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Article

Leaching of Imidazolinones in Irrigation Systems in Rice Cultivation: Sprinkling and Flooding

Lixiviação de Imidazolinonas em Sistemas de Irrigação na Cultura do Arroz: Aspersão e Inundação

HELGUEIRA, D.B.[1]*
ROSA, T.D[1]
MOURA, D.S.[1]
GALON, L.[2]
PINTO, J.J.O.[1]

ABSTRACT - Herbicides of the imidazolinone group have been used in irrigated rice and presented a long persistence in the soil, especially in floodplain areas with a low drainage, and could cause environmental contamination. This study aims to evaluate the leaching and residual of herbicides belonging to the imidazolinone group in sprinkler and flood irrigation systems. The experiment was carried out under greenhouse conditions, with the application of the herbicides imazethapyr, imazethapyr + imazapic, and imazapyr + imazapic in soil irrigated by flooding and sprinkling. Subsequently, the soil was collected from the layers of 0-5, 5-10, 10-15, 15-20, and 20-25 cm and packed in 500 mL capacity plastic pots in order to sow tomato as a bioindicator plant of the presence of the herbicides belonging to the imidazolinones. Phytotoxicity, length, and shoot dry matter mass of tomato plants were evaluated at 10 and 20 days after emergence. The herbicides of the imidazolinone chemical group presented a high potential for leaching and persistence with effects for more than 180 days after application. Based on the symptoms presented by the sensitive crop, the degradation of imazethapyr, imazethapyr + imazapic, and imazapyr + imazapic in the 0-15 cm layers was higher in soil with sprinkler irrigation when compared to flood irrigation. Thus, non-flooded soils present a greater capacity to degrade the herbicides belonging to the imidazolinone chemical group.

Keywords: *Oryza sativa* L., environmental contamination, ALS inhibitors.

RESUMO - Herbicidas do grupo das imidazolinonas têm sido utilizados em arroz irrigado e apresentado longa persistência no solo, principalmente em áreas de várzea, com baixa drenagem, podendo ocasionar contaminação ambiental. Objetivou-se, com este trabalho, avaliar a lixiviação e o residual dos herbicidas pertencentes ao grupo das imidazolinonas em sistemas de irrigação por aspersão e inundação. O experimento foi conduzido em casa de vegetação, sendo realizada a aplicação dos herbicidas imazethapyr, imzethapyr + imazapic e imazapyr + imazapic em solo irrigado por inundação e aspersão. Posteriormente, o solo foi coletado nas camadas de 0-5, 5-10, 10-15, 15-20 e 20-25 cm e acondicionado em vasos plásticos com capacidade para 500 mL, para se efetuar a semeadura de tomate como planta bioindicadora da presença dos herbicidas pertencentes às imidazolinonas. Avaliou-se a fitotoxicidade, o comprimento e a massa seca da parte aérea das plantas de tomate aos 10 e 20 dias após a emergência. Os herbicidas do grupo químico das imidazolinonas apresentaram alto potencial de lixiviação e persistência, cujos efeitos permanecem por mais de 180 dias após a aplicação. A degradação do imazethapyr, imazethapyr + imazapic e imazapyr + imazapic, nas camadas de 0-15 cm, foi superior em solo com irrigação por aspersão,

*** Corresponding author:**
<diogobalbe@gmail.com>

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[1] Universidade Federal de Pelotas, Capão do Leão-RS, Brasil; [2] Universidade Federal da Fronteira Sul, Erechim-RS,Brasil.

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comparativamente à irrigação por inundação, com base nos sintomas apresentados pela cultura bioindicadora. Pode-se afirmar que solos não inundados apresentam maior capacidade de degradação dos herbicidas pertencentes ao grupo químico das imidazolinonas.

Palavras-chave: *Oryza sativa* L., contaminação ambiental, inibidores da ALS.

INTRODUCTION

To control the rice weed (red and black rice) in cultivated rice fields, herbicide-tolerant cultivars of the imidazolinone chemical group were developed (SOSBAI, 2012). However, the use of this herbicide group, which is sometimes inadequate, leads to environmental contamination risks due to its residual effect, high solubility, and mobility in the soil, thus contaminating groundwater (Jourdan et al., 1998).

Some herbicides in the imidazolinone chemical group are selective to important crops, such as soybean and rice, and are broad-spectrum on weeds in these two cultivated species. These herbicides are usually applied in pre- or post-emergence, controlling magnoliopsid and liliopsid species (Steele et al., 2002), but can also be used as non-selective herbicides in non-agricultural areas because of their high persistence in the soil (Masters et al. (1996), which is very important for this herbicide group (Villa et al., 2006).

The herbicides belonging to the imidazolinone group are generally absorbed by roots and leaves and transported by the phloem and xylem, being accumulated in the meristems, where their mechanism of action occurs, with a reduction of the branched-chain aliphatic amino acid levels valine, leucine, and isoleucine through the inhibition of the enzyme acetolactate synthase (ALS) or acetohydroxyacid synthase (AHAS) (Kraemer et al., 2009). The main effects are the decrease of the synthesis of these amino acids and, consequently, the reduction of the synthesis of proteins, DNA, and a reduction in the transport of photoassimilates from the green leaves. The symptoms of the action of these herbicides are visible, such as the decrease of plant growth, elongation, and chlorosis between the ribs of the leaves (Tan et al., 2006).

Microbial and photolytic degradation are the principal means of dissipation of herbicide molecules of the imidazolinone group (Mallipudi et al., 1991). Hydromorphic soils have a low microbial activity and this characteristic hinders the degradation of the herbicide molecule since an anaerobic condition occurs in irrigated rice areas (Mangels, 1991). In addition to this, there is the maintenance of a water slide during most of the rice cycle, which decreases the period in which the soil is under favorable conditions for a higher microbial activity. In this case, with a reduced degradation, the herbicide shows its high persistence in the soil and can trigger phytotoxic effects for crops grown after rice (Ball et al., 2003).

