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Potential Use of Tembotrione (HPPD-Inhibitor Herbicides) in Grain Sorghum

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1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a very important cultivated species in India, United States and some countries in Africa due to its high nutritional value both for food (grains) and feed (forage and grains) (Dahlberg *et al.*, 2004). In Brazil, sorghum has increasingly attained a level of recognition mainly as an option for the second crop cycle known as “safrinha”. It has also been considered a viable alternative to replace crops such as cotton [*Gossypium hirsutum* (L.) Moench], corn (*Zea mays* (L.) Moench] and millet [*Pennisentum glauco* (L.) Moench] in crop rotations, serving not only for straw residue in conservation agriculture systems but also for the production of grains and forage as well (Gontijo Neto *et al.*, 2002).

Grown in tropical and subtropical climate regions, grain sorghum presents upright growing habit, mid-range height and uniform development even under limited water availability (Kismann, 2007). Despite its rusticity, grain sorghum has a slow initial growth, becoming vulnerable to the interference caused by weed competition. In this context, weeds may become a limiting factor for the development of the crop. It is estimated that the coexistence of weeds along with grain sorghum during the four first weeks after crop emergence may cause reductions ranging from 40 to 97% in grain yield (Tamado *et al.*, 2002).

In spite of being a remarkable crop on grain production worldwide, there are a limited number of studies on the selectivity of herbicides for this species, making weed control options more limited, mainly in large areas (Abit *et al.*, 2009). One of the major obstacles that has limited sorghum expansion is the difficulty to manage weeds due to the crop sensitivity to grass herbicides currently available (Archangelo *et al.*, 2002). Since the aggravating factor is the difficulty to control grass weeds, new research on this issue must be considered.

The identification of post-emergence herbicides capable of controlling grasses, with suitable crop selectivity, is crucially important to keep sorghum cultivated areas expanding. Most of the registered herbicides used on sorghum farming were initially developed to be used on other large scale crops, particularly on corn and sweet corn (Stahlman & Wicks, 2000).

In this regard, the objective of this study is to gather information concerning the actual status of reported effects of weed interference on grain sorghum and also discuss options of chemical weed control through post-emergence herbicides including tembotrione.

2. Importance of weed control in sorghum

Sorghum, as well as other agricultural plant species, is subjected to a series of biotic and abiotic factors, which directly or indirectly influence its growth and development (Magalhães *et al.*, 2000). Among these factors, weed-imposed interference on crops is one of the most remarkable. Low sorghum yields have been correlated both to the absence and inefficient weed control (Erasmio & Pitelli, 1997).

The negative effects of weeds on sorghum agrosystems occur mainly due to the competition for crops' vital resources, such as water, light and nutrients. Furthermore, weeds can host pests and diseases, raising the cost of production, not to mention the depreciation of the product's quality (Grichar *et al.*, 2005; Andres *et al.*, 2009).

Initial development of sorghum is slow when compared to other cultivated species, which ensures that weeds, mainly those with a more aggressive growth habit, are more advantaged in the competition for resources, making sorghum more susceptible to interference exerted by weed community (Rizzardi *et al.*, 2004). Even showing a slow initial growth, sorghum utilizes a C4 photosynthetic pathway and is able to grow under low soil moisture conditions (Rodrigues *et al.*, 2010). Noteworthy for fodder sorghum, an annual crop used for feeding during dry periods, dense sowing increases this crop's competitive efficiency in relation to weeds, due to a faster land cover and, therefore, to the limited available spaces for weed emergence and growth.

For the majority of cultivated species, most troublesome weeds are those with a similar morphophysiology and life cycle, such as *Echinochloa crus-galli* and *Brachiaria plantaginea*, in areas cultivated with corn, sorghum and pear millet (Andres *et al.*, 2009; Rodrigues *et al.*, 2010; Dan *et al.*, 2011a).

However, in the United States and Mexico, the biggest problems to weed competition are related to the presence of broadleaves. These species have caused steep yield reductions, encouraging research focused on such weeds (Grichar *et al.*, 2005; Rosales-Robles *et al.*, 2005). Weed density increases of one single plant of *Amaranthus palmeri* per square meter have caused a 1.8% reduction on grain yield (Moore *et al.*, 2004). In subtropical areas, some grasses are still considered even more aggressive. According to Norris (1980), the presence of 175 *Echinochloa crus-galli* plants per square meter was enough to cause a 52% reduction on grain sorghum yield.

Weed management on sorghum crops in small properties has been carried out during the first 40 to 50 days after emergence, and two to three manual weedings are required. From this point on, the sorghum canopy will contribute to reduced favorable conditions for weed

germination, growth and development, mainly by reducing the incidence of radiation (Rizzardi *et al.*, 2001). In larger areas, weed control is usually accomplished by herbicide applications. Despite the method used for weed control, it is also important to observe that the period within the crop cycle when weed interference is prevented may also be a determinant for crop success. The stage of the crop cycle when weed control is established strongly influences competition levels, bringing about impacts on crop growth, development and grain yield (Silva *et al.*, 2009).

