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CONTROL OF VOLUNTEER CORN AS A FUNCTION OF LIGHT RESTRICTION PERIODS AFTER DIQUAT APPLICATION[1]

GUILHERME MENDES PIO DE OLIVEIRA[2]*, HALLEY CAIXETA OLIVEIRA[2],
MARCELO AUGUSTO DE AGUIAR E SILVA[2], GILIARDI DALAZEN[2]

ABSTRACT - The action of photosystem I (PSI) inhibiting herbicides depends on light to cause oxidative stress in plants. However, their translocation is inhibited due to their rapid action in the presence of light. The aim was to evaluate the efficacy of the herbicide diquat for control of corn plants subjected to different periods of absence of light after application. Two experiments (field and greenhouse) were conducted, applying the herbicide diquat (200 g a.i. ha^{-1}) to maize plants at stage V4. The plants were subjected to different periods of absence of light after diquat application: 0; 1; 2; 3; 4; 5 and 6 hours. A treatment without herbicide application was used as a control. The control (%) and biomass of corn plants were evaluated in both experiments, and photosynthetic activity and hydrogen peroxide (H_2O_2) accumulation in leaves were evaluated in the greenhouse experiment. The results showed that diquat needs at least 5 hours of absence of light after application to fully control corn plants. The plants recovered when using shorter periods (4 hours or less) of darkness, and injuries were restricted to points where the herbicide had contact with the plant. The ability of plants to recover was related to the higher photosynthetic activity and oxidative stress induction due to early light exposure. Thus, the lower production of H2O2 in plants kept in the dark for longer periods after herbicide application allows the translocation of the herbicide to meristems, which prevents regrowth of corn plants.

Keywords: Bipyridyliums. Chlorophyll fluorescence. Oxidative stress. Photosystem I inhibiting herbicides. *Zea mays* L.

CONTROLE DE MILHO VOLUNTÁRIO EM FUNÇÃO DE PERÍODOS DE AUSÊNCIA LUMINOSA APÓS A APLICAÇÃO DE DIQUAT

RESUMO - A ação de herbicidas inibidores do fotossistema I (FSI) depende da luz para causar estresse oxidativo nas plantas. No entanto, sua translocação é autoinibida devido à sua rápida ação na presença de luz. Objetivou-se avaliar a eficácia do herbicida diquat no controle de plantas de milho submetidas a diferentes períodos de ausência de luz após a aplicação. Foram realizados dois experimentos (campo e casa de vegetação), aplicando diquat (200 g ia ha^{-1}) em plantas de milho em V4. As plantas foram submetidas a 0; 1; 2; 3; 4; 5 e 6 horas de ausência luminosa após a aplicação. Um tratamento sem aplicação de herbicida foi usado como controle. O controle (%) e a biomassa das plantas foram avaliados em ambos os experimentos, e a atividade fotossintética e o acúmulo foliar de peróxido de hidrogênio (H_2O_2) foram avaliados no experimento em casa de vegetação. Os resultados demonstraram que o diquat necessita de pelo menos 5 horas de ausência de luz após a aplicação para controlar totalmente as plantas. As plantas se recuperaram em períodos mais curtos (4 horas ou menos) de escuro, e as injúrias ficaram restritas aos pontos onde o herbicida teve contato com a planta. A capacidade de recuperação das plantas relacionou-se à maior atividade fotossintética e indução de estresse oxidativo pela exposição precoce à luz. Portanto, a menor produção de H_2O_2 em plantas mantidas no escuro por maior período após a aplicação do herbicida permite a translocação do herbicida para os meristemas, o que previne a rebrota.

Palavras-chave: Bipiridilos. Fluorescência da clorofila. Estresse Oxidativo. Inibidores do fotossistema I. *Zea mays* L.

*Corresponding author
[1]Received for publication in 07/16/2020; accepted in 11/29/2021.
[2]Department of Agronomy, Universidade Estadual de Londrina, Londrina, PR, Brazil; guilhermemendespio@gmail.com - ORCID: 0000-0001-6752-3963, halleycaixeta@gmail.com - ORCID: 0000-0002-5487-4964, aguiaresilva@uel.br - ORCID: 0000-0003-3835-1124, giliardidalazen@gmail.com - ORCID: 0000-0003-2510-8264.

INTRODUCTION

The loss of grains and ear segments is common during mechanized corn harvesting, reaching up to 12,7000 g ha^{-1} of grains lost (SHAUCK et al., 2010), equivalent to 39 plants m^{-2} if all these grains were germinated (ALMS et al., 2016). This scenario contributes to the presence of volunteer corn plants in soybean crops (PIASECKI et al., 2018; GAIARIN; PRIMIERI, 2020), which compete for water, light, space, and nutrients (PITELLI, 2015).

