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Potential selectivity of herbicides in pre-and post-emergent linseed (*Linum usitatissimum* L.)

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ABSTRACT

Linseed is an oilseed crop that is widely used in human and animal feed, as a cover crop in agroecosystems, and for fiber production. To facilitate the management of weeds in the crop, this study aimed to evaluate potential selective herbicides for linseed cultivation applied in pre-planting and incorporation (PPI), pre-emergence (PRE), and early (POST) and late (late POST) post-emergence stages, since there are presently no herbicides registered for use on linseed in Brazil. Therefore, four experiments were conducted in a completely randomized design with four replications, and five (exp. 1), 21 (exp. 2), 26 (exp. 3), and four (exp. 4) treatments. Crop injury and the fresh and dry matter of the plants were evaluated. Experiment 4 was conducted until seed production, and data on the final height, number of capsules, and yield were obtained. The results were characterized by the low selectivity of herbicides during pre-emergence, whether incorporated or not, and indicated 11 herbicides with potential selectivity in post-emergence, whether early or late, namely: bentazon, bentazon + imazamox, clethodim + fenoxaprop, clethodim, flumiclorac, fluazifop, flumioxazin, haloxyfop, nicosulfuron, tembotrione, and tepraloxydim. Linseed is demonstrated to be susceptible to or has low tolerance to various herbicides.

Keywords: Injury, Bentazon, Protoporphyrinogen oxidase (PPO) inhibitors, Acetolactate synthase (ALS) inhibitors, Acetyl-CoA carboxylase (ACCase) inhibitors.

Potencial seletividade de herbicidas em pré e pós-emergência em linhaça (*Linum usitatissimum* L.)

RESUMO

A linhaça é uma oleaginosa amplamente utilizada na alimentação humana e animal, como cultura de cobertura em agroecossistemas e para produção de fibras. Para facilitar o manejo de plantas daninhas na cultura, este trabalho teve como objetivo avaliar potenciais herbicidas seletivos para o cultivo de linhaça aplicados em pré-plantio incorporado (PPI), pré-emergência (PRE), pós-emergência inicial (POS), pós-emergência tardia (POS tardio) uma vez que ainda não existem herbicidas registrados para uso em linhaça no Brasil. Portanto, quatro experimentos foram conduzidos em delineamento inteiramente casualizado com quatro repetições, e cinco (exp. 1), 21 (exp. 2), 26 (exp. 3) e quatro (exp. 4) tratamentos. Foram avaliadas a injúria na cultura e a matéria fresca e seca das plantas. O Experimento 4 foi conduzido até a produção de sementes, obtendo-se os dados de altura final, número de cápsulas e produtividade. Os resultados foram caracterizados pela baixa seletividade dos herbicidas durante a pré-emergência, incorporados ou não, e indicaram 11 herbicidas com potencial seletividade na pós-emergência, seja precoce ou tardia, os quais foram: bentazon, bentazon + imazamox, clethodim + fenoxaprop, clethodim, flumiclorac, fluazifop, flumioxazin, haloxyfop, nicosulfuron, tembotrione e tepraloxydim. A linhaça demonstrou ser suscetível ou com baixa tolerância a vários herbicidas.

Palavras-chave: Injúria, Bentazon, Inibidores da protoporfirinogênio oxidase (PPO), Inibidores da acetolactato sintase (ALS), Inibidores da acetil-CoA carboxilase (ACCase).

1. Introduction

Linum usitatissimum L. (linseed) belongs to the family Linaceae, which comprises approximately 200 species worldwide (Novello and Pollonio, 2012). It is also known as flax, and its exact origin is not clear. However, Mediterranean countries have the oldest records of its cultivation (Vieira et al., 2012). It is extensively cultivated in Canada, with a focus on obtaining seeds during the breeding process (Zhang et al., 2014). Brazilian production is concentrated in the south of the country, with Rio Grande do Sul currently being the largest producer of this oilseed (Stank et al., 2017).