At the start of crop development, sorghum and weeds can coexist for a given period without the latter affecting either quantitatively or qualitatively crop production. This phase is called 'period prior to interference' (PPI). By determining interference periods in sorghum crops in tropical regions, Rodrigues *et al.* (2010) concluded that sorghum and the weed community could coexist for 42 days (PPI) with no yield reduction (Figure 1). On the other hand, this interference could occur earlier in the crop cycle depending on the density and species of weeds.

The period of time after sorghum emergence during which it must be free from weed competition is called 'total period of interference prevention' (TPIP).

By definition, the period in which weeds effectively interfere with the crop and the period during which competition must not exist is called 'critical period of competition' (PCPI) (Pitelli & Durigan, 1984). During this period, there has been observed a drastic crop yield reduction (54%) when the control was achieved late in time. Silva *et al.* (1986) observed that the absence of weed control on the first four weeks after sorghum emergence can lead to a reduction in grain production of 35% and that, without any control during the entire crop cycle, the reduction can be as high as 70%.

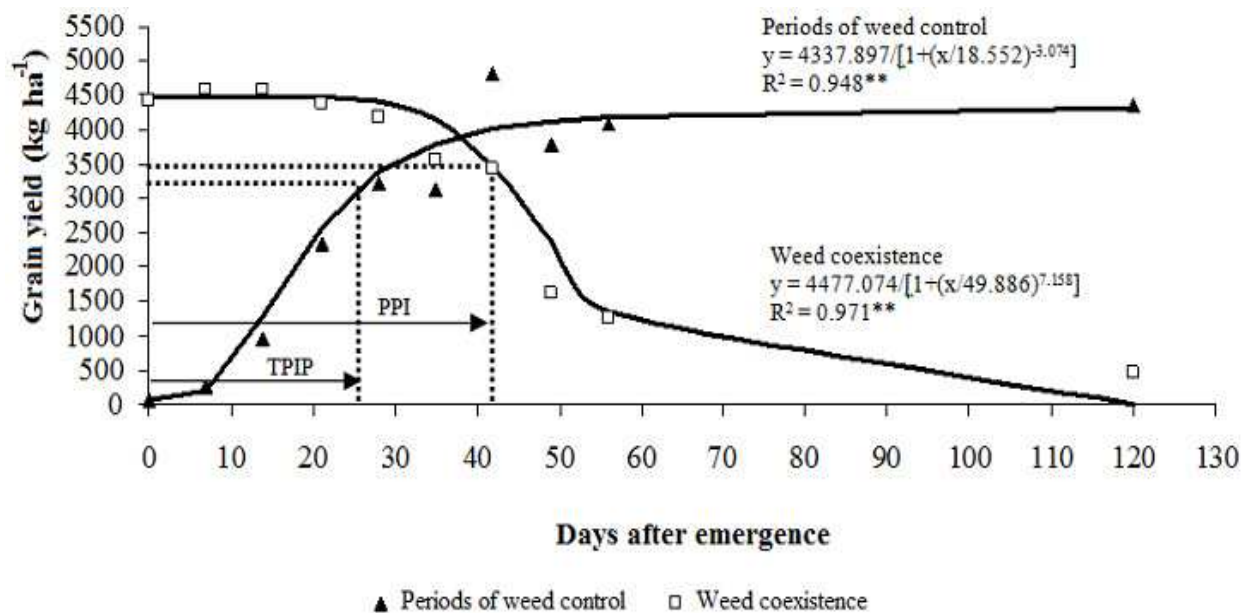


Fig. 1. Sorghum grain yield as a function of periods of weed control and weed coexistence in tropical regions (Rodrigues *et al.*, 2010).

However, total period of interference prevention (TPIP) was 26 days (Rodrigues *et al.*, 2010). On this basis, it can be concluded that PPI was longer than TPIP, and, in this case, there was no PCPI. Under this scenario, accomplishing weed control just once during the crop cycle would be enough to preserve yield crop potential, as long as it is carried out between the end of PPI and the end of TPIP. Nevertheless, it must be understood that those periods may vary, mainly in relation to the intensity of competitive potential of weeds and to the density range as well as the predominant environmental conditions which may be more or less favorable to weeds. *Abutilon theophrasti* is noted to be more competitive than *Ipomoea purpurea* and *I. hederacea* in relation to sorghum, but the period of competition varies according to soil moisture level, exposure to solar radiation and nitrogen fertilization (Feltner *et al.*, 1973). Further studies should be carried out to determine critical periods of weed interference under different environmental and soil conditions.

Another approach to study weed interference on crops is based on crop development stage. For sorghum, the plant's phenological stage is usually a better indicator than the number of days after crop emergence due to both biotic and abiotic factors affecting crop growth (Larcher, 2000).

Losses can reach 80% of grain production under no weed control method (Andres *et al.*, 2009). Weed control on fodder sorghum crop should be accomplished along the period of the crop cycle between third and seventh leaf emission. Proper weed control during this period ensures no significant damage to the crop's grain yield. Figure 2 represents sorghum grain yield in relation to the phase of crop cycle in which weed control was accomplished (Andres *et al.*, 2009).