The cultivation of corn hybrids containing traits that confer tolerance to glyphosate and ammonium glufosinate limits the options of mechanisms of action for the management of volunteer corn plants (ALMS et al., 2016). The control of volunteer corn in desiccation operations prior to soybean seeding is performed mainly with cyclohexanedione (DIM) and aryloxyphenoxypropionate (FOP) herbicides, which inhibit acetyl coenzyme carboxylase (ACCase) in the post-emergence stage (CARVALHO et al., 2019). However, an accession that gives tolerance to FOPs in corn genotypes is being approved in Brazil for commercialization, and has already been approved in the United States, Canada, and Mexico (WRIGHT et al., 2010; CTNBio, 2015), which will further reduce the number of herbicide options and may also contribute to the selection of resistant weeds to ACCase inhibiting herbicides.

In addition to the herbicides mentioned, bipyridylium herbicides, such as diquat and paraquat, inhibit the electron transport chain in PSI and are nonselective herbicides that can be used in burndown (COBB; READE, 2010). However, from 2020, phytosanitary products based on the active ingredient paraquat cannot be marketed in Brazil due to their toxicity and risks to human health (ANVISA, 2017). Thus, an increase in the use of diquat as an alternative to paraquat is expected.

Diquat [6,7-dihydrodipyrido (1,2-a:2',1'-c) pyrazinediium dibromide] is a contact action herbicide that kills green tissues in points where herbicide spray solution contacts the plants. This effect depends on light to produce reactive oxygen species (ROS) and consequently damaging cell membranes, causing cell death (COBB; READE, 2010; LIMA-MELO et al., 2019). Although diquat is an PSI inhibiting herbicide, the action of the ROS produced affects various components of chloroplasts (including photosynthetic membranes and pigments), which also leads to the inhibition of the activity of photosystem II (PSII) (BRUNHARO; HANSON, 2017).

The translocation of this herbicide is inhibited because of the rapid action and intense induction of cell death in the presence of light, and the effect of the herbicide is restricted (TAHMASEBI et al., 2018). Its action is greater in eudicotyledon than in Poaceae species due to its difficulty in reaching the meristem of grasses (CALDERBANK; SLADE, 1976). The application of PSI inhibiting herbicides at low light intensity may result in a better weed control, possibly by reducing ROS accumulation and cell death, which allows greater translocation of herbicides (MONTGOMERY et al., 2017). The delay in light reception by plants can improve the herbicide distribution and increase the intensity of oxidative stress as soon as the plants have contact with light (PITELLI et al., 2011). However, it is necessary to investigate the period of absence of light required for the distribution of the herbicide to the growth points, so that no regrowth of plants occurs. Therefore, the aim of this study was to evaluate the efficacy of diquat for the control of corn plants subjected to different periods of absence of light after the herbicide application and the photosynthetic activity and ROS accumulation in these plants.

MATERIAL AND METHODS

The research was conducted in Londrina, Paraná, Brazil (23°20'30"S, 51°12'40"W, and altitude of 560 m). Two experiments were performed during November and December 2018, one in the field (experiment I) and other in a greenhouse (experiment II).

Experiment I was conducted to evaluate the effect of light restriction periods after application of the herbicide diquat on the control and shoot matter accumulation of corn plants under field conditions. The results obtained in the field were used to conducted experiment II in a greenhouse and add physiological evaluations, such as photosynthetic activity and H_2O_2 accumulation. This second experiment was conducted in a greenhouse to enable the transport of plants pots to perform a non-destructive photosynthetic activity analysis in the laboratory.

Thus, the experiments complement each other and their results allow a better understanding of the effect of light restriction after diquat application, considering the control and physiological parameters of corn plants.

Experiment I – Field

Plant Growth

The experiment was conducted in plots with length of 4.0 m and width of 2.7 m. The soil of the experimental area was classified as a Typic Hapludox, which presented 12% sand, 36% silt, and 52% clay; pH 5.50; 2.28 10^{-6} kg m^{-3} organic matter, and 9.25 10^{-5} molc m^{-3} cation exchange capacity. Seeds of the corn hybrid 30F53® were mechanically sown in the plots, using four seeds per meter, placed at approximate 0.04 m depth in rows spaced 0.50 m apart. The total rainfall depth during the experiment was 240 mm, and the mean air temperature was 24 °C.

Experimental Design and Treatments

A completely randomized design was used, with seven treatments and four replications. The herbicide diquat (Reglone®, 200 g a.i. L^{-1}; Syngenta, Basel, Switzerland) was used at the rate of 200 g a.i. ha^{-1}, plus 0.2% (v v^{-1}) nonylphenoxypoly (ethylenoxy) adjuvant (Agral®; Syngenta, Basel, Switzerland).

