Differential response of photosystem II and I photochemistry in leaves of two Crambe abyssinica Hochst lineages submitted to water deficit


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Abstract

Water stress is one of the most important abiotic factors affecting plants worldwide. This study compared the photochemical responses of two lineages of Crambe abyssinica (FMS CR 1307 and 1326) under water deficit (WD) conditions. The relative water content (RWC), stomatal conductance, chlorophyll (Chl) index, and Chl a fluorescence were evaluated. FMS CR 1326 showed greater reductions in RWC under WD. The FMS CR 1307 showed greater reductions in the connectivity of energy (L-band) and electron transfer from the oxygen-evolving complex (K-band), followed by a lower ability to maintain the reduction of plastoquinone. However, the increased size of the pool of the final electron acceptors in PSI for this lineage was observed. The FMS CR 1326 plant lineage showed an advantage over the FMS CR 1307 in terms of stability and efficiency of PSII under low water availability conditions.

Keywords: chlorophyll a fluorescence; JIP-test; K-band; OJIP curves; performance index; photochemical tolerance.

Introduction

Water deficit (WD) is one of the most important and complex factors that hinder plant development and crop productivity (Lang et al. 2018). With an increase in global temperature, changes in the world rainfall distribution patterns are expected to occur, favoring more drought periods in many regions (Lau and Kim 2015). Furthermore, the increase in air temperature has caused a decrease in soil capacity to retain moisture, resulting in the acceleration of WD conditions (Sikder et al. 2015). Consequently, farmers have increased irrigation practices to sustain the high productivity of plants. However, the high cost and inadequate engineering of the irrigation systems associated with limited water resources have restricted its use (Çakir 2004).

Plants have developed many strategies to maintain growth when under limited or irregular water availability (Hummel et al. 2010). Drought tolerance is defined as the capacity of plants to grow and produce satisfactorily under limited water availability or periodic deficiency of rainwater (Ashley 1993). Nevertheless, WD negatively affects growth and other physiological processes, even in drought-tolerant plants (Covre et al. 2016, Wang et al. 2017). These effects are the result of osmotic stress, which reduces cell turgescence, stomatal conductance, and transpiration rates, which negatively affect CO₂ assimilation and cause damages to the reaction centers of PSII (Mehta et al. 2010). Consequently, those effects can confer low PSII efficiency, which may lead to reduced plant productivity (Velázquez-Márquez et al. 2015).

Chl a fluorescence is a noninvasive method that can reveal the functional state or efficiency of the photosynthetic apparatus (Borawska-Lurrulowićz et al. 2020). As such, it has been widely used in experiments for photochemical identification of species/genotypes of plant tolerance/susceptibility to abiotic stresses (Mehta et al. 2010, Falqueto et al. 2017, Kalaji et al. 2018). Under WD, Chl a fluorescence analyses have shown positive values for L- and K-bands in two cultivars of Passiflora edulis L.,

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Abbreviations: ABS/RC – absorption flux (of antenna Chl) per RC; Chl – chlorophyll; OEC – oxygen-evolving complex; DL/RC – dissipation flux per RC; DM – dry mass; ET/RC – electron transport flux (further than Qa) per RC; F₀ – minimum fluorescence, when all PSII RCs are open; FM – fresh mass; Fm – maximum fluorescence, when all PSII RCs are closed; gₛ – stomatal conductance; P₆₈₀ – primary electron donor of PSII; P₉₆₀ – primary electron donor of PSI; PIₜₒₒ – performance index; PQ – plastoquinone; PQH₂ – plastoquinol; RC – reaction centre; RWC – leaf relative water content; TM – turgid mass; TR/RC – trapping flux per RC; Vₛ – variable fluorescence between steps I (30 ms) and P (300 ms); Vₛₐ – variable fluorescence between steps O (2 ms) and J (2 ms); Vₒₖ – variable fluorescence between steps O (0.02 ms) and K (0.3 ms); Vₒₑ – variable fluorescence between steps O (0.02 ms) and P (300 ms); WD – water deficit; ΔVₒₑ – amplitude of the relative variable fluorescence of the I-to-P-rise; φₒₑ – maximum quantum yield of primary PSI photochemistry.