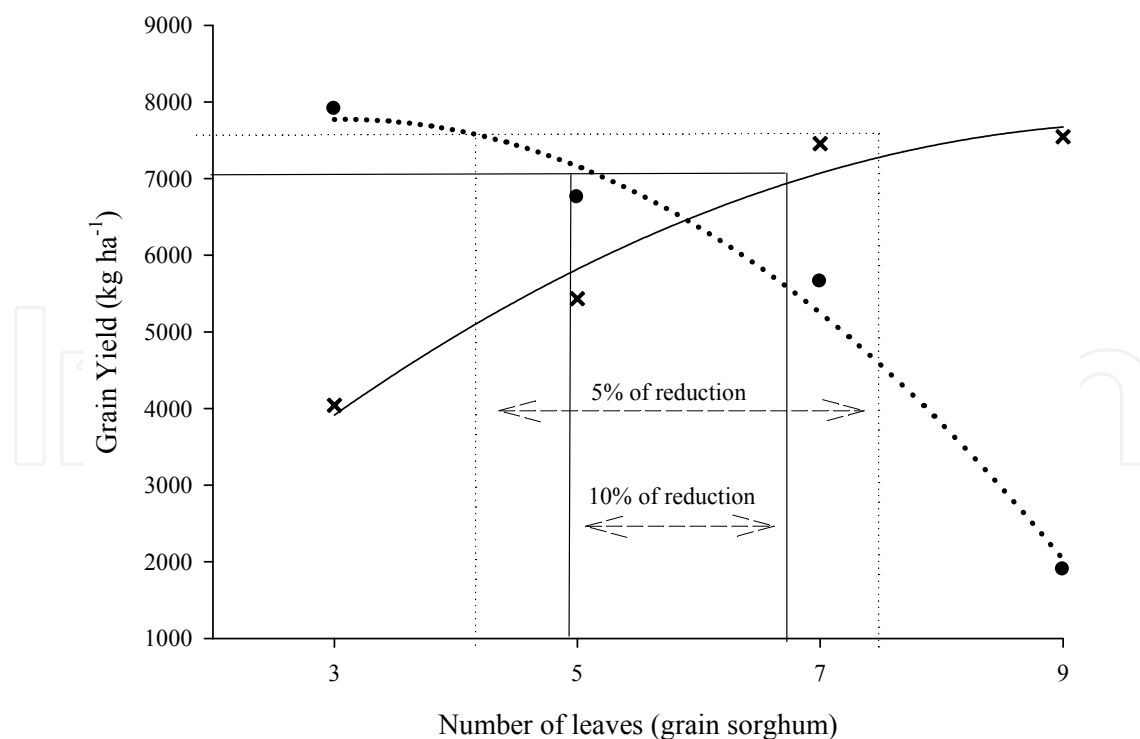


Fig. 2. Sorghum grain yield in relation to periods of initial control and coexistence of weeds in sorghum crop cv. BRS 305 in temperate climate lowlands. (x) periods of initial control; (•) periods of initial coexistence (Andres *et al.*, 2009).

Lack of adoption of weed control measures may affect sorghum quality and/or productivity, and, as a result, decrease a farmer's profitability. However, management of the weed community at specific periods of time ensures lower damages because sorghum can exert the crop's control as well as express its full productive potential.

Local variations on the critical period of weed interference are due to differences in crop genotype, sowing and emergence timing, water and nutrients availability, and density and composition of the weed community.

3. Selectivity of herbicides to grain sorghum

Traditionally, sorghum is more susceptible to herbicides than corn, mainly for graminicides applied postemergence. This response limits the utilization of chemical control as the main tool for weed management in sorghum areas.

To date, most studies have focused on the selectivity of herbicides applied pre-emergence such as s-metolachlor, dimethenamid and atrazine. However, the use of s-metolachlor has always been limited to the utilization of protective agents known as "safeners". Seed treatment using protectors such as fluxofenim, oxabetrinil, benoxacor, cyometrinil and naphthalic anhydride improves selectivity of s-metolachlor for sorghum (Horky & Martin, 2005).

It is estimated that approximately 95% of sorghum area is treated with post-emergence herbicides, particularly with atrazine. In Brazil, little attention has been given to pre-emergent herbicides in sorghum, due to the fact that most areas are cultivated in no or minimum-tillage areas. Therefore, sorghum sowing is often associated with the presence of a variable amount of straw (ranging from 2 to 8 ton dry matter per hectare) from the previous cropping cycle, usually following soybeans. With the increasing area of no-till farming and the growing problems of herbicide-resistant weeds, there has been a growing demand for herbicides with different mechanisms of action, mainly those applied post-emergence. Table 1 summarizes main current post-emergence options studied and utilized in weed management for grain sorghum.

Common Name	Level of selectivity	Author
atrazine	Good	Martin (2004)
bentazon	Good	Ferrell <i>et al.</i> (2008)
bromoxynil	Good	Rosales-Robles <i>et al.</i> (2005)
2,4-D (amine)	Inter.	Dan <i>et al.</i> (2010b)
carfentrazone	Good	Ferrell <i>et al.</i> (2008)
dicamba	Good	Smith & Scott (2006)
halosulfuron	Inter.	Ferrell <i>et al.</i> (2008)
mesotrione	Inter.	Abit <i>et al.</i> (2009)
prosulfuron	Good	Rosales-Robles <i>et al.</i> (2005)

Inter: Intermediate (Some restrictions); Good: (No restrictions)

Table 1. Compilation of results related to herbicide selectivity in post-emergence application in sorghum

One of the most commonly used herbicides to control weeds post-emergence in sorghum is atrazine. Atrazine has been the basis of chemical weed control in corn for the last 50 years and its mechanism of action inhibits the electron flow in photosystem II; other than its known selectivity to corn, it has been considered selective to other grass crops such as pearl millet and sorghum (Dan *et al.*, 2011a). In contrast, one of the main limitations of this herbicide is its low effectiveness on grasses. Previous reports confirm the limited effectiveness of atrazine post-emergence applications to control grass weeds like *Cenchrus echinatus* and *Digitaria horizontalis* in corn and sorghum (Dan *et al.*, 2011a,b).