The treatments consisted of different periods of absence of light (0, 1, 2, 3, 4, and 5 hours) after diquat application; a treatment without herbicide application was used as a control. The absence of light was achieved by completely covering one linear meter of plants in each plot with boxes made of three layers of corrugated cardboard.

Experiment II– Greenhouse

Plant Growth

The experiment was conducted using 0.005 m^3 plastic pots filled with a sieved soil (Typic Hapludox) that presented 30% sand, 25% silt, and 45% clay; pH 5.30, 20.10 g kg^{-1} organic matter, and 0.0001 molc m^{-3} cation exchange capacity.

Three seeds of the corn hybrid 30F53® were sown to a depth of 0.04 m in each experimental unit. The plants were thinned at seven days after emergence, keeping one plant per experimental unit. The pots were irrigated daily from the sowing to the end of the evaluations, maintaining the soil close to the field capacity.

Experimental Design and Treatments

A completely randomized design was used, with eight treatments and four replications. The treatments consisted of different periods of absence of light (0, 1, 2, 3, 4, 5, and 6 hours) after application of the spray solution; a treatment without herbicide application was used as a control. Considering the results of the field experiment, a 6-hour period of absence of light was also evaluated in the greenhouse experiment. The spray solution (herbicide, rate, and adjuvant) used and the light restriction simulation followed the same methodologies described in experiment I.

Application of Diquat

In both experiments, the herbicide diquat was applied when the corn plants were at vegetative stage V4. The spraying was performed using a CO_2-pressurized backpack sprayer equipped with pre-orifice flat fan spray nozzles (ADI 11002) spaced 0.5 m apart. The sprayer was positioned at 0.5 m above the target surface, set to a pressure work of 414,000 Pa, and run at a speed of 3.6 km h^{-1}, resulting in an application rate of the spray solution corresponding to 150 L ha^{-1}. The solution was sprayed at 11:00 a.m. under suitable weather conditions: air temperature below 30 °C, relative air humidity above 55%, and clear skies.

Evaluations

The control of corn plants was evaluated in both experiments at 7 and 15 days after application of the treatments (DAT), and their shoot fresh weight (SFW) and shoot dry weight (SDW) were measured. In experiment II, conducted in a greenhouse, PSII activity and hydrogen peroxide (H_2O_2) accumulation were also evaluated.

Control of Corn Plants

Visual evaluations of control of corn plants were performed at 7 and 15 days after treatment (DAT). In each evaluation, the control of corn plants was graded using a scale of percentages where 0% and 100% represented absence of injury and plant death, respectively.

Shoot Fresh and Dry Weight

Corn plants were collected at 15 DAT and weighed to determine the SFW. The plants were then placed in paper bags and dried in a forced air-circulation oven at 60 °C until constant weight to determine the SDW. In the field experiment (I), these evaluations were performed on four plants per experimental unit.

PSII Activity

PSII activity was assessed by chlorophyll fluorescence, measured on intact leaves from the middle third of the plant at 07:00 a.m., 20 hours after the herbicide application, using an OS1p fluorometer (Opti-Sciences, Hudson, USA). The maximum quantum yield of PSII was determined by the F_v/F_m ratio in leaves adapted to the dark for 0.25 hours, where F_v is the variable fluorescence and F_m is the maximum fluorescence obtained after applying a saturating light pulse (BAKER, 2008). The effective quantum yield of PSII (YII) was obtained through the $\Delta F/F_m'$ ratio, where ΔF and F_m' are the chlorophyll and maximum fluorescence variables, respectively, measured in leaves adapted to light. The relative electron transport rate of PSII (rETR) was calculated as $rETR = \Delta F/F_m' \times PAR \times 0.5 \times 0.84$, where *PAR* is the photosynthetically active radiation, *0.5* is the light partition between the photosystems, and *0.84* is the leaf absorption coefficient (BAKER, 2008).

Leaf Hydrogen Peroxide Level

ROS were evaluated by determining the H_2O_2 content in the leaves. The samples consisted of one leaf from the middle third of one plant per experimental unit, collected at 7 hours after the diquat application. The samples were individually placed in aluminum foil envelopes at the time of collection, immediately immersed in liquid nitrogen, and transferred to a bio-freezer at -80 °C until the time of analysis. The leaves (0.1 g) were macerated in a mortar with liquid nitrogen and extracted with 0.0015 L of trichloroacetic acid (0.2%) diluted in methanol. After centrifugation at 13,700 xg at 4 °C for 0.08 hours, the supernatant was used to measure H_2O_2 by reaction with 1 M potassium iodide in 0.1 M potassium phosphate buffer solution (pH 7.5). The absorbance was read using a spectrophotometer at 3.9 10^{-7} m, and H_2O_2 levels were calculated using a standard curve made with known concentrations of H_2O_2 and expressed in µmol per gram of shoot fresh weight (nmol g^{-1} FW) (ALEXIEVA et al., 2001).