In plants sensitive to herbicides of the imidazolinone group, phytointoxication (carryover) has been observed in successor crops after the application of these products (Villa et al., 2006). In addition to the risk of contaminating surface water through leaching, the persistence of herbicides of the imidazolinone group for long periods limits the use of sensitive crops sown in rotation or succession to irrigated rice when conducted under the Clearfield® technology (Roman et al., 2007).

The behavior of imidazolinones can be influenced by soil properties as these herbicides are strongly affected by characteristics such as pH, moisture, organic matter, and texture (Goetz et al., 1990). Imidazolinone molecules may behave both as an acid or base because of the presence of the carboxylic (acid) and amino (base) functional groups, and the action is dependent on the pH of the medium in which they are found (Pusino et al., 1997). The higher or lower availability of these herbicides in the soil solution is related to their ionization coefficient (pKa) and solution pH.

Imidazolinone degradation is closely related to the characteristics and conditions of soils, but there is a lack of studies that evaluate the dissipation of these herbicides attributed to different irrigation systems. This study had as objective to evaluate the leaching and residual of herbicides of the imidazolinone group in sprinkler and flood irrigation systems.

MATERIAL AND METHODS

The experiment was carried out in two stages: the first one in the field, at the Terras Baixas Experimental Station, Embrapa Temperate Agriculture; and the second stage in a greenhouse of the Eliseu Maciel Agronomy College, Universidade Federal de Pelotas. The research aimed to evaluate the interaction between irrigation systems (flooding and sprinkling) and the efficiency and permanence of herbicides with residual activity in the soil used in pre- and post-emergence in the irrigated rice.

In the field, the experiment was carried out in the 2012/13 season in a completely randomized design, arranged in a 2 x 9 x 5 factorial scheme, with four replications. In factor A, rice was cultivated under two irrigation systems (sprinkling and flooding). In factor B, the following herbicide treatments were applied when rice plants were at the phenological stage V3: T1 - without herbicide; T2 - imazethapyr + imazapic – 75 + 25; T3 - imazethapyr + imazapic – 150 + 50; T4 - imazapic + imazapyr – 73.5 + 24.5; T5 - imazapic + imazapyr – 147 + 49; T6 - imazethapyr – 106; T7 - imazethapyr – 212; T8 - sequential application of imazethapyr + imazapic – 75 + 25; and T9 - sequential application of imazapic + imazapyr – 73.5 + 24.5 g ha^{-1}. In factor C, soil samples were randomly collected from the 0-5, 5-10, 10-15, 15-20, and 20-25 cm layers in the plots that had previously been applied the herbicide treatments (factor B). Four sub-samples were used for each treatment and then they were homogenized.

The soil where the experiment was installed is classified as a solodic Eutrophic Haplic Planosol, Pelotas mapping unit (Embrapa, 2012). The physicochemical characteristics of the soil on which the experiment was conducted are shown in Table 1.

Table 1 - Soil physicochemical characteristics of the experimental area (solodic Eutrophic Hydromorphic Planosol). Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

pH_{water}	Clay	OM	Phosphorus	Potassium	Calcium	Magnesium	Aluminum
(1:1)	(%)		(mg dm^{-3})		($cmol_c$ dm^{-3})		
5.5	16	1.3	6.7	43	4.3	2.0	0.1

Sprinkler irrigation was performed every time soil water pressure reached a level of 0.2 kPa, which was monitored by sensors installed in the area. The conventional irrigation was carried out 24 hours after the application of herbicide treatments and the first nitrogen application, being maintained an 8 cm water depth until the crop physiological maturation.

Subsequently, in the first semester of 2013, the second stage of the study was conducted in a greenhouse. The homogenized soil samples were conditioned in 500 mL capacity plastic pots, where eight tomato seeds were sown. This species is considered as a bioindicator plant because it is sensitive to the herbicides of the imidazolinone group. Each soil layer had four replications, totaling 360 experimental units. To perform the bioassay, the excess of plants was thinned, maintaining five tomato plants per pot. Thus, in this stage, the experimental design was a completely randomized design arranged in a 2 x 9 x 5 factorial scheme with four replications, with the same treatments already described in the experiment of the first stage.

Herbicide phytotoxicity to tomato plants was evaluated at 10 and 20 DAE (days after emergence), being performed visually, assigning percentage values from 0 to 100 for the absence of symptoms and the complete death of plants, respectively (SBCPD, 1995). Shoot length (SL) was determined with a millimeter ruler at 10 and 20 DAE by measuring the distance from the ground up to the end of the last fully developed leaf. Shoot dry matter (SDM) was determined by cutting the five tomato plants close to the soil, drying them in a forced air circulation oven at 60 °C until constant weight, and weighing them in a precision balance. Herbicide leaching was estimated by a bioassay, using the previously described evaluations.

The data were analyzed for homoscedasticity and normality. Subsequently, the data were submitted to the analysis of variance ($p \leq 0.05$). In case of statistical significance, the treatments corresponding to the residual of herbicides, as well as their effects at different depths (soil layers), were compared by the Tukey's test (p≤0.05), and the irrigation systems (flooding and sprinkling) were compared by the Student t test (p≤0.05).

RESULTS AND DISCUSSION

The interactions were irrigation systems with soil layers and herbicides with irrigation system for all the analyzed variables. The data of phytotoxicity, shoot length, and shoot dry matter showed leaching of the herbicide treatments and its phytotoxic effects were detected up to a depth of 20-25 cm. A difference was observed between irrigation systems, in which the herbicides had the highest effect on tomato plants in the flooded system in the surface layers of the soil profile.