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FB200 and FB300 (Gomes et al. 2012), two cultivars of Zea mays L., SD609 and ZD958 (Zhang et al. 2015), two genotypes of Crambe abyssinica Hochst, FMS Brilhante and FMS CR 1101 (Martins et al. 2017), and two clones of Hevea brasiliensis L., RRIM600 and FX3864 (Falqueto et al. 2017), and these results have revealed a decrease in energy connectivity between PSII units and impaired performance of the oxygen-evolving complex (OEC). Thus, it is possible to differentiate the tolerance of species/cultivars/genotypes to drought using this method.

Crambe (Crambe abyssinica Hochst, Brassicaceae) is an annual plant that is native to East Africa, particularly Ethiopia (formerly called Abyssinia, from where its name is derived), and was first domesticated in the Mediterranean region. It is now cultivated in various tropical and subtropical regions. The grains are produced only for industrial purposes, aiming at the extraction of valuable oil and other substances (e.g., erucic acid) that have various applications, such as the manufacture of plastics, lubricants, and biodiesel (Carlsson et al. 2007).

As it does not compete with oilseeds used for human nutrition and occupies arable lands in the winter (as a second crop), crambe has become an innovative crop in Brazil. Also, according to Oliveira (2015), the FMS CR 1307 line, one of those being considered as a pilot candidate, while the FMS CR 1326 lineage is still under analysis by the Mato Grosso do Sul Foundation for Research and Diffusion of Agricultural Technologies (Fundação MS). Both lineages have yields greater than the cultivar FMS Brilhante, the only registered genotype (approximately 1,368; 1,357; and 1,254 kg ha⁻¹, respectively) in conditions with adequate water supply.

Considering that water resources are limited and that agriculture consumes large amounts of water, demands for water resources can be mitigated by the selection of species/genotypes of plants that are tolerant to WD (Meng and You 2020).

Statistical analysis: The experiment was performed following a completely randomized design in a factorial scheme, considering two water treatments [daily irrigated (control) and nonirrigated plants (WD)] and two crambe phosphates were added per pot at three separate intervals during the experiment. Besides, insecticides (Evidence®) and fungicides (Ridomil®) were applied according to the culture manual. After 20 d, the seedlings were thinned to one per pot.

All plants (both lineages) were watered daily to maintain the soil humidity at approximately 80% of field capacity, e.g., 0.20 m³ m⁻³. At the age of 50 d, the plants were split into two groups: for each lineage, the first group of plants was maintained with daily irrigation (used as control); and the others were subjected to progressive drought by withholding watering. When the humidity level reached 30% (around 0.06 m³ m⁻³) and the stomatal conductance (gₛ) reached values below 10 mmol(H2O) m⁻² s⁻¹ (Martins et al. 2017), the analysis was performed at 7 d without irrigation and plants presented visual symptoms of predawn wilting. All sampling and measurements were conducted between 5 and 9 h using the third or fourth fully expanded leaf from the apex.

Leaf relative water content (RWC), stomatal conductance (gₛ), and Chl index were measured in 3, 9, and 11 plants per treatment, respectively; the plants were randomly selected. For RWC measurements, five leaf discs (0.78 cm²) were extracted, and they were immediately weighted for obtaining the fresh mass (FM). Then, the turgid mass (TM) was obtained after the hydration of the leaf discs through submersion in distilled water for 24 h in Petri dishes. The dry mass (DM) was obtained after drying the leaf discs over 72 h at 65°C (Martins et al. 2017). The RWC was calculated according to the following expression, and the results expressed in percentage [%]:

\[
\text{RWC} = \frac{[(\text{FM} – \text{DM})/\text{(TM} – \text{DM})]}{\text{TM} – \text{DM}} \times 100
\]

The gₛ and Chl index were measured using a leaf porometer (SC-1, Decagon Devices, USA) and a ChlorofiLOG (CFL 1030, Falkor, Porto Alegre, Brazil), respectively (Arunyanark et al. 2008, Maes et al. 2009). The gₛ was measured on the leaf abaxial surface.

Chl a fluorescence (OJIP transients and JIP-test): Fluorescence signals were registered using a plant efficiency analyzer (Handy-PEA, Hansatech, King’s Lynn, Northfolk, UK), as described by Strasser and Strasser (1995). The measurements were collected from five plants per treatment in leaves that were previously adapted to the dark for 20 min using leaf clips (Hansatech, UK). The fast fluorescence kinetics (F₃ to F₅) was recorded from 10 μs to 1 s after the application of saturated light flash with intensity reaching 3,000 μmol(photon) m⁻² s⁻¹. The fluorescence intensity at 0.02 ms (considered as F₁), 0.15 ms (Fₛ), 0.3 ms (Fᵢ), 2 ms (Fᵢ), 30 ms (Fᵢ), and 300 ms (Fᵢ₃) was collected and used to obtain the parameters from JIP-test (Strasser et al. 2004, Stirbet and Govindjee 2011). OJIP curves were normalized according to the method of Yusuf et al. (2010).