Statistical Analysis

The data collected in both experiments were analyzed by descriptive statistics to study the central tendency, dispersion, and verification of presence of outliers. The means found in the evaluations were described by regression models ($p<0.05$). Estimating parameters of the model to be used were defined, and the adequacy of the model to describe the phenomenon was evaluated. The regression model was chosen according to the hypothesis test, the simulated envelope, the coefficient of determination (R^2), Pearson's coefficient of correlation (r), residual analysis, and the partial F test.

After the exploratory analysis, residual analyses were performed for the data distribution after the normality and homoscedasticity of variance tests by the Shapiro-Wilk and Bartlett, respectively ($p<0.05$). The data of the control without herbicide application were not considered in the regression analysis to meet the assumptions of the analysis of variance. The data of control of corn plants at 7 DAT and SFW in the greenhouse experiment were transformed into $\frac{x^{1.5}-1}{1.5}$ and $\frac{x^{0.4}-1}{0.4}$, respectively, to meet the assumptions of the analysis of variance. Pearson's correlation was performed for the variables of experiment II. The statistical analyses were performed using R program (R CORE TEAM, 2021).

RESULTS AND DISCUSSION

Experiment I – Field

In the field experiment, a positive correlation was found between the control of corn plants and period of absence of light after diquat application. Five hours of absence of light after diquat application was needed for the total control (100%) of corn plants at 7 DAT (Figure 1A) and 15 DAT (Figure 1B). The plants in treatments with periods shorter than 3 hours of absence of light recovered at 15 DAT, with lower control compared to that in the evaluation at 7 DAT. The control of plants kept under sunlight after the application was only 20%, denoting the inefficiency of this herbicide when applied under light conditions.

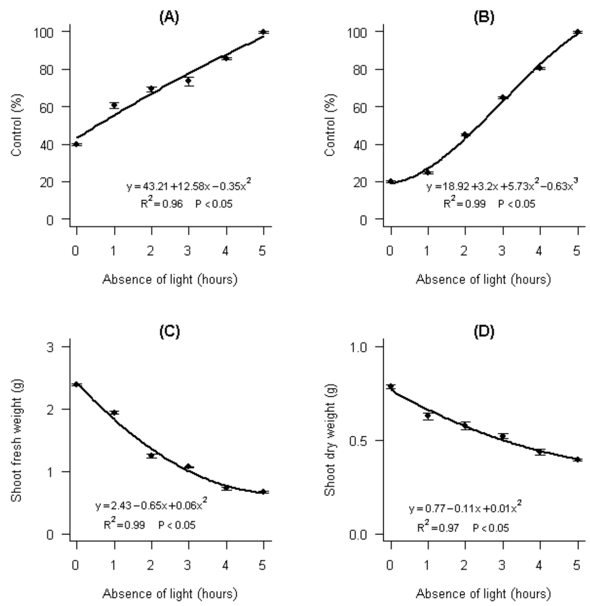

Figure 1. Control (%) at 7 (A) and 15 days after treatment (B), shoot fresh weight (C), and shoot dry weight (D) of corn plants as a function of periods of absence of light after diquat application under field conditions. Dots represent the means and vertical bars represent the standard deviation.

There was a negative association between SFW and SDW and the absence of light after diquat application (Figures 1C and 1D). Corroborating the control data, the largest decreases in SFW and SDW was found in the treatment with longer light restriction periods, which were 72% and 50%, respectively, compared to those in the treatment without light restriction.

Experiment II – Greenhouse

The control of corn plants with diquat under greenhouse conditions also presented a positive correlation to the period of absence of light after the herbicide application. Plants kept for 5 or 6 hours in the dark after herbicide application presented full control at 7 DAT (Figure 2A) and 15 DAT (Figures 2B and 3). Plants under dark for 4 hours presented control of approximately 80% in both evaluations, showing necrosis in practically all leaf tissue but maintaining turgid and green stem, with possibility of recovery (Figure 3). In the other treatments, the control was lower than 80%, mainly in the second evaluation, at 15 DAT (Figure 2B), with lower control compared to that in the evaluation at 7 DAT (Figure 2A). In treatment 0, in which the plants were kept under sunlight after diquat application, the control was 51% at 7 DAT, and only 25% in the evaluation at 15 DAT, denoting plant recovery (Figures 2A, 2B and 3). The lower control found in these treatments was due to the occurrence of plant regrowth with exposure of green tissues in the whorl of corn plants (Figure 3). In these treatments, the typical injury caused by diquat occurred only at the points where the herbicide had contact with the plant.

