ABSTRACT - Among the methods of weed control, stands out chemical control. However, even selective, herbicides can trigger the production of reactive species of oxygen and cause oxidative stress. The aim of the study was to evaluate changes in photosynthetic parameters, oxidative damage, antioxidant enzyme activity and altered metabolism of rice plants after applying pre-emergent herbicides. The experiment was conducted in a greenhouse and herbicides used were oxadiazon, pendimethalin and oxyfluorfen, beyond the control without herbicide. There was a reduction of photosynthetic rate and efficiency of carboxylation, compared to the control, when applied herbicides oxyfluorfen and pendimethalin. The major lipid peroxidation and proline accumulation was observed for the herbicide oxyfluorfen. The oxyfluorfen and oxadiazon herbicides also resulted in increased activity of superoxide dismutase, compared to control. When evaluated ascorbate peroxidase activity, there was a higher enzyme activity in plants treated with oxadiazon and pendimethalin. Even selective herbicides registered for weed control in rice crops cause phytotoxicity, reduce height and alter the metabolism of plants, generating reactive oxygen species, which activate enzymatic and non-enzymatic defense systems and result in the degradation of photosynthetic pigments and in reduced protein content.

Key words: Antioxidant system. Chemical control. Reactive oxygen species. Selectivity.

RESUMO - Dentre os métodos de controle de plantas daninhas, destaca-se o controle químico. No entanto, mesmo seletivos a cultura, os herbicidas podem desencadear a produção de espécies reativas de oxigênio e causar estresse oxidativo. O objetivo do estudo foi avaliar alterações nos parâmetros fotossintéticos, danos oxidativos, atividade das enzimas antioxidantes e alterações do metabolismo de plantas de arroz após a aplicação de herbicidas pré-emergentes. O experimento foi conduzido em casa de vegetação e os herbicidas utilizados foram: oxadiazon, oxyfluorfen e pendimethalin, além do controle sem herbicida. Observou-se redução da taxa fotossintética e na eficiência da carboxilação, em relação à testemunha, quando aplicado os herbicidas oxyfluorfen e pendimethalin. A maior peroxidação lipídica e acúmulo de prolinha foi observado para o herbicida oxyfluorfen. Os herbicidas oxyfluorfen e oxadiazon também resultaram em maior atividade da superóxido dismutase, comparado à testemunha. Quando avaliada a atividade da ascobato peroxidase, verificou-se maior atividade da enzima em plantas tratadas com oxadiazon e pendimethalin. Mesmo seletivos e registrados para controle de plantas daninhas na cultura do arroz, os herbicidas causam fitotoxicidade, reduzem a estatura e alteram o metabolismo das plantas, gerando espécies reativas de oxigênio, as quais ativam o sistema de defesa enzimático e não enzimático e resultam em degradação dos pigmentos fotossintéticos e redução no teor de proteínas.

INTRODUCTION

The interference of weeds may cause a reduction of 80-90% in grain yield of irrigated rice (FLECK et al., 2008). In order to avoid losses arising from competition with weeds, several phytosanitary managements are used. The chemical control within the integrated management program is the main weed control tool for rice fields. Even if a particular active ingredient (a.i.) is culture-selective and does not cause a severe injury to the plants, biochemical and physiological changes may occur (SONG et al., 2007). Especially if they are not used according to the recommended dosages.

The injuries are usually evaluated through of visual scores on a scale of zero to 100, where zero is the absence of symptoms and 100 is the plant death. However, the criterion used by each evaluator may generate different results. Thus, assessments in relation to the plant metabolism can assist in verifying the selectivity of herbicides.

The negative effect of stress is often mediated by the oxidative damage initiated by reactive oxygen species (ROS) such as superoxide radicals ($O_2^{-}$), hydroxyl radicals ($OH$), hydrogen peroxide ($H_2O_2$) and singlet oxygen ($O_2$) (GILL; TUTEJA, 2010). The formation of reactive oxygen species has been described as being a result of several abiotic stresses, including the application of herbicides (SONG et al., 2007). The elimination of reactive oxygen species is necessary for cells to survive in an oxygen-rich environment, especially under stress conditions.

The most important ROS detoxification mechanism is the activity of superoxide dismutase (SOD), ascorbate peroxidase (APX) and catalase (CAT) enzymes. In general, the antioxidant response varies according to the mode of action of the applied herbicide and according to the crop. Thus, the role of antioxidant enzymes in stress situations is to control the accumulation of ROS, thus limiting oxidative damage (SHARMA et al., 2012).