Materials and methods

Plant growth conditions and treatments: Seeds of Crambe abyssinica Hochst, lineages FMS CR 1307 and FMS CR 1326, were previously disinfected with ethanol 70% for 2 min, 1% sodium hypochlorite [v/v] for 20 min, and Ridomil® fungicide for 10 min, followed by multiple cleanings with autoclaved distilled water and placed to germinate in pots of 5.5 L (15 seeds per pot) filled with soil (75.5% sand, 17.2% clay, and 5.2% silt). Previously, chemical analysis of soil was performed to adjust nutrient concentrations and pH, following the recommendations of Oliveira et al. (1991). Thirty grams of single superphosphate were added per pot at three separate intervals during the experiment. Besides, insecticides (Evidence®) and fungicides (Ridomil®) were applied according to the culture manual. After 20 d, the seedlings were thinned to one per pot.

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lineages (FMS CR 1307 and 1326). All statistical analysis was conducted using the statistical software SISVAR version 5.6. Significant differences between the treatments were evaluated using analysis of variance (ANOVA) and Tukey’s test \((p \leq 0.05)\).

Results

RWC, \(g_s\), and Chl index: Significant differences of RWC were observed as a function of WD and crambe lineages (Fig. 1). The RWC values obtained for plants irrigated daily (control) were 65.7 and 62.7\% for the lineages FMS CR 1307 and 1326, respectively. After water deficit conditions, reduced values of RWC were observed in both crambe lineages compared to the control plants. Lower RWC values were obtained for the FMS CR 1326 (25.9\%) in comparison to the lineage FMS CR 1307 (34.9\%).

Reductions in \(g_s\) were also observed when crambe lineages were submitted to WD \([152.3 \text{ to } 7.7 \text{ mmol(H}_2\text{O)} \text{ m}^{-2} \text{ s}^{-1}]\). No significant differences in \(g_s\) were observed between the crambe lineages (Fig. 2A). The Chl index \(a\) and \(b\) increased significantly when the plants were submitted to WD (Chl \(a\) from 36.9 to 40.05 and Chl \(b\) from 15.8 to 23.7), but no significant difference was observed between crambe lineages (Fig. 2B).

OJIP Chl \(a\) fluorescence and normalizations: To evaluate the polyphasic behavior of OJIP curves for the photochemical events reflected in the O–J, J–I, and I–P phases, the Chl \(a\) fluorescence data were double normalized between \(F_0\) and \(F_m\) as \(\Delta V_\text{OP} = (F_t – F_0)/(F_m – F_0)\) and showed the difference kinetic, \(\Delta V_\text{OK} = V_\text{OK(treatment)} – V_\text{OK(control)}\) (Strasser et al. 2007). Under WD, the positive amplitudes of \(\Delta V_\text{OP}\) were obtained for both crambe lineages. However, the higher positive amplitude \((\approx 0.08)\) was obtained for the FMS CR 1307 lineage when compared to FMS CR 1326 lineage \((\Delta V_\text{OP} \approx 0.06)\) (Fig. 3A).

The relative fluorescence between the O- and K-steps (obtained at 0.02 and 0.3 ms, respectively), reported as \(V_\text{OK} = (F_i – F_\text{0})/(F_K – F_\text{0})\), and between O- and J-steps (obtained at 0.02 and 2 ms, respectively), reported as \(V_\text{OJ} = (F_i – F_\text{0})/(F_J – F_\text{0})\), were normalized and presented as the kinetics difference \(\Delta V_\text{OK} = V_\text{OK(treatment)} – V_\text{OK(control)}\) and \(\Delta V_\text{OJ} = V_\text{OJ(treatment)} – V_\text{OJ(control)}\), respectively. The kinetic difference \(\Delta V_\text{OK}\) and \(\Delta V_\text{OJ}\) made the L- and K-bands visible, respectively. In this study, both crambe lineages presented an L-band (obtained at 0.15 ms) and K-band (obtained at 0.3 ms) with positive amplitudes after submission to WD (Fig. 3B,C). The larger K-band values were obtained from the FMS CR 1307 crambe lineage (0.13), followed by the FMS CR 1326 lineage (0.06). Similarly, a higher positive amplitude for the L-band was observed in the FMS CR 1307 crambe lineage when compared to FMS CR 1326 (0.19 and 0.12, respectively).