The damage caused by diquat resulted in interference in SFW and SDW accumulation. The linear regression model showed a negative correlation between absence of light after diquat treatment and plant growth (Figures 2C and 2D). The SFW and SDW of corn plants decreased as the period of absence of light after herbicide application was increased. In the treatment with 6 hours of absence of light, SFW and SDW were 77% and 54% lower than those of plants exposed to light immediately after application, respectively.

The evaluations of photosynthetic parameters showed that the photosynthetic activity of corn plants treated with diquat decreased in response to the period of absence of light, especially in the treatment with 2 hours of absence of light (Figure 4). The F_v/F_m ratio decreased from 0.23 in plants exposed to light after herbicide application to less than 0.07 in treatments with 2 or more hours of absence of light (Figure 4A). Control plants without herbicide application presented a F_v/F_m ratio of 0.79 (data not shown). The $\Delta F/F_m'$ ratio decreased from 0.09 to 0.02, when comparing treated plants kept under light to plants kept in the dark for 6 hours (Figure 4B). The $\Delta F/F_m'$ of the control treatment was 0.558 (data not shown). Similarly, rETR decreased as the period of absence of light was increased (Figure 4C). Pants kept under light after diquat application presented rETR of 24 µmol m^{-2} s^{-1}, and those maintained for 6 hours in the dark after diquat application, 4 µmol m^{-2} s^{-1}. The rETR of the control treatment was 137.67 µmol m^{-2} s^{-1}.

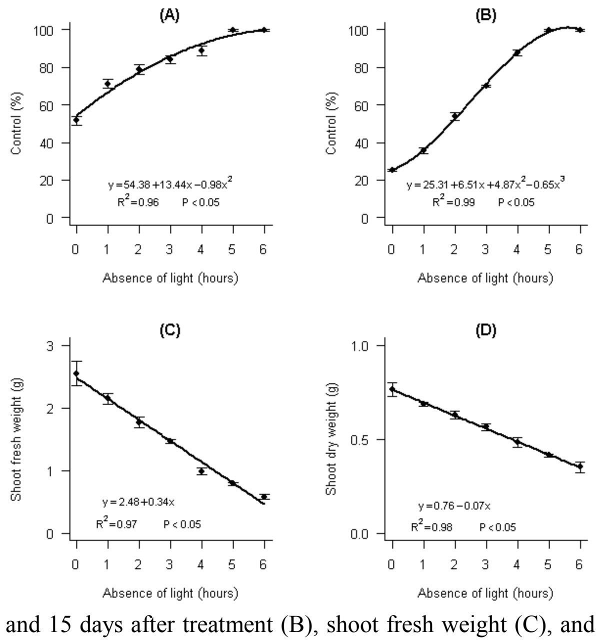

Figure 2. Control (%) at 7 (A) and 15 days after treatment (B), shoot fresh weight (C), and shoot dry weight (D) of corn plants as a function of periods of absence of light after diquat application under greenhouse conditions. Dots represent the means and vertical bars represent the standard deviation.

Figure 3. Corn plants subjected to different periods of absence of light (0, 1, 2, 3, 4, 5, and 6 hours) after herbicide application. The symptoms were recorded at 15 days after diquat application. Control refers to the control without herbicide application.

The results found for H_2O_2 accumulation were consistent with the results found for the photosynthetic parameters evaluated. The accumulation of this ROS decreased as the period of absence of light after the diquat application was increased (Figure 4D). In the treatment without absence of light after application, the H_2O_2 accumulation was approximately 3,300 nmol g^{-1} FW. However, plants kept in the dark for 6 hours presented H_2O_2 accumulation of approximately 1,500 nmol g^{-1} FW, which was even lower than the value in the control treatment without herbicide (2,111 nmol g^{-1} FW).

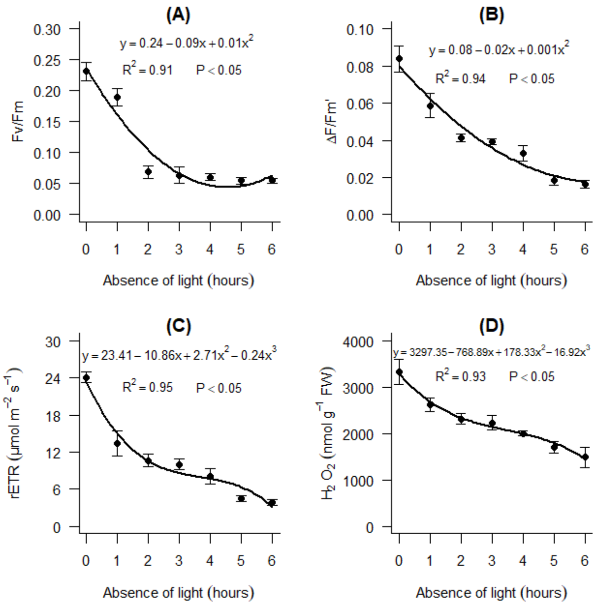

Figure 4. Maximum quantum yield of photosystem II (F_v/F_m) (A), effective quantum yield of photosystem II ($\Delta F/F_m'$) (B), relative electron transport rate of photosystem II (rETR) (C), and hydrogen peroxide (H_2O_2) accumulation (D) in corn plants as a function of periods of absence of light after diquat application under greenhouse conditions. Dots represent the means and vertical bars represent the standard deviation.