The linseed plant is erect and reaches an average of 60 cm and 100 cm in height, has narrow leaves, and its flowering is indeterminate, with fruits arranged in globular capsules that house approximately 10 seeds. Its root system is concentrated in the first 20 cm of soil, with pivoting roots (Kohn et al., 2016). The fall-winter period is the most suitable for sowing, and the productivity of the crop is directly related to the planting density, capsule formation, and the number of seeds per capsule (Castro and Martins, 2010; Copur et al., 2006). Challenges in linseed production include better management of agronomic practices in the crop, particularly the control of weeds, where there is insufficient information about effective chemical control strategies and the effects caused by the herbicides used in the crop (Mankowski et al., 2015).

Studies carried out by Soliman and Hamza (2010) indicate that linseed growth is affected by the presence of weeds, which can cause losses of up to 50% productivity. As the competitive ability of linseed crops is low, chemical control is the best option, supported by its operational advantage and good efficiency (McSheffrey et al., 1992). As most herbicides used in linseed crops were initially developed for use in other crops, the occurrence of phytotoxic symptoms after use is not uncommon.

In the analysis of transgenic linseed cultivars resistant to acetolactate synthase (ALS)-inhibiting herbicides, the possibility of using chlorsulfuron and metsulfuron methyl without damaging the crop was observed (McSheffrey et al., 1992). The genetically modified technology has been used in Canada, the world's largest producer, for six years, but its use and commercialization were banned because of safety concerns raised in the European Union, the largest importer of linseed (McHughen, 2002). In Brazil, there is no registration or use of transgenic linseed cultivars.

To date, there has been no registration of herbicides for linseed in Brazil (MAPA, 2022). Thus, to elucidate this issue, the objective of the present study was to evaluate the potential of using selective herbicides for pre-planting, pre-emergence, and post-emergence golden linseed crops.

2. Material and Methods

The experiments were conducted in a completely randomized design, with four replicates. Experiment 1 consisted of the application of herbicides in pre-planting and incorporation (PPI); Experiment 2 in pre-emergence (PRE); Experiment 3 in post-emergence (POST), when the plants had four to five pairs of leaves (10 cm); Experiment 4 in late post-emergence (late POST), when the linseed plants were in the full bloom stage. The herbicides in each mode of application and their respective rates are listed in Tables 1 and 2, respectively.

The experiments were carried out in a greenhouse (24°17'36.2"S 53°50'27.5"W, Palotina, Paraná, Brazil) from July to September 2016, with an average temperature of 25 ºC, monitored by thermometers and maintained by a ventilation system and 60% relative humidity. The experimental units consisted of plastic pots with a volumetric capacity of 5 L, filled with topsoil collected from 0–20 cm deep layer. The soil used is classified as eutrophic Red Latosol with a very clayey texture (Santos et al., 2018), with 61.25% clay, 20% sand, and 18.75% silt, with the following chemical characteristics: pH ($CaCl_2$) 5.10 $Cmol_c\ dm^{-3}$; 31.48 g dm^{-3} OM; 4.53 mg dm^{-3} P; 0.76 $Cmol_c\ dm^{-3}$ K; 6.96 $Cmol_c\ dm^{-3}$ Ca; 1.57 $Cmol_c\ dm^{-3}$ Mg; and 0.00 $Cmol_c\ dm^{-3}$ Al. The genotype used was a lineage of Golden Linseed supplied by the Agronomic Institute of Paraná (IAPAR), with a germination rate of 85%. Ten seeds were sown per pot for all experiments. In experiments 3 and 4, after germination, the seedlings were removed and standardized to four uniform plants per pot.

Herbicides were applied with a CO_2 pressurized sprayer, at a constant pressure of 2 bar and flow rate of 0.65 L min^{-1}, equipped with Teejet type XR 110.02 fan nozzles, with a spray volume of 150 L ha^{-1}. For experiment 1 (PPI), herbicides were applied, then the soil was stirred to a depth of 10 cm, and after 12 hours of application linseed was sown. In experiment 2 (PRE), the herbicide was applied, and the linseed was sown 12 hours later. In Experiment 3 (POST), herbicides were applied when the plants had four or five pairs of leaves (10 cm). In experiment 4 (late POST), herbicides were applied when plants were in full bloom.

A crop injury assessment was carried out for all experiments at 7, 14, 21, and 28 days after application (DAA) on a percentage scale of 0–100, where 0 represents the absence of visual symptoms and 100 represents complete plant death (Velini et al., 1995). At 28 DAA, fresh mass was collected and weighed after After that, plants were stored in a paper bag and dried in a forced air oven at 60 °C to a constant mass, after which the plants were weighed and their dry mass obtained for experiments 1, 2, and 3. Experiment 4 (late POST) was carried out until the end of the crop cycle. The final plant height, number of capsules, and weight of seeds per plant were evaluated. All values were obtained by calculating the average of four plants per pot.