The metabolism of proline is also involved in regulating intracellular redox potential and storage, transferring energy and reducing power (GIBERTI; FUNCK; FORLANI, 2014). The biosynthesis of proline occurs in the cytoplasm of plant cells, but it is possible that the production moves to chloroplasts under stress conditions, thus being able to detoxify the hydroxyl radical (SIGNORELLI et al., 2014). According to its chemical properties, proline may be involved in stress caused by metals, by mechanisms of osmotic and redox regulation, complexation of metals and detoxification of ROS (SHARMA; DIETZ, 2006).

Thus, the aim of the study was to evaluate changes in photosynthetic parameters, oxidative damage, antioxidant enzyme activity and alterations in the metabolism of rice plants after applying preemergent herbicides.

MATERIAL AND METHODS

The experiment was conducted in the greenhouse in a completely randomized design with four replications. The cultivar used was Puíta INTA-CL in a population of six plants per plot. Plants were placed in pots with a volumetric capacity of three liters filled with soil from a rice crop. The treatments consisted of the application of different preemergence herbicides: oxyfluorfen (960 g ai ha$^{-1}$), oxadiazon (1,000 g ai ha$^{-1}$) and pendimethalin (1,600 g ai ha$^{-1}$), as well as a control without application of herbicides. Herbicide application was performed one (1) day after sowing using a pressurized backpack sprayer with CO$_2$ and a bar with four array Teejet 110015 nozzles spaced 0.5 m, with a spray volume 120 L ha$^{-1}$.

The variable phytotoxicity was evaluated at eight (8) days after emergence (DAE) through visual notes following a scale from zero to 100, where zero is the absence of symptoms and 100 is plant death. Height measurement was performed at 8 and 12 DAE with the aid of a graduated ruler. All plants of the experimental unit were measured following their length from the ground level to the apex with the leaf blade distended.

Leaf samples were collected at 8 and 12 DAE and stored at -80 °C until the analyses of enzymatic activity and oxidative damage. The variables analyzed were chlorophylls and carotenoids contents, hydrogen peroxide content, lipid peroxidation, total protein content, activity of catalase, ascorbate peroxidase and superoxide dismutase enzymes and proline content.

Physiological assessments related to net photosynthesis, transpiration rate, stomatal conductance and substomatal CO$_2$ concentration were performed at 12 DAE. For this, the middle third of the last fully expanded leaf was used, and the evaluation was performed using an infrared gas analyzer (IRGA) LI-COR, model LI-6400. The carboxylation efficiency was calculated by the net photosynthesis/concentration of substomatal CO$_2$ ratio, and the water use efficiency by net photosynthesis/transpiration rate ratio.

The chlorophyll and total carotenoids contents were measured according to the methodology described by Arnon (1949), with modifications. Chlorophyll $a$, $b$, total and carotenoids contents were calculated from the absorbance of the solution obtained by spectrophotometry.
Oxidative stress caused by the use of preemergent herbicides in rice crops

at 647, 663 and 470 nm, respectively. The results were expressed in mg g\(^{-1}\) of fresh weight (FW).

Cellular tissue damage was determined according to hydrogen peroxide levels (H\(_2\)O\(_2\)), as described by Sergiev, Alexieva and Karanov (1997), and species reactive to thiobarbituric acid (TBARS) by accumulation of malondialdehyde (MDA), as described by Heath and Packer (1968). The concentration of H\(_2\)O\(_2\) was determined using a standard curve with known concentrations of H\(_2\)O\(_2\) and expressed in mM g\(^{-1}\) FW. For the determination of TBARS, the MDA concentration was calculated using the absorption coefficient of 155 mM cm\(^{-1}\) and the results were expressed as nM MDA g\(^{-1}\) FW.

To determine the activity of antioxidant enzymes, superoxide dismutase (SOD), catalase (CAT) and ascorbate peroxidase (APX), an extraction was performed and from this extract, the protein of samples was quantified by the method of Bradford (1976). Results were calculated in function of the casein standard curve and expressed in milligrams of protein per mL (mg of casein mL\(^{-1}\)).