Pearson's correlation analysis was used to understand the correlation between the evaluated variables, mainly between physiological and control variables. There was a positive correlation between the control percentages evaluated at 7 and 15 DAT (Figure 5). The control in both evaluations was negatively correlated with the corn shoot fresh and dry weights measured at the end of the evaluations. The control percentages at 7 or 15 DAT were negatively correlated with the photosynthetic parameters of the corn plants (F_v/F_m, $\Delta F/F_m'$, rETR, and leaf H_2O_2 content). All photosynthetic and biomass variables were positively correlated with each other.

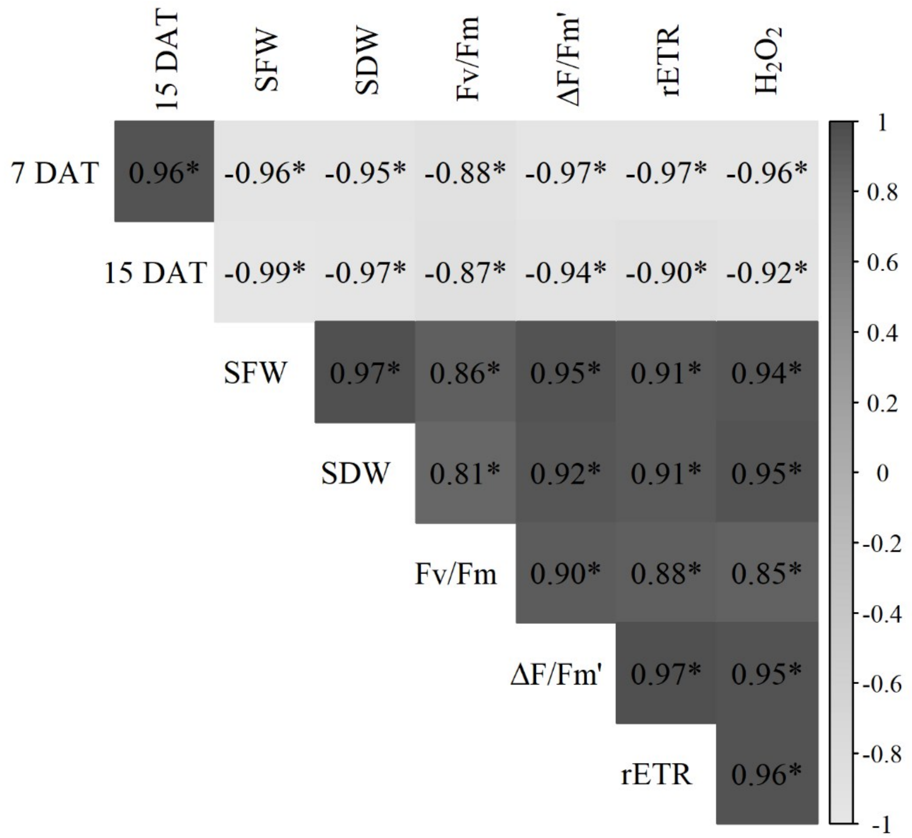

Figure 5. Pearson correlation for the variables: control (%) at 7 and 15 days after treatment (DAT), shoot fresh weight (SFW), shoot dry weight (SDW), maximum quantum yield of photosystem II (F_v/F_m), effective quantum yield of photosystem II ($\Delta F/F_m'$), relative electron transport rate of photosystem II (rETR), and leaf hydrogen peroxide concentration (H_2O_2) in corn plants as a function of absence of light after diquat application under greenhouse conditions. * Significant at $p<0.05$.

The results obtained in the field and greenhouse experiments showed that the application of the herbicide diquat fully controls maize plants at V4 phenological stage, when the treated plants are kept in the dark for at least 5 hours after application. The plants recover when using periods shorter than 4 hours, with injuries restricted to points where the herbicide had contact with the plant (Figures 1, 2, and 3). The ability of corn plants to recover when exposed to light immediately after diquat application is related to the higher photosynthetic activity and ROS production found at a short time after treatment (Figure 4). The Pearson's correlation analysis (Figure 5) showed that the control was negatively correlated with the photosynthetic activity (F_v/F_m, $\Delta F/F_m'$, and rETR), and H_2O_2 production in both evaluations.