A difference was observed in the phytotoxicity of tomato plants between soil layers, as well as irrigation systems, with the highest effects of herbicide residual activity observed in the flooded system and more pronounced in the 0-15 cm layer (Table 2). This result indicates that even imidazolinones have presented a high leaching potential, these herbicides tend to be concentrated in the layers closest to the soil surface, which is in accordance with the results obtained by Kraemer et al. (2009) and Martini et al. (2011), who obtained similar results when working in a soil classified as an arenic Eutrophic Hydromorphic Planosol.

Table 2 **-** Estimate of imidazolinone leaching at different soil layers observed by phytotoxicity at 10 days after emergence of tomato plants sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Layer (cm)	Phytotoxicity (%)	
	10 DAE[(1)]	
	Sprinkling	Flooding
0-5	5.19 b[(2)]B[(3)]	12.55 abA
5-10	10.33 abA	12.80 abA
10-15	12.77 aA	14.66 aA
15-20	12.94 aA	7.33 bcB
20-25	10.75 abA	5.47 cB
Mean	10.39	10.56
CV (%)	25.08	31.71

[(1)] Days after emergence of tomato plants. [(2)] Means followed by different lowercase letters in the column differ from each other by the Tukey's test (p≤0.05). [(3)] Means followed by different uppercase letters in the row differ from each other by the Student t test (p≤0.05).

The phytotoxicity evaluations showed for the sprinkler irrigation system that the highest values occurred in the 15-20 and 20-25 cm layers (Table 2). The difference of phytotoxicity for the irrigation systems is mainly because of the high microbial activity in the soil surface layers, which is favored in the sprinkler irrigation system, resulting in a higher degradation of herbicides when compared to the flood irrigation system.

In the interaction between herbicide treatments and irrigation systems, differences were observed in the herbicide activity regarding phytotoxicity (Table 3). For the sprinkler irrigation system, a difference was observed only in the formulated mixture of imazethapyr + imazapic (T2), which presented the lowest phytotoxicity value, with the same occurring in the flooded system.

Regarding the phytotoxicity evaluations, more than 50% difference was observed between the sprinkler and the flooded irrigation systems in the surface soil layer (0-5 cm), but in the intermediate layers (5-10 and 10-15 cm), the values were equivalent. However, in the 15-20 and 20-25 cm layers, a reduction in the herbicide effects was observed in the flooded system (Figure 1). Therefore, in general, a difference was observed in the residual distribution of herbicides of the imidazolinone group in the soil layers as a function of the irrigation system, which contributes differently to the herbicide degradation and, consequently, to its persistence in the soil (Table 4).

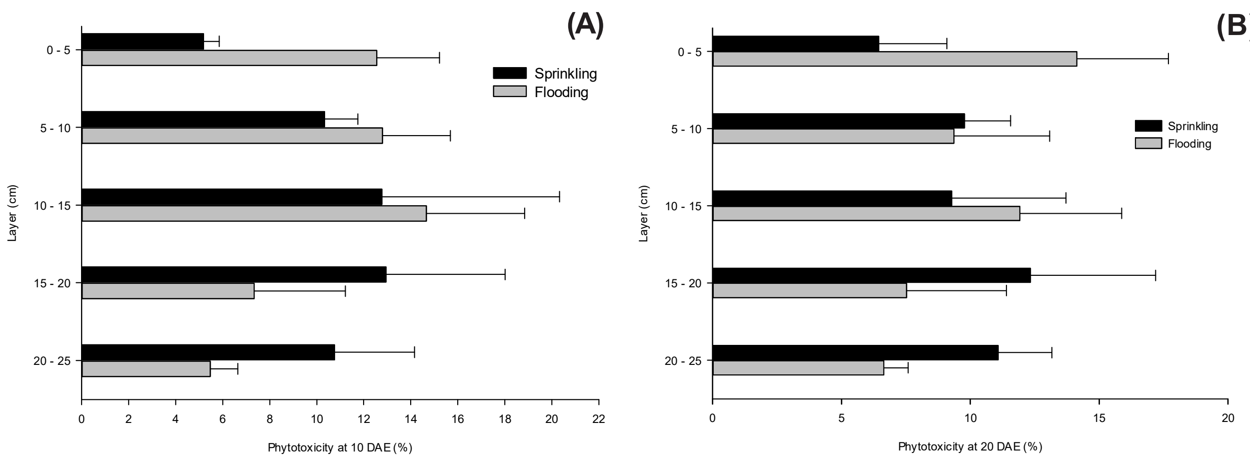
However, in the flooded system, the treatments that had the most expressive phytotoxicity values were T3 and T5, a behavior already expected since it was twice the commercial dose of imazethapyr + imazapic and imazapic + imazapyr, respectively. This characteristic was maintained for both phytotoxicity evaluations. However, these treatments did not maintain the same behavior in the sprinkler irrigation system (Figure 2), not differing from the others (Table 5).