Herbicides like 2,4-D, carfentrazone and dicamba have also been considered excellent alternatives for the control of broad-leaved weeds. However, they present limitations regarding grass control. Furthermore, additional caution concerning the use of synthetic auxins like 2,4-D and dicamba, should be taken since the combination of late applications and high doses of these chemicals can cause foliar and root dimorphism, which in some cases, leads to yield reduction (Dan *et al.*, 2010b).

Among the graminicides and broadleaf herbicides with potential post-emergence use in sorghum, carotenoid biosynthesis inhibitor herbicides, particularly those that inhibit the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD) are noteworthy (Miller & Regehr, 2002). The inhibition of HPPD blocks the pathway of prenylquinone biosynthesis in plants. Early effects, prior to the appearance of visible phytotoxicity symptoms, are decreased levels of tocopherols and plastoquinone in the plant tissue and a reduced photosynthetic yield. Indirect inhibition of phytoene desaturase as an effect of blocked plastoquinone biosynthesis leads to a decrease in carotenoid levels particularly in young, still expanding leaves. This causes typical foliar bleaching symptoms because the photosynthetic apparatus is no longer stabilized by these pigments. Under high light intensity, excess energy is not quenched and chlorophyll molecules are destroyed (Wichert *et al.*, 1999). Since carotenoids play an important role in dissipating the oxidative energy of singlet O₂, bleaching occurs due to the loss of the protection provided these pigments, leading to a chlorophyll oxidative degradation and, in some extreme cases, to cell membrane oxidation (Mitchell *et al.*, 2001; Armel *et al.*, 2003; Grossmann & Ehrhardt, 2007). Current carotenoid biosynthesis inhibitors registered for use in Brazil include clomazone, isoxaflutole, mesotrione and tembotrione, but clomazone and isoxaflutole have been limited to pre-emergence applications.

Some crops, such as corn, show good tolerance to these herbicides. It has been suggested that selectivity of HPPD inhibitors occur due to a rapid metabolism of herbicide molecules, mainly caused by the action of cytochrome P450 hemoprotein. The cytochrome P450 enzyme, responsible for this metabolism, is likely encoded by the active allele, *Nsf1* (Pataky *et al.*, 2008). Sweet corn hybrids, homozygous for the inactive allele (*Nsf1*), are highly sensitive to mesotrione (Pataky *et al.*, 2008).

Recent studies have demonstrated the possibility of using mesotrione in sorghum as post-emergence applications. Mesotrione is a HPPD inhibitor and belongs to triketone chemical family. It is derived from a natural phytotoxin (callistemone) obtained from the *Callistemon citrinus* plants. A large variability of crop response in the 85 sorghum hybrids treated with 0, 52, 105, 210, and 315 g ha⁻¹ mesotrione was found when plants were sprayed at the 3 to 4-leaf stage (Abit *et al.*, 2009). From the total number of hybrids tested, 23 were classified as susceptible, 45 as intermediate, and 17 as tolerant. From the 17 hybrids classified as tolerant, four were grown in the field. In field, the level of injury symptoms did not correlate to yield

reduction. Since sorghum hybrids were able to recover from injury as the growing season progressed, injury symptoms were not good predictors of yield loss. This study demonstrated that post-emergence applications of mesotrione to sorghum grain hybrids caused a differential crop injury response ranging from susceptible to tolerant. To develop mesotrione as a good alternative for post-emergence weed grass management in sorghum, it may be crucially important for regionalized studies to understand the diversity of genotype tolerance across different producing regions throughout the world.

3.1 Selectivity of tembotrione to grain sorghum

Tembotrione was discovered in 1997 and launched as a commercial herbicide in 2007/2008 in Austria, Hungary, USA and Brazil. When tembotrione is applied to the foliage, a very high percentage of the applied compound is rapidly absorbed. In cases where the herbicide comes in contact with the soil, only small amounts enter the plants via the roots. Accordingly, this herbicide acts after post-emergence application predominantly via the foliage. Tembotrione is mobile both in the plant symplast (phloem) and in the apoplast (xylem). The mobility in the phloem is of particular importance, since it ensures that after a post-emergence spray application the herbicide will be distributed in the stream of assimilates from the mature leaves (metabolic sources) to the developing, highly susceptible leaves (metabolic sinks) at the shoot apex. In accordance with the translocation data obtained with ^{14}C -labeled tembotrione, it can be demonstrated that after controlled foliar placement of the herbicide on susceptible weed species new shoot growth is inhibited due to phloem systemicity (Van Almsick *et al.*, 2009).