Bipyridyliums are divalent cations that inhibit PSI by competing with $NADP^+$ for ferredoxin electrons (COBB; READE, 2010). In the presence of light, these herbicides are rapidly reduced and transfer electrons to oxygen molecules, resulting in the production of ROS such as $O_2^{-\bullet}$ (superoxide anion), H_2O_2 (hydrogen peroxide) and $OH^\bullet$ (hydroxyl radical) (NORSWORTHY; SMITH; GRIFFITH, 2011). High levels of these substances are harmful to cell components, especially phospholipid membranes, leading to leakage of intracellular content, cell death, and tissue necrosis (COBB; READE, 2010).

Diquat [6.7-dihydrodipyrido (1.2-a:2'.1'-c) pyrazinediium dibromide] exhibits rapid absorption in leaves and, in the presence of light, it rapidly initiates induction of oxidative stress, which is restricted to the sprayed area (BRUNHARO;

HANSON, 2017). However, the physicochemical characteristics of diquat allow it to be translocated by phloem and, mainly, by xylem (COBB; READE, 2010). Diquat has an octanol-water partition coefficient (log K_{ow}) of -4.26, which characterizes it as a hydrophilic and mobile compound in plants (RODRIGUES; ALMEIDA, 2018). However, the rapid and intense cell death at the herbicide contact sites limits its translocation inside the plant (COBB; READE, 2010). Therefore, the presence of light during or shortly after application is what characterizes diquat as contact herbicide, rather than its physicochemical characteristics. In this context, the absence of light after application appears to be a strategy that favors the translocation of the herbicide to all parts of the plants, including meristems. The subsequent exposure of plants to sunlight causes oxidative stress throughout the plant, which makes the regrowth unlikely.

Even plants exposed to light during and after diquat application presented lower F_v/F_m, $\Delta F/F_m'$, and rETR (Figure 4) than plants not treated with diquat, showing the negative effect of this herbicide on photosynthetic electron transport due to the inhibition of PSI (BRUNHARO; HANSON, 2017). However, the lower photosynthetic activity of corn plants subjected to dark periods resulted in less H_2O_2 accumulation (Figures 4 and 5). The photosynthetic activity decreased as the period of absence of light was increased, up to a level that caused considerably decreases in ROS production (Figures 4 and 5). This should have prevented the herbicide restriction to absorption points, allowing its translocation through meristems.

The results obtained in this study can be applied by using night applications of diquat, provided that there is 5 hours of absence of light after the application. Some experiments have evaluated the effect of application time for bipyridylium herbicides. Better control of water hyacinth (*Eichhornia crassipes* (Mart.) Solms) was found for nocturnal applications of diquat, and regrowth plants were found for daytime applications (PITELLI et al., 2011). The effect of light restriction on herbicidal activity of diquat and paraquat was evaluated for tomato (*Solanun lycopersicum* L.), common bean (*Phaseolus vulgaris* L.) and beet (*Beta vulgaris* L.) plants, showing that dark periods, followed by light periods, improve the efficiency of these herbicides (BRIAN, 1967). Similarly, Montgomery et al. (2017) found that paraquat applications before night (07:30 p.m.) resulted in 96% control of horseweed (*Conyza canadensis* (L.) Cronquist), but applications at dawn (06:00 a.m.) and noon resulted in 66% and 25% control, respectively; however, the authors point out that other herbicides, such as 2,4-D, dicamba, ammonium glufosinate, and saflufenacil present the best results when using midday applications.

These studies evaluated the effect of time of diquat application on eudicotyledonous plants, because this herbicide has low efficiency for Poaceae weeds (CALDERBANK; SLADE, 1976). Puri et al. (2008) evaluated the control of various plants to different diquat rates and found that corn is more tolerant to diquat than soybean and cotton. The results of this work also confirm that the control found for applications carried out under light conditions is far below a satisfactory level, only 25% control and zero plant mortality (Figures 1, 2 and 3). However, this study showed that the control efficiency can reach 100% when plants are subjected to 5 hours of darkness after application, leading to total plant mortality (Figures 2B and 3).

CONCLUSION

The results found in the present study showed that the application of the herbicide diquat fully controls corn plants at the V4 stage when the plants are kept in the dark for at least 5 hours after the application. Corn plants under full sun conditions maintain their regrowth ability, with the control reaching only 25% after two weeks. A 5-hour period of absence of light for plants treated with diquat decreases the photosynthetic activity of the plants and, consequently, the production of reactive oxygen species, which allows the herbicide translocation to meristems, preventing the plant regrowth.