For the variable shoot length, the behavior of values remained similar to that of phytotoxicity. A reduction was observed in the height of tomato plants in the flooded system when compared to

Table 3 **-** Phytotoxicity in tomato plants at 10 days after emergence observed in different herbicide treatments sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Herbicide	Dose (g a.e. ha^{-1})	Phytotoxicity (%) 10 DAE[3]	
		Sprinkling	Flooding
T1 - control	-	0 c[4]	0 c
T2 - imazethapyr + imazapic[1]	75 + 25	3.70 Bc	4.95 bc
T3 - imazethapyr + imazapic[1]	150 + 50	10.60 Ab	21.8 a
T4 - imazapyr + imazapic[1]	73.5 + 24.5	11.90 Ab	8.20 bc
T5 - imazapyr + imazapic[1]	147 + 49	10.05 Ab	19.35 a
T6 - imazethapyr[1]	106	11.65 Ab	8.95 bc
T7 - imazethapyr[1]	212	16.00 A	9.40 bc
T8 - imazethapyr + imazapic[1, 2]	75 + 25	11.45 Ab	7.90 bc
T9 - imazapyr + imazapic[1, 2]	73.5 + 24.5	17.25 A	13.55 ab
Mean	-	10.40	10.56
CV (%)	-	29.53	32.87

[1] Applied in post-emergence in 3 to 4 leaf rice plants. [2] Applied in pre-emergence after sowing the irrigated rice. [3] Days after herbicide application. [4] Means followed by different lowercase letters in the column differ from each other by the Tukey's test (p≤0.05).



* The confidence interval (95%) compares the irrigation systems at each soil layer. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013.

Figure 1 **-** Estimate of leaching of imidazolinones from the phytotoxicity observed at different soil layers at 10 (A) and 20 (B) days after emergence in tomato plants sown 180 days after herbicide application as a function of two irrigation systems.

the sprinkler irrigation system, which occurred up to the 10-15 cm layer (Figure 3). This would be the breakeven point between both systems. From this point on, the scenario reverses and so does the phytotoxicity and shoot dry matter.

The reduction in plant height is one of the characteristics that has been sensitive to the action of herbicides of the imidazolinone group (Silva et al., 1999; Pinto et al., 2009). Studying the herbicide behavior of the imidazolinone chemical group, Briguenti et al. (2002) demonstrated that imazaquin and imazethapyr present long residual effects, which may negatively alter crops in succession or rotation.

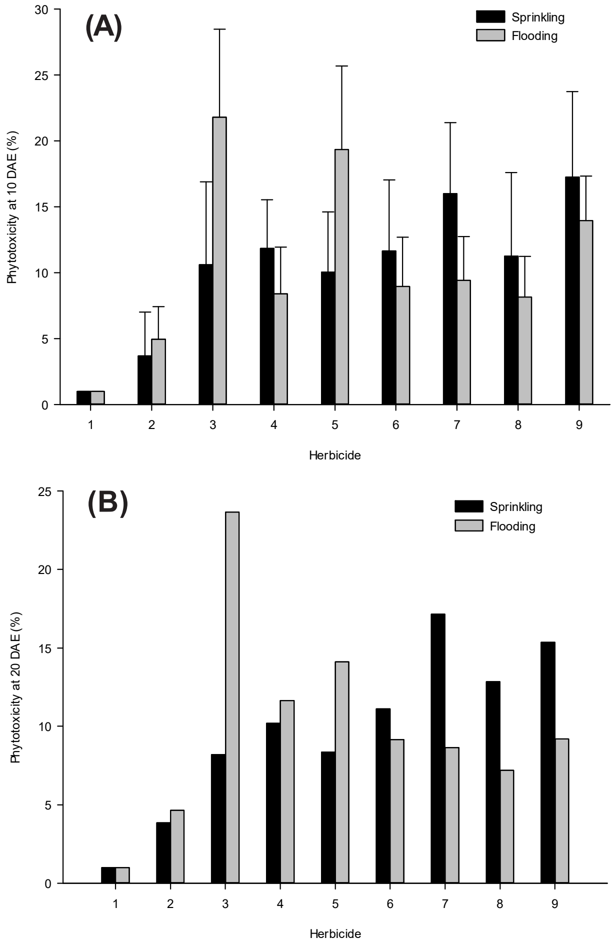
For the variable shoot dry matter (SDM), an interaction was observed between herbicide treatments and irrigation systems, as well as between soil layers and irrigation systems. As previously observed, all herbicide treatments had a similar behavior as a function of irrigation systems. The difference in herbicide leaching was demonstrated by the values, in grams, obtained from the dry matter of tomato plants.

In the sprinkler irrigation system, the herbicides remain at a higher concentration at layers below 15 cm. For the herbicide imazethapyr + imazapic (T3), SDM values were around 50% lower

Table 4 **-** Estimate of imidazolinone leaching at different soil layers observed by phytotoxicity at 20 days after emergence of tomato plants sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Layer (cm)	Phytotoxicity (%)	
	20 DAE[1]	
	Sprinkling	Flooding
0-5	6.44 b[2]B[3]	14.13 aA
5-10	9.17 abA	9.36 abA
10-15	9.27 abA	11.91 abA
15-20	12.33 aA	7.52 bB
20-25	11.08 abA	6.64 bB
Mean	9.65	9.91
CV (%)	22.68	24.51

[1] Days after emergence of tomato plants. [2] Means followed by different lowercase letters in the column differ from each other by the Tukey's test (p≤0.05). [3] Means followed by different uppercase letters in the row differ from each other by the Student t test (p≤0.05).



* The confidence interval (95%) compares the irrigation systems at each soil layer. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013.

Figure 2 **-** Estimate of the herbicide leaching control (1), imazethapyr + imazapic (2), imazethapyr + imazapic – dose x 2 (3), imazapyr + imazapic (4), imazapyr + imazapic – dose x 2 (5), imazethapyr - dose x 2 (7), imazethapyr + imazapic – sequential application (8), and imazapyr + imazapic – sequential application (9) from the phytotoxicity observed at different soil layers at 10 (A) and 20 (B) days after emergence in tomato plants sown 180 days after herbicide application as a function of two irrigation systems.

in the flooded system when compared to the sprinkler system (Table 6). However, for the sprinkler system, the lowest SDM values were concentrated at lower layers (15-20 and 20-25 cm) (Table 7).