The SOD activity was determined according to the methodology adapted by Peixoto et al. (1999). Using this method, the inhibition of the reduction of NBT (p-nitro blue tetrazolium) by the enzymatic extract was thus determined, avoiding the formation of the chromophore. In this assay, one enzyme activity unit (AU) of SOD was considered as the amount of enzyme required to obtain a 50% inhibition of NBT reduction by SOD contained in the enzyme extract. The activity was determined by calculating the amount of extract that inhibits 50% of the NBT reaction expressed in AU mg\(^{-1}\) of protein min\(^{-1}\).

CAT and APX activity were determined, according to the methodology described by Azevedo et al. (1998), by the consumption of H\(_2\)O\(_2\) (CAT extinction coefficient 39.4 mM cm\(^{-1}\) and APX extinction coefficient 2.9 mM cm\(^{-1}\)). Both for CAT activity and APX activity, for calculation purposes, it was considered that the decrease of one absorbance unit is equivalent to one active unit (AU). The activities of total extract were determined by calculating the amount of extract that reduced the absorbance reading by one AU expressed in AU mg\(^{-1}\) of protein min\(^{-1}\).

The proline content was determined according to the methodology described by Bates, Waldren and Teare (1973), with modifications. The results are expressed in micromoles of proline g\(^{-1}\) FM by designing a proline standard curve with known concentrations.

Data were analyzed for normality and homoscedasticity and then subjected to analysis of variance (p<0.05). If statistically significant, the effects of the herbicides were separately evaluated by a Duncan test (p<0.05) for each experiment.

**RESULTS AND DISCUSSION**

The higher phytotoxicity and height reduction was observed when plants were subjected to treatment with oxyfluorfen followed by oxadiazone and pendimethalin (Table 1).

A reduction in the photosynthetic rate and in the carboxylation efficiency, compared to the control, was observed when the herbicides oxyfluorfen and pendimethalin were applied (Table 2). The herbicide pendimethalin also affected the concentration of substomatal CO\(_2\), transpiration rate and water use efficiency. Yet the herbicide oxadioazone only differed from the control regarding the variable water use efficiency.

The oxyfluorfen is an inhibitor of protoporphyrinogen oxidase (PROTOX), and because it has a direct effect on chlorophyll synthesis route, it may interfere with photosynthesis. Chlorophyll molecules are the main pigments responsible for the capture of light for photochemical reactions. Therefore, the decline of these compounds may compromise photosynthetic

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Phytotoxicity (%)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 DAE</td>
<td>12 DAE</td>
</tr>
<tr>
<td>Control</td>
<td>0 c(^1)</td>
<td>16.9 a</td>
</tr>
<tr>
<td>Oxyfluorfen</td>
<td>35.5 a</td>
<td>8.4 c</td>
</tr>
<tr>
<td>Oxadiazone</td>
<td>16.7 b</td>
<td>12.4 b</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>14.0 b</td>
<td>13.3 b</td>
</tr>
<tr>
<td>CV (%)</td>
<td>27.4</td>
<td>14.8</td>
</tr>
</tbody>
</table>

\(^1\)Means followed by different letters in the column differ by Duncan test (p<0.05)
activity, hindering the development of plants. The main reason is the stomatal closure, which leads to a decrease in the internal concentration of CO2 and may lead to transfer of an electron to the O2, thus being a major cause of ROS production (RODZIEWICZ et al., 2014). The herbicide oxadiazon is also an inhibitor of PROTOX. However, plants have a differential selectivity even within the same group of herbicides and may be more susceptible or tolerant to a given product.

The high concentration of substomatal CO2 verified for the herbicide pendimethalin (Table 2) may be linked to a lower consumption of CO2 in plants treated with the herbicide. This variable may be influenced by the application of herbicides and by environmental factors such as water, light and energy availability. Yet, the response of rice plants after the application of the herbicide pendimethalin showed an increase in transpiration rates probably due to an increase in metabolic activity linked to a detoxification, inactivation or compartmentalization processes of the herbicide (AHSAN et al., 2008).

Because of the use of pendimethalin, there was a reduction in water use efficiency and carboxylation (Table 2). The reduction in these variables is linked to a lower absorption of CO2 resulting in a lower photosynthetic activity. It is suggested that under the stress caused by the herbicide, the available CO2 is not converted efficiently into photosynthetic products, thereby increasing its concentration in the substomatal cavity.