As a member of the triketone family of active ingredients, tembotrione shows properties of a weak acid ($\text{pK}_a = 3.18$), resulting in high water solubility and low lipophilicity, e.g. a low octanol/water partition coefficient. These properties are pH-dependent in the environmentally relevant pH range between pH 5 to 9 ($\log \text{Pow} = -1.09$ at pH 7 and -1.37 at pH 9). Consequently, it can be assumed that the behavior of tembotrione in soil and aqueous systems is also influenced by pH. This expectation was confirmed by the differences in the water solubility of tembotrione. Solubility is low at pH 4 (0.22 g L^{-1}) and significantly higher at pH 7 and 9 ($28\text{-}29 \text{ g L}^{-1}$). The high solubility in water at neutral to weakly alkaline pH correlates favorably with the low $\log \text{Pow}$. Therefore, under environmentally relevant pH conditions, tembotrione is mainly present in its ionic form indicating a very low potential for accumulation in biological systems and a tendency to form salts in the environment. In addition, with the values determined for vapor pressure and the Henry's law constant it is estimated that no significant volatilization from soil or water surfaces will occur (Tarara *et al.*, 2009). Typical bleaching caused by tembotrione applications in sorghum occurs in leaves that develop after spraying (Figure 3).

Tembotrione is currently registered for post-emergence use in corn in the United States and Brazil and has showed quite satisfactory results on weed control, particularly for grasses. Commercial formulations of this herbicide include the safener isoxadifen-ethyl, granting higher selectivity to corn and popcorn crops (Waddington & Young, 2006). Field evaluations of crop tolerance provided by mesotrione, topramesone and tembotrione applications in corn, lead to the conclusion that tembotrione caused the least crop injury when compared to topramesone and mesotrione (Bollman *et al.*, 2008).



Fig. 3. Symptoms of tembotrione (200 g ha^{-1}) injuries in late post-emergence application in sorghum.

When assessing selectivity of tembotrione applied to 4-leaf stage in five sorghum cultivars, different levels of crop tolerance were found (Dan *et al.*, 2009a). Results from evaluation performed seven days after application (DAA) of tembotrione demonstrated typical injuries of carotenoid pigment biosynthesis inhibitor herbicides (Figure 3). Throughout the post-application evaluation period, all cultivars showed intoxication (0 to 23% crop injury) when compared to those plants with no herbicide treatment (Table 2). Although there have been visible injuries in all cultivars at 7 DAA, progressive recovery of sorghum plants lead to less than 5% of visual injuries and no bleaching at 21 DAA (Table 2).

Cultivar AG-1020 was the most susceptible genotype among cultivars, and its shoot dry biomass was severely ($\sim 30\%$) affected when plants were harvested 28 DAA. Cultivars have not differed concerning the extent to herbicide sensitivity after 75.5 ha^{-1} tembotrione application to sorghum crop in tropical regions.

Based on the effect of crop dose-response in relation to stages when the herbicide application was performed, results so far indicate that earlier applications are more harmful to grain sorghum development (Dan *et al.*, 2010a). In this study, they evaluated the effect of tembotrione (0, 42, 88, 126, and 168 g ha^{-1}) applied to three phenological stages of sorghum (S1: 3-leaf stage, 15 days after emergence; S2: 5-leaf stage, 23 days after emergence; S3: 8-leaf stage, 31 days after emergence). Cultivar AG-1040 presented the greatest injury levels (59, 46

and 38% at 7 DAA), respectively for the highest dose of 168 g ha⁻¹. Results are shown below (Figure 4).

Cultivar	Visual crop injury (%)			SDW (g plot ⁻¹)				
	Dose (g ha ⁻¹)							
	7 DAA	14 DAA	21 DAA	0.0		75.5		
DKB 599	17.0	6.5	4.4	13.2	abA	11.2	abA	
AG 1020	23.0	19.4	2.3	12.9	abA	9.1	bB	
BRS 308	13.5	4.3	1.5	10.3	bA	9.3	bA	
AG 1040	14.7	8.6	3.2	15.3	aA	13.4	aA	
AGN-8040	11.3	10.3	4.3	12.6	bA	10.2	aA	
CV%							13.12	
DMS							3.23	

Means followed by the same letter (low case letter in the column and capital letter in the row) do not differ from each other by Tukey $p \geq 0.05$ test (Dan *et al.*, 2009a).

Table 2. Visual rating of crop injury and shoot dry weight (SDW) of five sorghum cultivars after application of two doses of tembotrione.