The results of our study are in accordance with those obtained by Silva et al. (1999), who observed a high inhibition in shoot and root dry matter production of sorghum sown at 60 days after imazethapyr application. Alister and Kogan (2005) evaluated 11 crops sown at 300 days after herbicide application and nine of them presented a biomass production reduced by the residual action of imazapyr + imazapic or imazapyr + imazethapyr.

For SDM, the same breakeven point between the carryover effects in the intermediate layer (10-15 cm) (Figure 4) is confirmed, which corroborates the hypothesis that there is a difference in the degradation dynamics and leaching of imidazolinones in areas of irrigated rice cultivation as a function of the irrigation system.

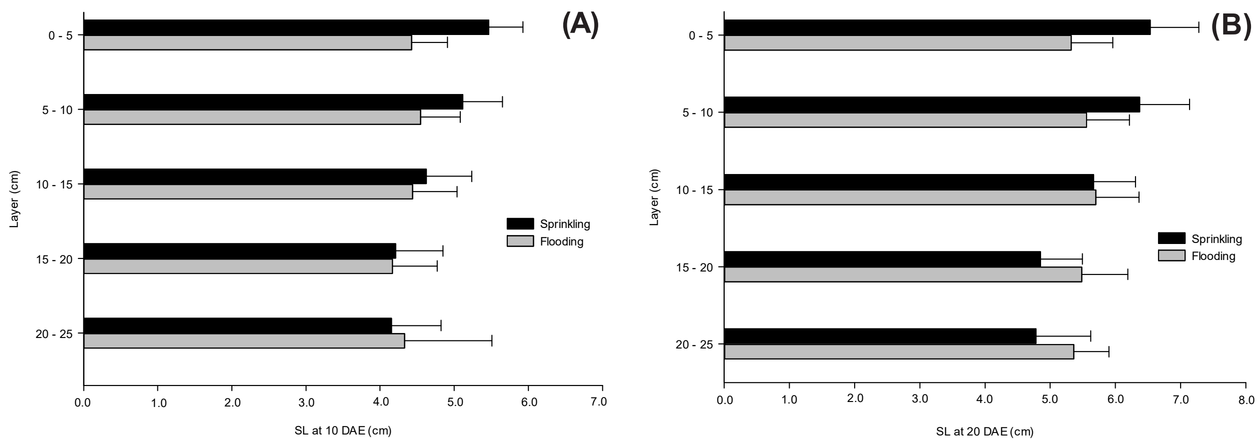
Renner et al. (1988) verified that herbicides from the imidazolinone chemical group might present a residual effect in the soil for up to two years and cause phytotoxicity depending on the successor crop (Ball et al., 2003). Johnson et al. (1993) verified injuries in corn, cotton, sorghum, and rice up to 52 weeks after imazethapyr application. Curran et al. (1992) also observed injury in corn due to residues of imazethapyr applied to soybean in the previous year. These injuries may be characterized by symptoms such as internodes shortening and yellowing of leaves (York et al., 2000), reduction in plant height and increased lateral branching (Ball et al., 2003), and reduction in plant stand or productivity (Loux and Reese, 1993).

Analyzing all the parameters evaluated in this study, the dynamics of residual distribution of herbicides of the imidazolinone group in soils with the characteristics evaluated in these surveys (low clay and organic matter contents) for the sprinkler irrigation system is inversely

Table 5 **-** Phytotoxicity in tomato plants at 20 days after emergence observed in different herbicide treatments sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Herbicide	Dose (g a.e. ha^{-1})	Phytotoxicity (%) 20 DAE[3]	
		Sprinkling	Flooding
T1 - control	-	0 d[4]	0 d
T2 - imazethapyr + imazapic[1]	75 + 25	3.85 cd	4.65 cd
T3 - imazethapyr + imazapic[1]	150 + 50	8.2 bcd	23.65 a
T4 - imazapyr + imazapic[1]	73.5 + 24.5	10.20 abc	11.65 bc
T5 - imazapyr + imazapic[1]	147 + 49	8.35 bcd	14.10 b
T6 - imazethapyr[1]	106	11.10 abc	9.15 bcd
T7 - imazethapyr[1]	212	17.15 a	8.65 bcd
T8 - imazethapyr + imazapic[1, 2]	75 + 25	12.85 ab	7.20 bcd
T9 - imazapyr + imazapic[1, 2]	73.5 + 24.5	15.35 ab	9.20 bcd
Mean	-	9.78	9.91
CV (%)	-	45.20	39.12

[1] Applied in post-emergence in 3 to 4 leaf rice plants. [2] Applied in pre-emergence after sowing the irrigated rice. [3] Days after herbicide application. [4] Means followed by different lowercase letters in the column differ from each other by the Tukey's test ($p \leq 0.05$).



* The confidence interval (95%) compares the irrigation systems at each soil layer. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013.

Figure 3 **-** Estimate of leaching of imidazolinones from the shoot length observed at different soil layers at 10 (A) and 20 (B) days after emergence in tomato plants sown 180 days after herbicide application as a function of two irrigation systems.

related to the results obtained for the flood irrigation system observed in this study and in the literature. Thus, we attempted to fit a linear equation that demonstrates, for the conditions under which this research was carried out, the residual dynamics of herbicides used in Clearfield® technology (imidazolinones) as a function of both irrigation systems, through two straight lines that represent each system, with an intersection point located in the 10-15 cm layer (Figure 5).