A high lipid peroxidation, both at 8 and at 12 DAE, was observed for the herbicide oxyfluorfen (Tables 3 and 4). This herbicide inhibits protoporphyrinogen oxidase (PROTOX, EC 1.3.3.4), an enzyme located on the inner membrane of the chloroplast responsible for the oxidation of protoporphyrinogen IX into protoporphyrin IX by establishing a conjugated system of double bonds. With the inhibition of PROTOX, the protoporphyrinogen IX accumulates in the chloroplast and diffuses into the cytosol, where it undergoes auto-oxidation, converting into protoporphyrin IX due to the action of the cytosolic enzyme, insensitive to the inhibitor. The protoporphyrin IX interacts with molecular oxygen and light, forming singlet oxygen, which in turn triggers oxidative processes such as the peroxidation of membrane lipids (TRIPATHY; MOHAPATRA; GUPTA, 2007), accelerating the oxidative stress process.

The lipid peroxidation generates malondialdehyde (MDA), a product of the decomposition of fatty acids of biomembranes. Lipid peroxidation is one of the most investigated consequences of the actions of ROS on membrane structures, being one of the first responses to damage induced by stress in plant tissues (AMRI; SHAHSAVAR, 2010). The lipid peroxidation is the last step and also a physical action of herbicides related directly or indirectly to photosynthesis.

In a similar study, it was observed that soybean plants treated with oxyfluorfen showed almost doubled malondialdehyde values in comparison to the control (CATANESE et al., 2010). In addition, lipid peroxidation could have damaged the chloroplast by inhibiting the synthesis of chlorophyll and thus photosynthesis (ELLA; KAWANO; ITO, 2003). It was expected that the herbicide oxyfluorfen caused changes in the chlorophyll content. This hypothesis is based on the mechanism of action of the herbicide, which inhibits PROTOX enzyme, involved in the synthesis route of chlorophylls in plants. Thus, it is possible to infer that, in this experiment, because the herbicide application was performed at the preemergence of plants, it caused an adaptation of plants to the production of these light-receptor pigments.

**Table 2** - Net photosynthesis (A) (µmol CO2 m-2 s-1), CO2 substomatal concentration (Ci) (µmol CO2 mol-1), transpiration rate (E) (mmol H2O m-2 s-1), water use efficiency (WUE) (µmol CO2 mol-1 H2O), e efficiency of carboxylation (CE) (µmol m-2 s-1) in rice plants subjected to the application of pre-emergent herbicides, evaluated at 12 days after emergence (DAE).

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>A</th>
<th>Ci</th>
<th>E</th>
<th>WUE</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>12.5 a 1</td>
<td>327 b</td>
<td>6.7 b</td>
<td>1.86 a</td>
<td>0.038 a</td>
</tr>
<tr>
<td>Oxyfluorfen</td>
<td>7.9 b</td>
<td>333 ab</td>
<td>5.4 b</td>
<td>1.46 ab</td>
<td>0.024 b</td>
</tr>
<tr>
<td>Oxadiazon</td>
<td>10.5 ab</td>
<td>340 ab</td>
<td>6.9 b</td>
<td>1.52 bc</td>
<td>0.030 ab</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>8.2 b</td>
<td>345 a</td>
<td>9.1 a</td>
<td>0.90 c</td>
<td>0.024 b</td>
</tr>
<tr>
<td>CV (%)</td>
<td>19.7</td>
<td>2.8</td>
<td>18.1</td>
<td>20.8</td>
<td>31.1</td>
</tr>
</tbody>
</table>

1Means followed by different letters in the column differ by Duncan test (p<0.05)
Table 3 - Lipid peroxidation in terms of thiobarbituric acid reactive species (TBARS) (nM MDA g\(^{-1}\) FW), activity of superoxide dismutase (SOD) (AU mg\(^{-1}\) protein min\(^{-1}\)), catalase activity (CAT) (AU mg\(^{-1}\) protein min\(^{-1}\)), protein (PROT) (mg casein g\(^{-1}\) FW) and proline content (PROL) (mg proline g\(^{-1}\) FW) in rice plants subjected to application of pre-emergent herbicides, at eight days after emergence (DAE)