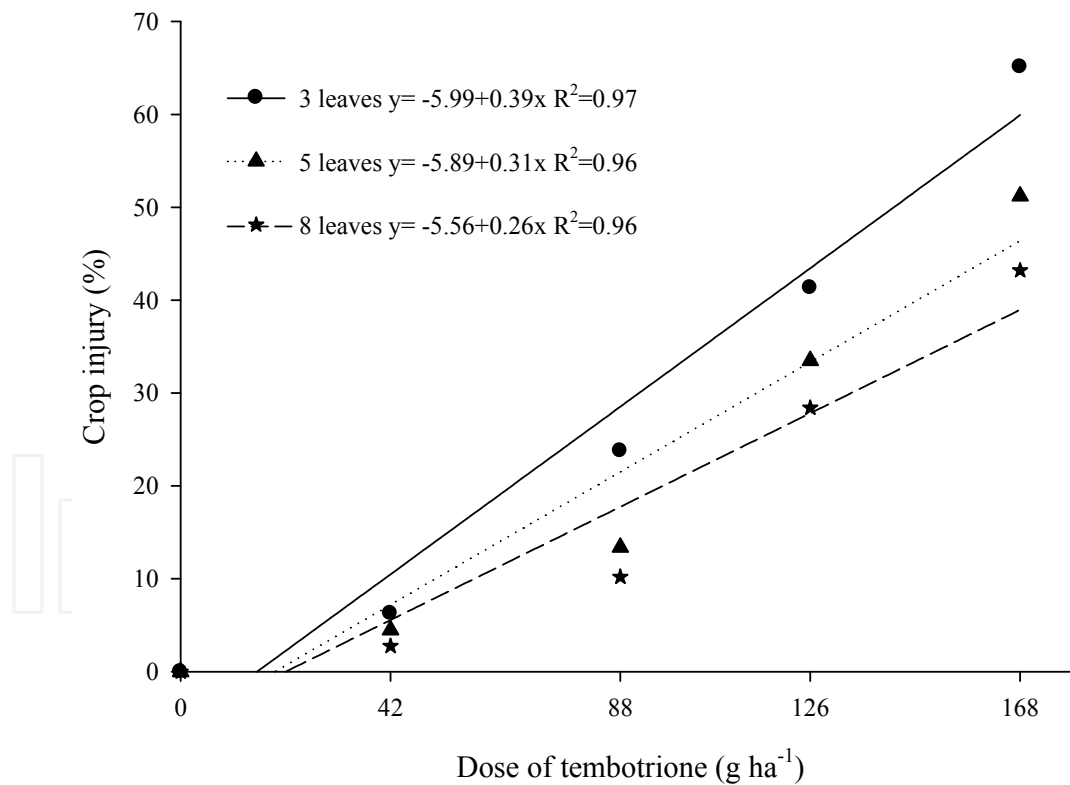


Fig. 4. Sorghum visual injury seven days after application for different doses of tembotrione in three crop growth stages. Source: Dan *et al.* (2010a).

Despite the rapid injuries recovery at 21 DAA, the authors have reported that trends evidenced at 7 DAA were maintained, indicating that applications accomplished in the earlier stages of sorghum crop development have provided the highest levels of crop injury,

implying that herbicide tolerance increases as plants get older. Similar effects related to tembotrione applications in pearl millet have also been described (Dan *et al.*, 2010c). In pearl millet, higher tolerance occurred when tembotrione (75 g ha^{-1}) was applied at the beginning of tillering, as compared to prior-tillering.

Increasing doses of tembotrione can trigger significant reductions on the amount of shoot dry weight and final plant height. More evident reductions of sorghum growth were observed when the herbicide application was carried out at earlier growth stages (3 leaves stage) (Dan *et al.*, 2010a). Injury reduction was twice as much more pronounced when compared to applications at 5- and 8-leaf stage. Nevertheless, effects on dry weight are directly related to crop stage at herbicide spraying. Abit *et al.* (2009) observed that all 85 sorghum hybrids evaluated showed significant reductions in the amount of dry weight after exposure to mesotrione, an herbicide which exhibits a very close chemical structure and similar mechanism of action to that of tembotrione.

Results lead to the conclusion that younger plants are less able to recover from injuries caused by tembotrione and that this fact directly reflects on dry weight accumulation, which may represent a negative factor for sorghum crops destined to forage production. For this reason, proper care should be taken concerning the dose and time of application of this herbicide.

In relation to grain yield, intoxication caused by tembotrione can cause significant reductions due to dose increment. Studies carried out with doses ranging from 0 to 168 g ha^{-1} , demonstrated grain yield reductions of 25, 16 and 15% for applications performed at 3, 5 and 8 expanded leaves stages, respectively (Figure 5) (Dan *et al.*, 2010a).