Considering that the experiments were conducted on a sandy clay loam soil with a low percentage of organic matter and that the adsorption of imazethapyr and imazapic to soil colloids is relatively weak (Senseman, 2007), the difference in the behavior of the studied imidazolinones in both irrigation systems is due not only to the irrigation method but also to the soil management. In fact, in the flood irrigation system the soil is managed in a conventional way, being disturbed up to the 15-20 cm layer, while in the sprinkler irrigation system it is cultivated under no-tillage, in which soil structure and microorganisms are preserved.

According to Zablotowicz et al. (2000), the adoption of no-tillage can affect the destination of herbicides through interactions with the organic carbon dissolved in the soil surface, microbial degradation, and sorption of these products and their metabolites. Herbicide sorption in soil affects to a lesser or greater degree its destination, activity, and persistence in the soil. For

Table 6 **-** Shoot dry matter of tomato plants at 20 days after emergence observed in different herbicide treatments sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Herbicide	Dose (g a.e. ha^{-1})	SDM (g)	
		20 DAE[3]	
		Sprinkling	Flooding
T1 - control	-	0.25 a[4]A[5]	0.23 aA
T2 - imazethapyr + imazapic[1]	75 + 25	0.22 abcA	0.20 abA
T3 - imazethapyr + imazapic[1]	150 + 50	0.22 abcA	0.11 cB
T4 - imazapyr + imazapic[1]	73.5 + 24.5	0.24 abA	0.20 abB
T5 - imazapyr + imazapic[1]	147 + 49	0.23 abA	0.16 bB
T6 - Imazethapyr[1]	106	0.23 abcA	0.19 abB
T7 - Imazethapyr[1]	212	0.22 abcA	0.18 abB
T8 - imazethapyr + imazapic[1, 2]	75 + 25	0.24 aA	0.23 aA
T9 - imazapyr + imazapic[1, 2]	73.5 + 24.5	0.18 aA	0.17 abA
CV (%)	-	22.3	19.78

[1] Applied in post-emergence in 3 to 4 leaf rice plants. [2] Applied in pre-emergence after sowing the irrigated rice. [3] Days after herbicide application. [4] Means followed by different uppercase letters in the row differ from each other by the Student t test (p≤0.05). [5] Means followed by different lowercase letters in the column differ from each other by the Tukey's test (p≤0.05).

Table 7 **-** Shoot dry matter of tomato plants observed at different soil layers at 20 days after emergence sown at 180 days after herbicide application as a function of two irrigation systems. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013

Layer (cm)	SDM (g)	
	20 DAE[1]	
	Sprinkling	Flooding
0-5	0.2814 a[2]A[3]	0.1717 bB
5-10	0.2628 aA	0.1975 aB
10-15	0.2058 abA	0.2061 aA
15-20	0.1736 bA	0.1964 aA
20-25	0.1900 bA	0.1792 bA
CV (%)	17.85	19.25

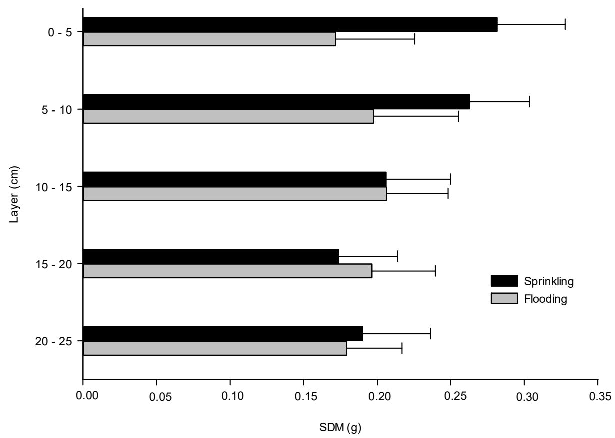
[1] Days after emergence of tomato plants. [2] Means followed by different lowercase letters in the column differ from each other by the Tukey's test (p≤0.05). [3] Means followed by different uppercase letters in the row differ from each other by the Student t test (p≤0.05).

most herbicides (anionic or cationic), a direct correlation is observed between sorption and the organic and mineral content of soils.

The leaching process and residual of the herbicide imazethapyr were observed by Kraemer et al. (2009), who evaluated two soil management systems and observed the herbicide leaching up to 20 cm in the soil. The imazethapyr concentration in the conventional system was concentrated in the 0-5 cm layer when compared to the no-tillage system. In contrast, the total amount of herbicide remaining in the soil 540 days after the last application was not affected by the soil tillage system.

The degradation rate and herbicide persistence of the imidazolinone chemical group, for example, are influenced by temperature, moisture, soil organic matter, and herbicide adsorption to the soil (Goetz et al., 1990). Imazethapyr can be released by volatilization, photodecomposition, microbial degradation, chemical degradation or plant absorption rate (Goetz et al., 1990). However, this herbicide dissipates mainly by biodegradation, with a half-life ranging from 53 to 122 days in aerobic soil (Flint and Witt, 1997). On the other hand, Mangels (1991) states that, under anaerobic conditions, as in irrigated rice crops, no significant degradation occurred in a period of two months.

Studies indicate that, with an increased soil pH, imazethapyr adsorption to soil decreases, while its adsorption increases with an increase in soil organic matter (Goetz et al., 1990). This is due to the anionic nature of the herbicide molecules (Loux and Reese, 1993), leading to the reduced availability of imazethapyr for microbial degradation. This can be observed in the difference of values of phytotoxicity and SDM between both irrigation systems in the soil surface layers. The area related to the flood irrigation system remained with the soil saturated after harvest due to a poor drainage, a situation in which the availability of herbicides in the soil solution occurs and makes its degradation by microbial action difficult, unlike the sprinkler system.