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>TBARS</th>
<th>SOD</th>
<th>CAT</th>
<th>PROT</th>
<th>PROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>12.78 b(^1)</td>
<td>1.93 c</td>
<td>0.157 a</td>
<td>20.97 a</td>
<td>0.194 ab</td>
</tr>
<tr>
<td>Oxyfluorfen</td>
<td>22.29 a</td>
<td>3.58 a</td>
<td>0.124 b</td>
<td>14.77 b</td>
<td>0.238 a</td>
</tr>
<tr>
<td>Oxadiazon</td>
<td>13.75 b</td>
<td>2.65 b</td>
<td>0.158 a</td>
<td>21.42 a</td>
<td>0.167 b</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>12.99 b</td>
<td>2.29 bc</td>
<td>0.144 ab</td>
<td>21.71 a</td>
<td>0.191 ab</td>
</tr>
<tr>
<td>CV (%)</td>
<td>15.7</td>
<td>15.7</td>
<td>11.8</td>
<td>8.5</td>
<td>14.8</td>
</tr>
</tbody>
</table>

\(^1\)Means followed by different letters in the column differ by Duncan test (p \(< 0.05)\)

Table 4 - Lipid peroxidation in terms of thiobarbituric acid reactive species (TBARS) (nM MDA g\(^{-1}\) FW), hydrogen peroxide content (H\(_2\)O\(_2\)) (mM g\(^{-1}\) FW) and activity of ascorbate peroxidase (APX) (AU mg protein \(^{-1}\) min\(^{-1}\)) in rice plants subjected to the application of pre-emergent herbicides, evaluated at 12 days after emergence (DAE)

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>TBARS</th>
<th>H(_2)O(_2)</th>
<th>APX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>16.27 b(^1)</td>
<td>2.93 ab</td>
<td>0.134 b</td>
</tr>
<tr>
<td>Oxyfluorfen</td>
<td>20.06 a</td>
<td>1.84 b</td>
<td>0.162 b</td>
</tr>
<tr>
<td>Oxadiazon</td>
<td>19.96 b</td>
<td>3.06 a</td>
<td>0.593 a</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>14.68 b</td>
<td>3.39 a</td>
<td>0.661 a</td>
</tr>
<tr>
<td>CV (%)</td>
<td>9.50</td>
<td>25.30</td>
<td>18.3</td>
</tr>
</tbody>
</table>

\(^1\)Means followed by different letters in the column differ by Duncan test (p \(< 0.05)\)

Oxidative stress caused by the use of preemergent herbicides in rice crops

The enzymes of the antioxidant system do not eliminate \(^*\)OH directly. Thus, the regulation of its precursors, O\(_2\)\(^-*\) and H\(_2\)O\(_2\)), is the key step in preventing \(^*\)OH risks, bringing together the action of SOD, APX and CAT enzymes. Thus, an efficient combination of SOD, CAT and APX would minimize the effects of oxidative stress, playing an important role in the regulation of ROS (DAMANIK et al., 2012).

The application of oxyfluorfen results in a lower activity of CAT (Table 3) and may be due to the low content of H\(_2\)O\(_2\) produced at the time of evaluation. CAT, together with APX, acts by removing the hydrogen peroxide resulting from SOD activity by converting it to water. However, there are different affinities of these two enzymes to their substrate, so that APX, with its high affinity, acts when H\(_2\)O\(_2\) is present in low concentrations. CAT, on the other hand, has an opposite behavior (GILL; TUTEJA, 2010). CAT enzyme inhibition was also observed in wheat plants subjected to high doses of the herbicide chlorotoluron (SONG et al., 2007). However, this is not completely known because, even with a high SOD activity, less accumulation of H\(_2\)O\(_2\) may occur. A possible explanation for this characteristic is the conversion of free radicals into \(^*\)OH. \(^*\)OH may react with all biological molecules such as DNA, proteins, lipids and nearly all of the cell constituents.

Another consequence of stress caused by herbicides is the reduction in the total protein content. This effect can be observed for the oxyfluorfen herbicide, which reduced protein levels compared to control and other herbicides (Table 3). Proteins are found in all parts of cells, as they are in all aspects fundamental to the cell structure and function. Changes in protein levels may cause a great damage to the growth and development of plants. Studies demonstrate that the application of herbicides may result in a decreased protein synthesis (SOOD et al., 2012).
It was observed that, in general, the proline content increased in plants subjected to the application of oxyfluorfen (Table 3). It is believed that this increase, because of the application of oxyfluorfen, is due to the role played by proline against oxidative damage due to the ability to eliminate ROS from the cell or activate an antioxidant defense mechanism (MOLINARI et al., 2007). Under stress, the protein synthesis is inhibited and protein degradation is accelerated, which leads to the accumulation of amino acids and free amines.