To evaluate the O–I phase that occurred between 0.02 and 30 ms, the normalizations \([V_\text{OJ} = (F_i – F_\text{0})/(F_J – F_\text{0})]\) and the kinetic differences \([\Delta V_\text{OJ} = V_\text{OJ(treatment)} – V_\text{OJ(control)}]\) were utilized, allowing observation of the O–I phase in \(V_\text{OJ} \leq 1\) (Strasser et al. 2004). In this study, the crambe lineages showed positive amplitudes in the O–I phase when submitted to water deficit. A greater incline was observed for \(V_\text{OJ} \leq 1\) in the FMS CR 1307 crambe lineage (Fig. 3D). Also, the I–P phase was evaluated as \(V_{\text{IR}} \geq 1\) and \(V_\text{IR} = V_\text{IR} – 1\) was plotted from 30 to 300 ms when the fluorescence data were normalized between the O–I phase (Fig. 4A). In the control group plants, higher values were obtained for \(V_\text{OJ} \geq 1\) in the FMS CR 1326 lineage \((1.25)\) when compared to the FMS CR 1307 lineage \((1.23)\). However, WD resulted in reduced \(V_\text{OJ} \geq 1\) values in both crambe lineages evaluated. The FMS CR 1326 lineage showed higher \(V_\text{OJ} \geq 1\) values \((1.4)\) when compared to the FMS CR 1307 crambe lineage \((1.36)\).

The normalization \(V_\text{IR} = (F_i – F_\text{0})/(F_m – F_\text{0})\) and the kinetic difference \(\Delta V_\text{IR} = V_\text{IR(treatment)} – V_\text{IR(control)}\) values were plotted between 30 and 300 ms (Fig. 4B,C). According to
the Michaelis-Menten equation, where $V_{IP} = 0.5$ (Yusuf et al. 2010), the $V_{IP}$ data showed higher velocity constants for the FMS CR 1326 compared to the FMS CR 1307 (0.80 and 0.54, respectively).

This result was better elucidated by analyzing the kinetic difference $\Delta V_{IP}$ (Fig. 4C), as it showed that the negative amplitude band was higher in the FMS CR 1326 lineage ($-0.08$).

**JIP-test:** The specific energy fluxes varied significantly in WD and crambe lineages (Fig. 5). However, for the $\varphi_{P0}$ and $P_{\text{total}}$, this variation occurred independently from WD treatment (Fig. 6). The specific energy flux values (ABS/RC, TR/RC, and DL/RC) increased significantly in plants exposed to WD. For ABS/RC, TR/RC, and DL/RC, the FMS CR 1307 and FMS CR 1326 crambe lineages presented 3.26, 2.42, and 0.84 and 2.74, 2.15, and 0.58, respectively. For ET/RC, no significant difference was observed between treatments and crambe lineages (Fig. 5). Also, WD reduced the maximum quantum yield of primary photochemistry of PSII ($\varphi_{P0}$) and the performance index (P$_{\text{total}}$) compared to control plants (from 0.86 to 0.76 and from 35.33 to 9.75, respectively), independent of crambe lineage evaluated (Fig. 6).

**Discussion**

The ability of plants to tolerate water deficit conditions can be attributed to several mechanisms, including the efficiency in maintaining a high RWC and stomatal closure (Oukarroum et al. 2007), by reducing water loss through transpiration (Lawson and Blatt 2014). The two crambe lineages evaluated in this study showed different RWC values. Under well-irrigated conditions (control), the plants of the FMS CR 1326 lineage showed RWC values 4.5% lower than that of the FMS CR 1307 lineage. Under WD, the plants of the FMS CR 1326 lineage
showed RWC of approximately 25.7% while FMS CR 1307 lineage had 34.9%. This difference in RWC between the lineages can be related to the different capacities for conducting water through the xylem in response to a specific hydraulic signal (Sinclair et al. 2008). This trait may have been acquired via natural selection since the two crambe lineages under the current study originated from natural crosses between different genotypes of the cultivar FMS Brillante. According to Lara-Fioreze et al. (2013), the FMS Brillante crambe cultivar is considered to be tolerant to WD. In this study, the higher RWC values observed in lineage FMS CR 1307 under water deficit and control conditions are associated with its greater ability to maintain a high water content in the leaf tissue, compared to FMS CR 1326 plants.