* The confidence interval (95%) compares the irrigation systems at each soil layer. Embrapa/UFPel Agreement – Capão do Leão, RS, 2013.

Figure 4 **-** Estimate of leaching of imidazolinones from the shoot dry matter observed at different soil layers at 20 days after emergence in tomato plants sown 180 days after herbicide application as a function of two irrigation systems.

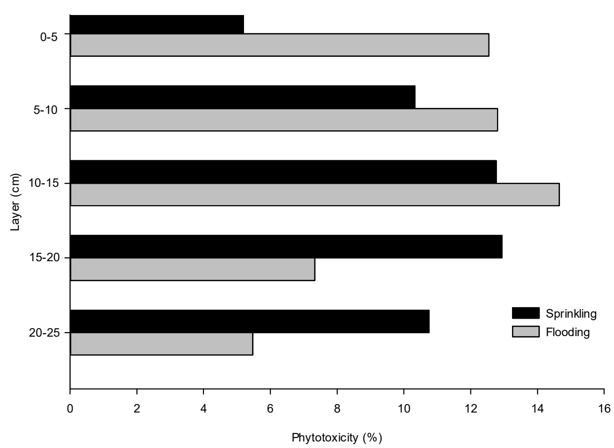


Figure 5 **-** Linear demonstration of the interaction of imidazolinone leaching in tomato plants sown 180 days after application of the herbicides in five soil layers as a function of the flood irrigation system. Capão do Leão, RS, 2013.

In contrast, the high solubility of herbicides used in the soil with a low organic matter and clay contents, better structural conditions that facilitate the gravitational drainage, and precipitations in the period may have facilitated their percolation, providing higher concentrations of the herbicide in deeper soil layers, where microbial degradation is not so efficient. Studies indicate that imazethapyr in undisturbed soils moves in the soil column up to 30 cm (O'Dell et al., 1992). The sorption has a strong impact on the distribution, bioavailability, and persistence of herbicides in the environment.

Thus, the herbicides used in the Clearfield® technology (imazethapyr and the formulated mixtures imazethapyr + imazapic and imazapyr + imazapic) has a high leaching potential, reaching depths of up to 25 cm in irrigated rice soil at six months after application. The herbicides of the imidazolinone group, recommended for rice weed control in Clearfield® rice, have a high persistence in the soil and their phytotoxic effects can be observed up to 180 days after application. According to Pinto et al. (2009), the presence of imidazolinones negatively interferes with ryegrass growth up to six months after application and the use of these Clearfield® herbicides in consecutive seasons may increase the persistence of these molecules in the soil.

The behavior of herbicides belonging to the imidazolinone chemical group has a relative variation depending on edaphoclimatic factors and molecule's own characteristics (Senseman, 2007). This makes the results found in the literature sometimes divergent when trying to compare the behaviors of the same herbicide. These divergences are related to the different environmental, soil, and management conditions found at each growing site.

The main soil-related variables that interfere with the dynamics of these herbicides are pH (Loux and Reese, 1993), organic matter content (Stougaard et al., 1990), texture (Loux and Reese, 1993), management Kraemer et al., 2009), and soil moisture (Baughman and Shaw, 1996). Regarding the molecules, characteristics such as solubility (Avila, 2005), ionization capacity (Inoue et al., 2007), soil adsorption coefficient, and type of degradation are the ones that most interfere with this behavior.

Leaching, drainage, and surface runoff are the main routes responsible for the movement of herbicides in the soil. The processes that occur between soil and herbicides that determine losses are also variable in time and space. Thus, it is necessary to understand the spatial characteristics of soils, their hydrology, and associated herbicide use patterns (Carter, 2000).

Therefore, the sprinkler irrigation system contributes to a higher degradation of imidazolinones located up to 15 cm deep, whose residual effect is detected with tomato plants. The herbicides of the imidazolinone chemical group present a high leaching potential and persistence for the conditions under which this research was carried out, whose effects remain for more than 180 days after application and can be observed by sensitive species. With the increased degradation in the upper soil layers, the risk of environmental contamination caused by surface runoff is lower. The degradation of the herbicides imazethapyr, imazethapyr + imazapic, and imazapyr + imazapic in the 0-15 cm layers is higher in the sprinkler irrigation when compared to the flood irrigation in the irrigated rice crop.

REFERENCES

Alister C, Kogan M. Efficacy of imidazolinone herbicides applied to imidazolinone-resistant maize and their carryover effect on rotational crops. Crop Prot. 2005;24(4):375-9.

Avila LA. Imazethapyr: Red rice control and resistance, and environmental fate: imazethapyr adsorption and availability in three soils as affected by soil moisture content. [these] College Station: Texas A&M University; 2005.

Ball DA, Yenish JP, Alby T. Effect of imazanox soil persistence on dryland rotational crops. Weed Technol. 2003;17:161-5.

Baughman TA, Shaw DR. Effect of wetting/drying cycles on dissipation patterns of bioavailable imazaquin. Weed Sci. 1996;44(2):380-2.

Briguenti AM, Moraes VJ, Oliveira Júnior RS, Gazziero DLP, Barroso ALL, Gomes JÁ. Persistência e fitotoxicidade de herbicidas aplicados na soja sobre o girassol em sucessão. Pesq Agropec Bras. 2002;37(4):559-65.

Carter AD. Herbicide movement in soils: principles, pathways and processes. Weed Res. 2000;40(1):113-22.

Curran WS, Loux MM, Liebl RA, Simmons FW. Photolysis of imidazolinone herbicides in aqueous solution and on soil. Weed Sci. 1992;40(1):143-8.