The proline accumulation occurs due to the increase of protein hydrolysis under stress or because of the conversion of sugars in the glutamate pathway. This is because proline acts as a mediator of osmotic adjustment and on integrity and protection of the plasma membrane as a source of carbon and nitrogen (HEMAPRABHA et al., 2013) and as an antioxidant agent, removing reactive oxygen species during oxidative stress.

Upon evaluating the changes at 12 DAE, there was a reduction in the levels of H$_2$O$_2$ in plants treated with oxyfluorfen (Table 4). Hydrogen peroxide is usually derived from the SOD activity, which converts O$_2^-$ into H$_2$O$_2$. However, if the superoxide anion was not converted by SOD, it may form the radical hydroxyl through a Haber-Weiss reaction, which is the radical most harmful to the cell.

Based on other variables, it is possible to suggest that low levels of H$_2$O$_2$ in plants treated with oxyfluorfen is not directly linked to a lower selectivity of this herbicide. That is, it does not mean that the formation of H$_2$O$_2$ is not happening: it may have been converted to ‘OH or dissipated into water by the activity of SOD. Furthermore, it is known that in low concentrations, H$_2$O$_2$ may act as a signaling molecule for the activation of the antioxidant defense system. Evidence report the response of the variable in face herbicide application (WU et al., 2010), which reinforces the relation between H$_2$O$_2$ and stress. When compared to other radicals, O$_2^-$ and H$_2$O$_2$ are more reactive. However, when in the presence of metal ions such as Fe, for example, they activate a sequence of reactions that lead to the formation of ‘OH by the Haber-Weiss reaction (BOWLER; MONTAGU; INZE, 1992).

Thus, the activation of the defense system is crucial to ensure the survival of plants.

A higher activity of the enzyme ascorbate peroxidase in plants treated with oxadiazon and pendimethalin was verified (Table 4). These results may be due to a greater accumulation of hydrogen peroxide because of the application of these herbicides. APX is known to play the most important role in eliminating ROS, thus protecting the cells of higher plants, algae and other organisms. This enzyme is involved in the elimination of H$_2$O$_2$ and uses ascorbate as an electron donor (GILL; TUTEJA, 2010). Furthermore, APX has a higher affinity for H$_2$O$_2$ when compared to CAT, that is, even in a lesser amount, H$_2$O$_2$ may activate APX in order to convert this radical into water. In a similar study, it was found that the activity of ascorbate peroxidase increased in both leaves and roots of wheat subjected to the application of chlorotoluron (SONG et al., 2007).

In general, major changes were caused by herbicides that inhibit PROTOX. These herbicides may have their action reduced by the increased activity of some antioxidant enzymes such as SOD, CAT and APX, which are able to mitigate oxidative stress (JUNG et al., 2008). Rice plants treated with inhibitors of PROTOX from various chemical groups (acifluorfen, oxyfluorfen, carfentrazone-ethyl and oxadiazon) showed an increased activity of SOD, CAT and APX (60, 17 and 68%, respectively) if compared to non-treated plants (JUNG et al., 2008).

It is noteworthy that over time, plants have evolved sophisticated strategies to withstand the adverse effects of herbicides and to reduce its phytotoxicity with a multiple detoxification system (KAWAHIGASHI, 2009). Numerous studies have shown that ROS (such as H$_2$O$_2$) may serve as signaling molecules involved in plant responses to biotic and abiotic stresses (GILL; TUTEJA, 2010). They may also activate enzymes of the antioxidant system (JIANG; YANG, 2009).

CONCLUSION

The herbicides pendimethalin and oxyfluorfen cause lower net photosynthesis, increase substomatic CO$_2$, a lower water use efficiency and carboxylation. Even selective herbicides registered for weed control in rice crops cause phytotoxicity, reduce height and alter the metabolism of plants, generating reactive oxygen species, which activate enzymatic and non-enzymatic defense systems and result in the degradation of photosynthetic pigments and in a reduced protein content.

REFERENCES


Oxidative stress caused by the use of preemergent herbicides in rice crops


