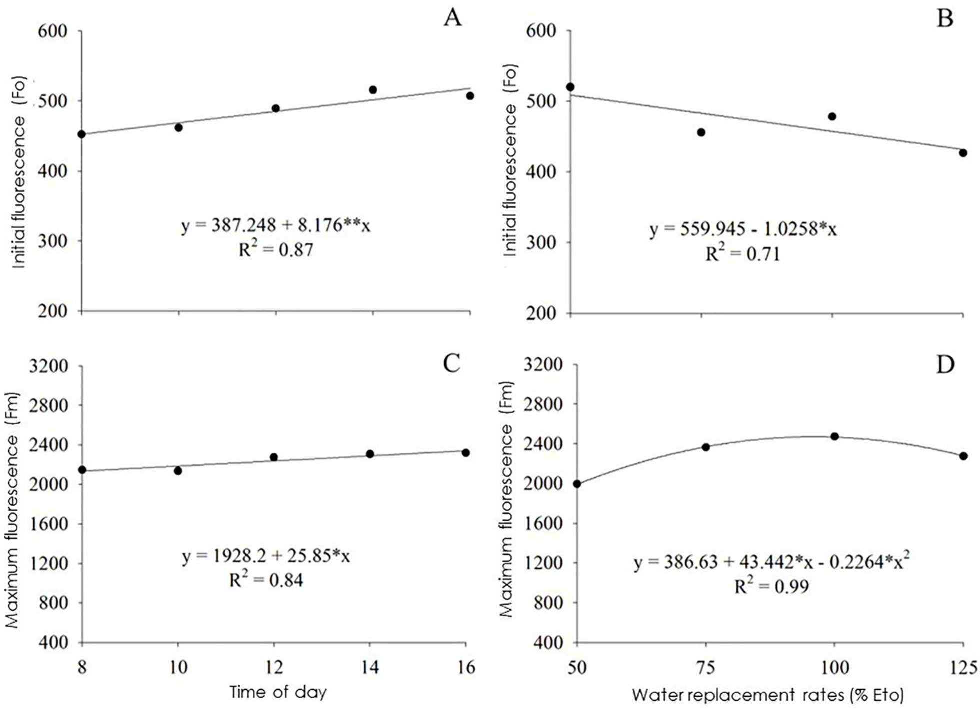

Figure 4. Initial fluorescence - Fo (A and B) and maximum fluorescence - Fm (C and D) of papaya "Calimosa" under water replacement rates.

The variable fluorescence (Fv) is the variation in between the initial and maximum fluorescence. Throughout the day, Fv had a crescent trend, with values ranging from 1674.50 to 1920.25 between 8:00 a.m. and 4:00 p.m., respectively, with an increase of 15% in the last assessment time (Figure 5A). Application of water replacement rates promoted increases in Fv up to 94% ETo, occurring reduction of 9% in Fv with the application of rates of irrigation above that level (Figure 5B).

Fv is an important analysis because the higher your value the greater is plant capacity on transfer energy from ejected electrons of the pigment molecules for the formation of the NADPH and ATP reducers, which reflects in higher photosynthesis CO_2 assimilation capacity (Baker, 2008). In this sense, papaya reached the higher energy transference capacity into the production of NADPH and ATP reducers when they were irrigated with 100% ETo, however, with water replacement rates lower than 100% ETo and with 125% ETo there was a reduction in Fv.

Similar behavior to Fv was observed in the photochemical efficiency of PSII (Fv/Fm) when supplied the water replacement rates, obtaining maximum estimated value (0.82) with the application of 93% ETo (Figure 5C). The low soil water availability with lower irrigation rates promoted low values of Fv/Fm, that according to Brestic et al. (2012) and Mathur et al. (2014) can is associated directly with the greater Fo and power dissipation as heat, and with low Fm in high-temperature environments. In addition, it should be pointed out that Fv/Fm reflects the photochemical efficiency of PSII and have been used in assessing damages done to the photosynthetic system. However, photoinhibition intensity may be assessed by reducing this parameter. According to Fan et al. (2014) and Yamamoto (2016), Fv/Fm values less than 0.8 are indicative of photoinhibition in the plants. Thus, lows values of Fv/Fm observed occurred due to water stress promoted by lows irrigation blades in which plants were submitted.

The water replacement rates significantly affected fruit mass, number of fruits per plant, and yield. The fruit mass increased gradually with supplying of water replacement rates up to 100% ETo (Figure 6A). On the other hand, the lower fruit mass (0.71 kg) was obtained with 50% ETo. The largest water availability in the soil contributed to developing more roots, occupying a larger dimension in soil and possibly absorption more nutrients, besides increase photosynthetic activity with intense gain assimilates, and, therefore, promote cell division, which enables maximum fruit development (Suassuna et al., 2011). The results found were higher than that one found by Garcia et al. (2007) which contested fruit mass of 0.89 kg with the application of 100% ETo.

The number of fruits variated with the different water replacement rates, obtained maximum values of 75 fruits per plant when was applied 95,6% ETo (Figure 6B). However, the application of 50% ETo promoted a reduction of 39% on number fruits, as well, a reduction of 13% when it was applied irrigation rate 125% ETo. Thus, water excess or water deficit reduces the number of fruits, once the soil humidity has relation with a decrease in the number of fruits because it may induce the formation of male and sterile papaya flowers, which compromise the number of fruits.