The lower g, values verified in plants of crambe under WD suggest that there was the closure of the stomatal pore. Plants close stomata to limit water loss, and this is a response to hydraulic signals from changes in leaf turgor (Huber et al. 2019). Stomatal closure generally restricts stomatal diffusion of CO₂ and is coupled with a decrease in the mesophyll conductance of CO₂ (internal CO₂ diffusion) (Guha et al. 2013). Thus, the reduced g, values of both crambe lineages may have hampered the supply of CO₂ to the carboxylation sites. Plants under moderate WD may present a reduced photosynthetic performance, mainly due to stomatal closure. However, if plants remain in such conditions (severe drought), the photosynthetic mechanism may also be affected by nonstomatal limitations, due to both reduced Rubisco content and activity and increased amounts of nonreducing Q₀, PSII centers (Stirbet et al. 2018). In this work, plants showed clear signs of drought stress, which compromised the photosynthetic apparatus performance.

The crambe lineages subjected to WD showed increases in the Chl index (dimensionless). According to Arunyanark et al. (2008), the Chl index values are associated with the Chl density. Thus, the results obtained in this study indicate increases in the Chl density in the plants submitted to WD. In this condition, the leaf thickness can decrease, which is also associated with the RWC and cell volume reductions, and this results in more Chl per unit of area (Arunyanark et al. 2008). An increase in the Chl density under WD was already described by Puangbut et al. (2017) in artichoke genotypes (Cynara scolymus L.).

The signs of stress were evidenced by the kinetics of Chl a fluorescence, as well as the JIP-test parameters. The analysis of ΔV_OP corresponds to the primary photo-chemical events of photosynthesis on the acceptor side of PSII (Joliot and Joliot 2002). In this study, the two crambe lineages submitted to WD showed positive ΔV_OP amplitudes. The higher positive ΔV_OP amplitude observed in the FMS CR 1307 lineage under WD might have been caused by the lower efficiency in reoxidizing Q₀ and the consequent reduction of electrons transport flux after Q₀ (Zhang et al. 2015).

The energetic connectivity or grouping among the PSII units is verified by analyzing the L-band (Oukarroum et al. 2007, Tsimilli-Michal and Strasser 2008). Positive L-band values indicate low energy connectivity (Yusuf et al. 2010). In this study, the higher positive L-band amplitude observed in the FMS CR 1307 crambe lineage suggests less stability of the system and/or reduction of active reaction centers associated with PSII (Sharma et al. 2014). This result indicates that FMS CR 1326 maintained
better utilization of excitation energy and greater stability of the system when exposed to WD (Oukarroum et al. 2007, Strasser et al. 2007). According to Redillas et al. (2011), increased connectivity can be considered a partially protective mechanism, directing more excitation energy to photochemistry. Therefore, the present results suggest that FMS CR 1326 lineage was more stable under WD for presenting a greater RWC maintenance. FMS CR 1326 lineage presented a 41.3% reduction and FMS CR 1307 a 53.1% reduction when they were compared to their control plants. Also, under WD, the RWC maintenance may be impaired by the osmotic action through the increase of proline content, which can indirectly affect the photosynthetic apparatus and stabilization of cell membranes (Rapacz et al. 2019).

The transfer of electrons from the oxygen-evolving complex (OEC) to the P_{680} reaction center refers to the K-band (Skotnica et al. 2000). Therefore, positive values indicate a reduction in the transfer of electrons to P_{680} (Jiang et al. 2008). The higher positive amplitude of the K-band observed in the FMS CR 1307 crambe lineage suggests the reduced transfer of electrons from the OEC to the P_{680} reaction center (Skotnica et al. 2000). De Ronde et al. (2004) suggested that positive K-band amplitudes indicate activation of some defense mechanisms, such as accumulation of glycine betaine, proline, and sugars.

In this study, the positive amplitude of the O–I phase (V_{o1} ≥ 1) was observed in the two crambe lineages, noting a higher positive amplitude for the FMS CR 1307 lineage. This result is an indicator of low capacity to maintain the reduction of PQ since the O–I phase allows for evaluation of the sequence of photochemical events from energy capture starting in PSII to a reduction of PQ (Yusuf et al. 2010). All these results indicate that the FMS CR 1326 lineage is more efficient in reoxidizing Q_{x} and in exchanging energy between the PSII units. Furthermore, the low damage to the OEC (K-band), as well as the higher capacity to maintain the reduction of PQ described in FMS CR 1326, evidences higher photochemical tolerance to WD by FMS CR 1307.