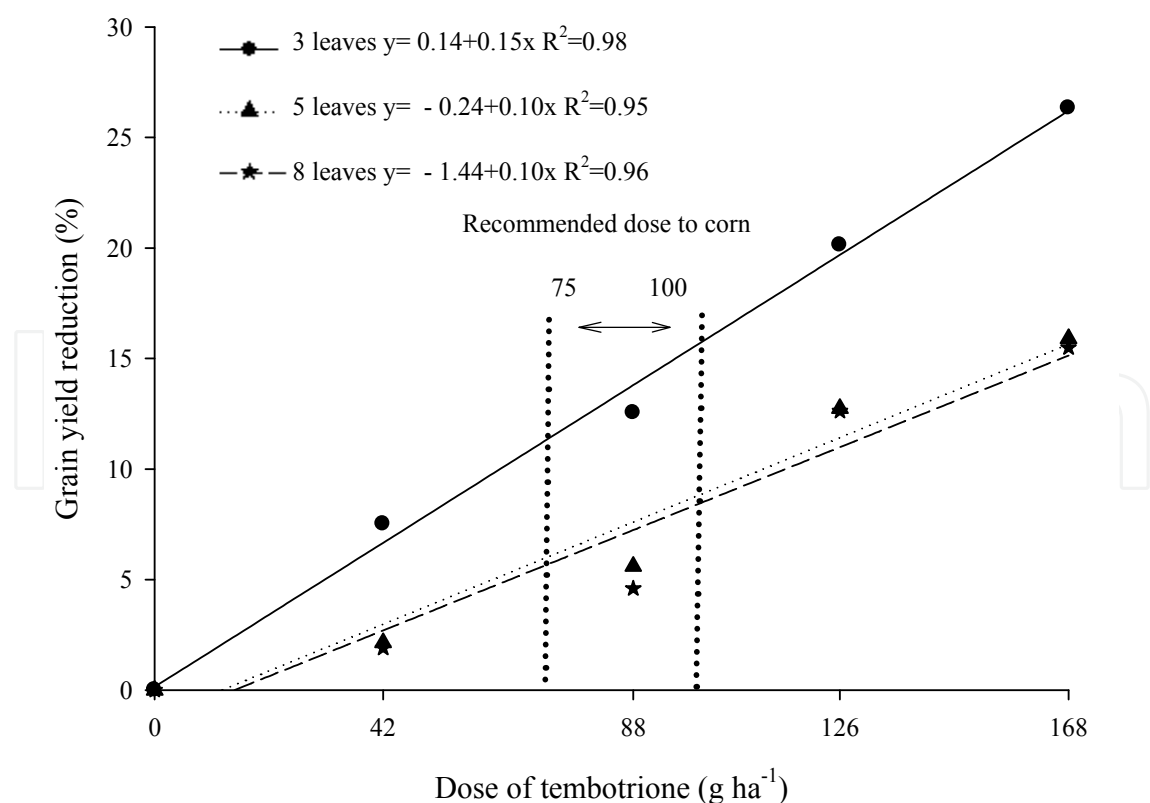


Fig. 5. Sorghum grain yield reduction as a function of increasing doses of tembotrione applied in three crop growth stages (Dan *et al.*, 2010a).

Currently, doses ranging from 75.6 to 100.8 g ha⁻¹ of tembotrione are recommended for weed control in corn in Brazil. Taking into account the lowest recommended dose (75.6 g ha⁻¹), for instance, the greatest reduction observed for sorghum grain yield was about 11% when applications were carried out at the 3-leaf stage. Applications performed in other crop stages reached 7.3% and 6.1% in 5- and 8- leaf stages, respectively. These results indicate a potential use of this herbicide on grain sorghum, however, further studies evaluating other cultivars are required to supplement information on the selectivity of this herbicide.

Despite the different levels of crop injury, it is important to highlight that interference caused by weeds could pose a much more important risk due to losses up to 97% on grain sorghum yield (Tamado *et al.*, 2001), justifying the need for weed control.

The tolerance of corn to tembotrione in combination with the safener isoxadifenethyl has been attributed to a much faster metabolic degradation of the herbicide than in susceptible dicotyledonous and grass weed species. Herbicide metabolism studies in corn, with and without a safener, reveal that isoxadifen-ethyl enhances tembotrione metabolism resulting in non-phytotoxic products. Corresponding to the specificity of safener action in corn, no significant enhancement of herbicide metabolism is found in *Brachiaria plantaginea* as one example of a representative target weed species (Tarara *et al.*, 2009).

3.2 Weed control by tembotrione in grain sorghum

Besides selectivity, another decisive factor leading to the adoption of a certain herbicide is related to the spectrum of weed control. The list of weeds controlled by tembotrione in Brazil comprises important grasses like *Brachiaria decumbens*, *Cenchrus echinatus*, *Digitaria horizontalis*, *D. ciliaris* and *Brachiaria plantaginea* and broad leaf species like *Alternanthera tenella*, *Commelina benghalensis*, *Ipomoea nil*, *I. purpurea*, *I. acuminata*, *Sida rhombifolia*, *Nicandra physaloides*, *Euphorbia heterophylla*, *Raphanus raphanistrum*, *Bidens pilosa*, *B. subalternans*, *Richardia brasiliensis* and *Leonurus sibiricus*, but the registration is limited to corn. However, the control on broad leaf species such as *A. tenella*, *B. pilosa* and *Ageratum conyzoides* is usually extended by using the combined use of atrazine and tembotrione (Barroso *et al.*, 2009). The efficiency of tembotrione alone is clearly limited when it is applied to weeds in a more advanced growth stage.

Among main grass species that are present in areas cultivated with sorghum in Midwestern Brazil, post-emergence applications of tembotrione may have a differential level of efficacy. *D. horizontalis* is more sensitive than *Cenchrus echinatus*; control of both species becomes more evident (>80%) in doses ≥ 88 g ha⁻¹ for *D. horizontalis* in applications carried out before tillering. However, similar levels of control of *C. echinatus* are obtained only by using doses of 126 g ha⁻¹ (Figure 6).

Other studies have also evaluated the spectrum of weeds controlled by tembotrione. Applied at 92 g ha⁻¹, control of broadleaves and grass species was reported (Hinz *et al.*, 2005; Lamore *et al.*, 2006), including redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), velvetleaf (*Abutilon theophrasti* Medic.), giant foxtail (*Setaria faberi* Herrm), barnyardgrass [*Echinochloa crusgalli* (L.) Beauv], and woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth].