Regarding fruit yield, it is showed a quadratic adjustment of the data with the increase of yield up to the estimated replacement of 95% ETo, which provided the maximum yield of 87.7 Mg ha^{-1} (Figure 6C). Plants irrigated with maximum water replacement (125% ETo) presented a reduction of around 20% on the yield compared to the plants irrigated with 95% ETo. The results found indicating that water excess or water deficit interferences in the yield of papaya. In addition, irrigation rates of 95% ETo may be recommended to papaya plants, due to higher fruit productivity is correlated with maximum fluorescence.

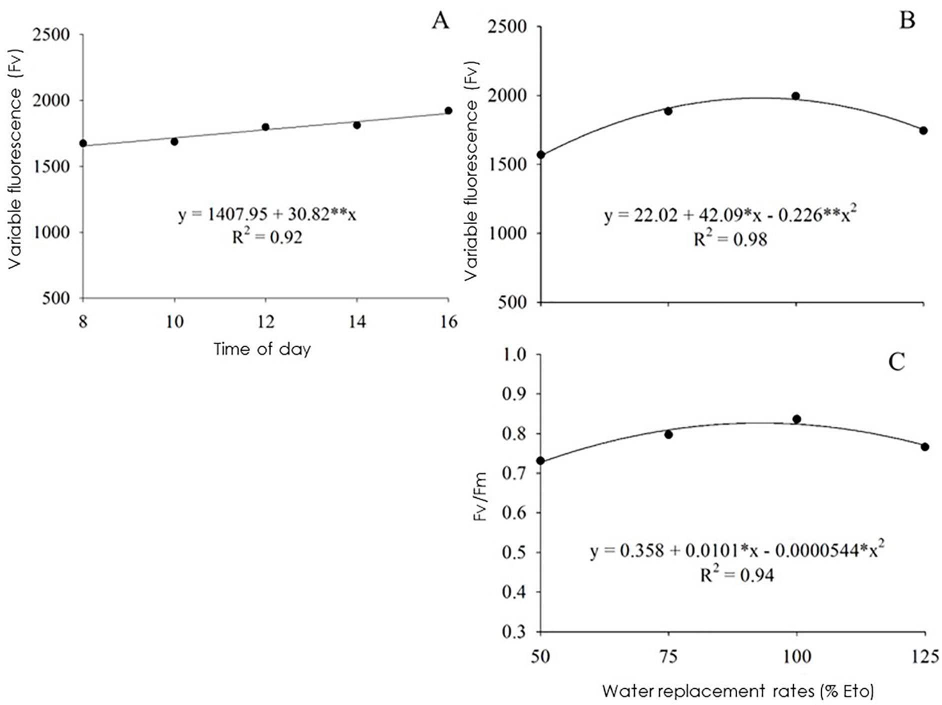

Figure 5. Variable fluorescence - Fv (A and B) and photochemical efficiency of PSII - Fv/Fm (C) of papaya “Calimosa” under water replacement rates

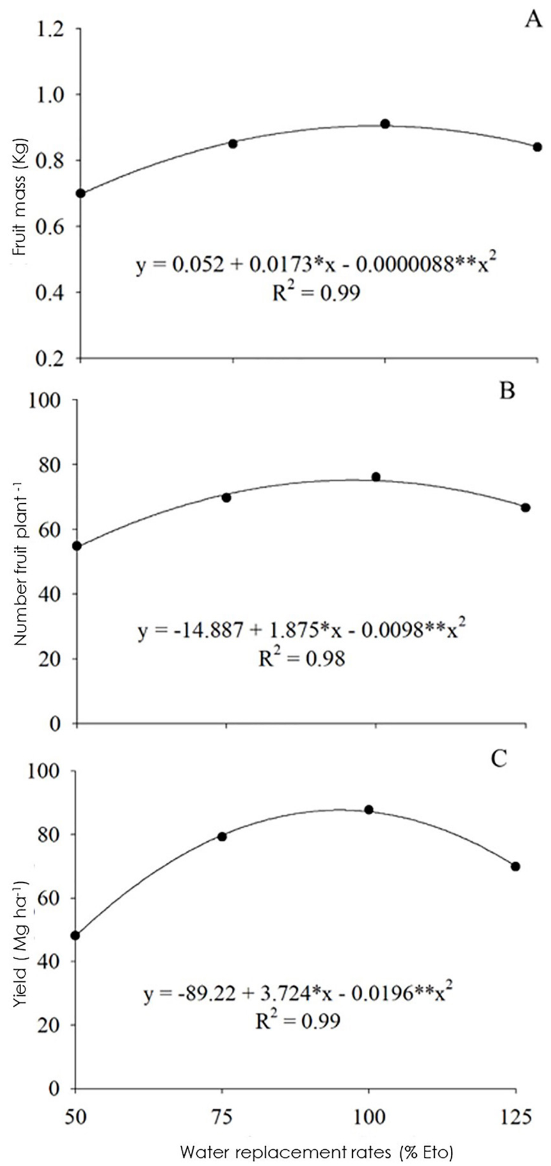

Figure 6. Fruit mass (A), number fruits (B) and yield (C) of papaya "Calimosa" under water replacement rates.

Conclusions

Application of water replacement rates of 100% ETo provide conditions adequate for the activity of gas exchange and better quantum efficiency of photosystem II, that contribute to fruit production in papaya.

Water replacement of 75% ETo can be used for growing papaya in semiarid climate conditions, with small fruit yield losses.

Water replacement with rates less than 75% ETo causes drastic reductions in gas exchange, quantum efficiency of photosystem II, and fruit production of papaya, which impairs its cultivation in semiarid environments.

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