The WD also resulted in decreased V_{o1} ≥ 1. The I–P phase reflects the events related to the electron flow from PQH_{2} to the final PSI acceptors. Thus, the repeated reduction of plastocyanin and P_{700} in PSI events can be evaluated (Chen et al. 2014). The lower V_{o1} ≥ 1 values obtained in the FMS CR 1307 lineage indicates that less electron flux reached the final PSI acceptors. In this study, this apparent decline in the I–P phase occurred due to the drastic decrease of water content in the leaves, which could have reached the threshold of acclimation for drought (Guha et al. 2013).

According to Yusuf et al. (2010), the inverse of the time to reach V_{o} = 0.5 provides an estimate of the overall reduction rate of the final electron acceptors of PSI. In turn, ΔV_{o} reflects the size of the final electron acceptors pool of PSI, i.e., the efficiency of the electron transport through PSI to reduce the final acceptors beyond PSI (Salvatori et al. 2015, Souza et al. 2019). The present results indicate both lower efficiency of electrons transfer to the acceptor side of PSI (reduction rate) and smaller size of the PSI final electron acceptor pool in both crambe lineages studied under water deficit, noting a stronger effect in the FMS CR 1326 lineage.

Under the suppression of the linear electron transport in PSII, Wang et al. (2017) suggested that the cyclic electrons transport (CET) probably compensates for the loss of reduction capacity in PSI. The activation of CET is a common photoprotective response to several stress factors, which prevents the formation of reactive oxygen species (ROS) (Oukarroum et al. 2015). In this study, the two crambe lineages probably increased the CET to improve the metabolic energy (ATP) under WD, considering the suppression of electron transport in PSII. The results obtained in this study indicate a possible correlation between the higher electron flow suppression in PSII (evaluated through ΔV_{o1} K-band, and L-band) and the increased cyclic electron flow (ΔV_{o}). This provided greater protection to FMS CR 1307 since this crambe lineage showed a higher photochemical loss in PSI under WD compared to FMS CR 1326 (2014). All these results indicate that some RCs were inactivated and the efficiency of the sequence of photochemical events in both crambe lineages increased (Meng et al. 2016). The inactivation of RC (decrease of nonreduced Q_{o} or heat dissipation) can be indicative of susceptibility to photoinhibition, i.e., the inactivation of RC is considered to be a downregulation mechanism to dissipate the excess of energy absorbed (Franic et al. 2018). Furthermore, increases of TR_{o}/RC can indicate impairment of the OEC, corroborated by positive K-band amplitudes, which showed higher amplitude in the FMS CR 1307 crambe lineage. The increase of ABS/RC and TR_{o}/RC did not result in increased transport flow (ET_{o}/RC) values, but rather, it caused an increase of DI_{o}/RC values, which implies a higher loss of excitation energy as heat (Kalaji et al. 2014).

The maximum quantum yield of the primary photochemistry of PSII (φ_{PSII}) and P_{lateral} were reduced in the crambe lineages submitted to WD. Reductions of φ_{PSII} are usually related to the degradation of the polypeptide D1, which results in an increased number of inactive RCs associated with PSII (Yusuf et al. 2010). P_{lateral} is considered one of the most sensitive parameters of the JIP-test. P_{lateral} measures the performance up to the final electron acceptors of PSI (Tsimilli-Michael and Strasser 2008, Yusuf et al. 2010).
2010). This shows that primary photochemical reactions were affected by WD.

**Conclusions:** The water deficit had a significant effect on the photochemical activity of crambe during the vegetative phase, reducing photosynthetic apparatus performance. Under WD, there were compromises in the energy fluxes per RC and reduction in the use of energy of crambe lineages, but WD affected the FMS CR 1307 plants to a greater extent (higher values of ABS/RC, TR0/RC, DL0/RC, and higher positive amplitudes of L- and K-bands). Plants of the FMS CR 1307 lineage presented an increase in the pool size of final electron acceptors in PSI (ΔV0). The FMS CR 1326 lineage plants presented an advantage over FMS CR 1307 in terms of stability and efficiency of PSI under low water availability conditions.

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