Empresa Brasileira de Pesquisa Agropecuária – Embrapa. Cultivo de arroz irrigado, 2007. [acessado em: 5 de abr. 2012]. Disponível em: http://sistemasdeproducao.cnptia.embrapa.br/FontesHTML/Arroz/ArrozIrrigadoBrasil/cap10.htm.

Flint JL, Witt WW. Microbial degradation of imazaquin and imazethapyr. Weed Sci. 1997;45(4):586-91.

Goetz AL, Lavy TL, Gbur EE. Degradation and field persistence of imazethapyr. Weed Sci. 1990;38(4/5):421-8.

Inoue NH, Oliveira Jr RS, Constantin J, Alonso DG. Potencial de lixiviação de imazapic e isoxaflutole em colunas de solo. Planta Daninha. 2007;25(3):547-55.

Johnson DH, Jordan DL, Johnson WG. Nicosulfuron, primisulfuron, imazethapyr, and DPXPE350 injure to succeeding crops. Weed Technol. 1993;7(3):441-64.

Jourdan SW, Majek BA, Ayeni AO. Imazethapyr bioactivity and movement in soil. Weed Sci. 1998;46(5):608-13.

Kraemer AF. Marchesan E, Grohs M, Avila LA, Machado SLO, Zanella R, et al. Lixiviação do imazethapyr em solo de várzea sob dois sistemas de manejo. Cienc Rural, 2009;39(6):1660-6.

Loux MM, Reese K. Effect of soil type and pH on persistence and carryover of imidazolinones herbicides. Weed Technol. 1993;7(2):452-8.

Mallipudi NM, Stout SJ, Cunha AR, Lee AH. Photolysis of imazapyr (AC 243997) herbicide in aqueous media. J Agric Food Chem. 1991;39(2):412-7.

Mangels G. Behavior of the imidazolinones herbicides in the aquatic environment. In: Shaner DL, O'Conner SL. The imidazolinone herbicides. Boca Raton: CRC Press; 1991. p.183-90.

Martini LFD, Avila LA, Souto KM, Cassol GV, Refatti JP, Marchesan E, et al. Lixiviação de imazethapyr e imazapic em função do manejo de irrigação do arroz. Planta Daninha, 2011;29(1):185-3.

Masters RA, Nissen S, Gaussoin RE, Beran D, Stougaard RA. Imidazolinone herbicides improve restoration of great plains grasslands. Weed Technol. 1996;10:392-403.

O'Dell JD, Wolt JD, Jardine PM. Transport of imazethapyr in undisturbed soil columns. Soil Sci Soc Am J. 1992;56:1711-5.

SBCPD

Pinto JJO, Noldin JA, Rosenthal MD, Pinho CF, Rossi F, Machado A, et al. Atividade residual de (imazethapyr+imazapic) sobre azevém anual (*Lolium multiflorum*), semeado em sucessão ao arroz irrigado, Sistema Clearfield®. Planta Daninha, 2009;27(3):609-19.

Pusino A, Petretto S, Gessa C. Adsorption and desorption of imazapyr by soil. J Agric Food Chem. 1997;45(3):1012-6.

Renner KA, Megitt WF, Penner D. Effect of soil pH on imazaquin and imazethapyr adsorption to soil and phytoxicity to corn (*Zea mays*). Weed Sci. 1988;36(1):78-83.

Roman ES, Beckie H, Vargas L, Hall L, Rizzardi MA, Wolf TM. Como funcionam os herbicidas: da biologia a aplicação. Passo Fundo: Berthier; 2007. 160p.

Senseman AS. Herbicide handbook. 9th.ed. Lawrence: Weed Science Society of America; 2007. 458p.

Silva AA, Oliveira Jr RS, Costa ER, Ferreira LR, Constantin J, Apoloni DKM, Oliveira MF. Persistência dos herbicidas do grupo químico das imidazolinonas e efeitos sobre as culturas sucessoras de milho e sorgo. Acta Sci. 1999;21(3):456-65.

Sociedade Brasileira da Ciência das Plantas Daninhas – SBCPD. Procedimentos para instalação, avaliação e análise de experimentos com herbicidas. Londrina: 1995.

Sociedade Sul-Brasileira de Arroz Irrigado – SOSBAI. Reunião Técnica da Cultura do Arroz Irrigado (29:2012: Gravatal, SC). Arroz irrigado: recomendações técnicas da pesquisa para o Sul do Brasil/Sociedade Sul-Brasileira de Arroz Irrigado. Itajaí, SC: SOSBAI; 2012. 179p.

Steele GL, Chandler JM, McCauley GN. Control of red rice (*Oryza sativa*) in imidazolinone-tolerant rice (*O. sativa*). Weed Technol., 2002;16(3):627-30.

Stougaard RN, Shea PJ, Martin AR. Effect of soil type and pH on adsorption, mobility, and efficacy of imazaquin and imazethapyr. Weed Sci. 1990;38(1):67-73.

Tan S, Evans R, Singh B. Herbicidal inhibitors of amino acid biosynthesis and herbicide-tolerant crops. Amino Acids, 2006;30:195-204.

Villa SCC, Marchezan E, Avila LA, Massoni PFS, Telo GM, Machado SLO, et al. Arroz tolerante a imidazolinonas: controle do arroz vermelho, fluxo gênico e efeito residual doherbicida em culturas sucessoras não-tolerantes. Planta Daninha, 2006;24(4):761-8.

York AC, Jordan DL, Batts RB, Culpepper AS. Cotton response to imazapic and imazethapyr applied to a preceding peanut crop. J Cotton Sci. 2000;4:210-6.

Zablotowicz RM, Locke MA, Gaston LA, Bryson CT. Interactions of tillage and soil depth on fluometuron degradation in a dundee silt loam soil. Soil Till Res. 2000;57:61-8.