REFERENCES

ALEXIEVA, V. et al. The effect of drought and ultraviolet radiation on growth and stress markers in pea and wheat. **Plant, Cell and Environment**, 24: 1337-1344, 2001.

ALMS, J. et al. Yield loss and management of volunteer corn in soybean. **Weed Technology**, 30: 254-262, 2016.

ANVISA - Agência Nacional de Vigilância Sanitária. **Resolução de diretoria colegiada – RDC nº 190, de 30 novembro de 2017**. 2017.

BAKER, N. R. Chlorophyll Fluorescence: A Probe of Photosynthesis In Vivo. **Annual Review of Plant Biology**, 59: 89–113, 2008.

BRIAN, R. C. Darkness and the activity of diquat and paraquat on tomato, broad bean and sugar beet. **Annals of Applied Biology**, 60: 77–85, 1967.

BRUNHARO, C. A. C. G.; HANSON, B. D. Vacuolar sequestration of paraquat is involved in the resistance mechanism in *Lolium perenne* L. spp. *multiflorum*. **Frontiers in Plant Science**, 8: 1485, 2017.

CALDERBANK, A.; SLADE, P. Diquat and paraquat. In: KEARNY, P. C.; KAUFMAN, D. D. (Eds.). **Herbicides: chemistry, degradation, and mode of action**. New York, NY: Dekker, 1976. v. 2, p. 501-540.

CARVALHO, S. J. P. et al. Control of glyphosate-resistant volunteer maize using ACCase inhibiting herbicides. **Revista Caatinga**, 32: 575-580, 2019.

COBB, A. H.; READE, J. P. H. **Herbicides and plant phisiology**. 2. ed. Hoboken, 2010. 286 p.

CTNBio - Comissão Técnica Nacional de Biosegurança. **Parecer Técnico Nº 4763/2015** - Relatório de biossegurança do milho DAS-40278-9 x NK603. Outubro 2015. 2015. Disponível em: <http://www.fao.org/fileadmin/user_upload/gmfp/docs/Parecer%20Final%204763Dow.pdf>. Acesso em: 15 jan. 2020.

GAIARIN, V. A.; PRIMIERI, C. Interferência do milho voluntário tolerante ao glifosato na cultura da soja RR. **Revista Cultivando o Saber**, 13: 14-20, 2020.

LIMA-MELO, Y. et al. Photoinhibition of photosystem I provides oxidative protection during imbalanced photosynthetic electron transport in *Arabidopsis thaliana*. **Frontiers in Plant Science**, 10: 1-13, 2019.

MONTGOMERY, G. B. et al. Effect of time of day of application of 2,4-D, dicamba, glufosinate, paraquat, and saflufenacil on horseweed (*Conyza canadensis*) control. **Weed Technology**, 31: 550-556, 2017.

NORSWORTHY, J. K.; SMITH, K. L.; GRIFFITH, G. Evaluation of combinations of paraquat plus photosystem II-inhibiting herbicides for controlling failed stands of maize (*Zea mays*). **Crop Protection**, 30: 307-310, 2011.

PIASECKI, C. et al. Interference of GR volunteer corn population and origin on soybean grain yield losses. **Planta Daninha**, 36: 1-9, 2018.

PITELLI, R. A. et al. Doses e horário de aplicação do diquat no controle de *Eichhornia crassipes*. **Planta Daninha**, 29: 269-277, 2011.

PITELLI, R. A. O termo planta-daninha. **Planta Daninha**, 33: 622-623, 2015.

PURI, A. et al. Effect of the foliar application of diquat herbicide on selected natural area and field crop species. **Weed Biology and Management**, 8: 133-138, 2008.

R CORE TEAM (2021). **R: A language and environment for statistical computing**. R Foundation for Statistical Computing, Vienna, Austria. Disponível em: https://www.R-project.org/.

RODRIGUES, B. N.; ALMEIDA, F. S. **Guia de herbicidas**. 7. ed. Londrina, PR: Edição dos autores, 2018. 764 p.

SHAUCK, T. C. et al. Corn (*Zea mays*) harvest inefficiencies and potential for volunteer corn. In: 65TH ANNUAL MEETING OF THE NORTH CENTRAL WEED SCIENCE SOCIETY, 2010, Lexington. **Proceedings of the North Central Weed Science Society**, Las Cruces, NM: NCWSS, 2010. v. 65.

TAHMASEBI, B. K. et al. Multiple resistance evolution in bipyridylium-resistant *Epilobium ciliatum* after recurrent selection. **Frontiers in Plant Science**, 9: 1-11, 2018.

WRIGHT, T. R. et al. Robust crop resistance to broadleaf and grass herbicides provided by aryloxyalkanoate dioxygenase transgenes. **Proceedings of the National Academy of Sciences of the United States of America**, 107: 20240-20245, 2010.