Further work on this issue must investigate the possibility of using mixtures with other herbicides such as atrazine, among others. In addition, it is equally important to highlight

other cropping techniques targeted to reduce the infestation in order to reduce pressure by making the control easier to ensure a more successful tillage management.

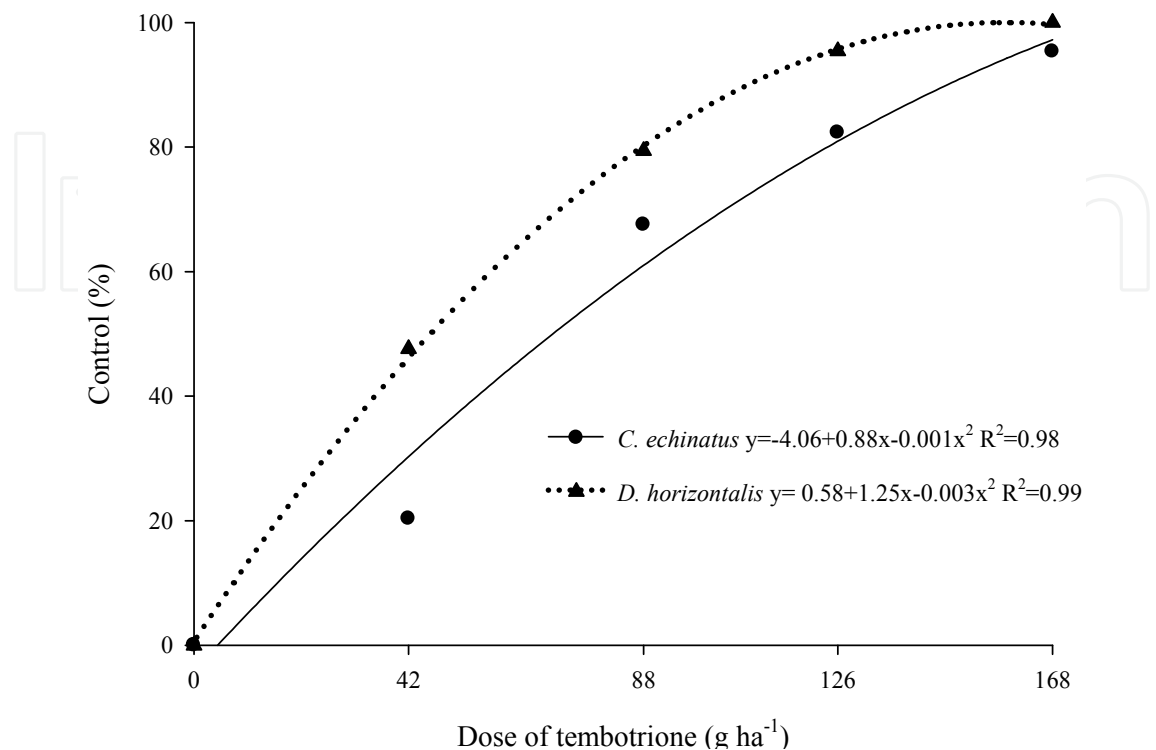


Fig. 6. Weed control for sorghum crop at 21 days after applying increasing doses of tembotrione (Dan et al., 2009b).

4. Concluding remarks

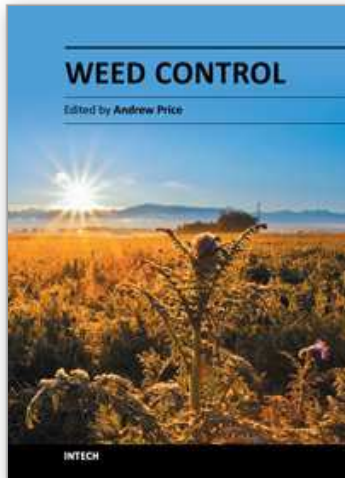
Weeds present a great competitive potential with grain sorghum. However, effects are converged by a number of factors such as weed species and densities, moment of crop cycle when control is imposed and farming practices such as tillage system. Results have demonstrated that more intense interference occurs, in most cases, starting at the 4-leaf stage, weed free period. Although sorghum cropping is widespread in a great variety of regions throughout the world, current selective herbicides have not been sufficiently evaluated and the options available so far are not enough. Studies have provided results that confirm HPPD-inhibitor herbicides potential, mainly for mesotrione and tembotrione, assisting mainly in post-mergence grass weed control. Nevertheless, regionalized studies on different genotypes of sorghum must be conducted to supplement information regarding the selectivity of this herbicide for grain sorghum and to support recommendations.

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Crop loss due to weeds has challenged agricultural managers since man began to develop the first farming systems. In the past century, however, much progress has been made to reduce weed interference in crop settings through effective yet mostly non-sustainable weed control strategies. With the commercial introduction of herbicides during the mid-1900's, advancements in chemical weed control tactics have provided efficient suppression of a broad range of weed species for most agricultural practices. Currently, with the necessity to design effective sustainable weed management systems, research has been pushing new frontiers on investigating integrated weed management options including chemical, mechanical as well as cultural practices. Author contributions to Weed Science present significant topics of research that examine a number of options that can be utilized to develop successful and sustainable weed management systems for many areas of crop production

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