After collecting data in all experiments according to the assumptions of Pimentel-Gomes and Garcia (2002), analysis of variance was applied using the F-test ($p \leq 0.05$). When significant, treatment means were compared using Tukey's test at 5% probability. The Sisvar 5.6 software was used for the analyses (Ferreira, 2011).

Table 1. Herbicides applied at pre-planting and incorporation (PPI) and pre-emergence (PRE) of linseed.

Mode of action	Herbicide	Commercial product	Rate (g a.i. ha^{-1})*
	PPI – experiment 1		
ALS inhibitors	Diclosulam	Spider® 840 WG	20
PSII inhibitors	Metribuzin	Sencor® 480	360
Microtubule formation inhibitor	Pendimethalin	Herbadox® 400 EC	1,250
Microtubule formation inhibitor	Trifluralin	Premerlin® 600 EC	1,800
	PRE – experiment 2		
Auxin mimics	2,4-D	DMA® 806 BR	335
PSII + DOXP synthase inhibitor	Ametryn + clomazone	Sinerge® EC	900 + 600
PSII inhibitors	Atrazine	Primóleo®	2,640
PPO inhibitors	Carfentrazone	Aurora® 400 EC	20
PPO inhibitors	Carfentrazone + sulfentrazone	Profit®	11.5 + 450
DOXP synthase inhibitor	Clomazone	Gamit®	500
ALS inhibitors	Diclosulam	Spider® 840 WG	25
PPO inhibitors	Flumioxazin	Sumisoya®	20
ALS inhibitor	Imazaquin	Topgan®	2,000
ALS inhibitor	Imazethapyr	Pivot® 100 SL	80
Carotene synthesis inhibitors	Isoxaflutole	Provence® 750 WG	45
PPO inhibitors	Lactofen	Cobra®	180
Carotene synthesis inhibitors	Mesotrione	Callisto®	240
PSII inhibitors	Metribuzin	Sencor® 480	360
ALS inhibitor	Metsulfuron	Ally®	18
Microtubule inhibitors	Pendimethalin	Herbadox® 400 EC	1,250
PPO inhibitors	Saflufenacil	Heat®	42
VLCFA synthesis inhibitors	S-metolachlor	Dual Gold®	1,200
PPO inhibitors	Sulfentrazone	Boral® 500 SC	400
Microtubule inhibitors	Trifluralin	Premerlin® 600 EC	1,800

ALS, acetolactate synthase; PSII, photosystem II; PPO, protoporphyrinogen oxidase; DOXP, 1-deoxy-d-xylulose-5-phosphate; VLCFA, very long-chain fatty acid. *Rates of active ingredient (a.i.), except for 2,4-D, imazaquin, and imazethapyr at acid equivalent (a.e).

Table 2. Herbicides applied at post-emergence (POST) and late post-emergence (late POST) of linseed.

Mode of action	Herbicide	Commercial product	Rate (g a.i. ha^{-1})*
	POST – experiment 3		
PSII + DOXP synthase inhibitor	Ametryn + clomazone	Sinerge® EC	900 + 600
PSII	Atrazine	Primóleo®	2,640
PSII	Bentazon	Basagran® 600	720
PSII + ALS inhibitors	Bentazon + imazamox	Amplo®	600 + 28
PPO inhibitors	Carfentrazone	Aurora® 400 EC	20
ALS inhibitor	Chlorimuron	Classic®	15
ACCase inhibitor	Clethodim + fenoxaprop	Podium® S	40 + 40
ACCase inhibitor	Clethodim	Select® 240 EC	84
ACCase inhibitor	Clodinafop	Topik® 240 EC	24
Auxin receptors	Fluroxypyr	Starane® 200	100
ACCase + PPO inhibitors	Fluazifop + fomesafen	Fusiflex®	200 + 200
ACCase inhibitors	Fluazifop	Fusilade® 250 EW	125
PPO inhibitors	Flumiclorac	Radiant® 100	40
PPO inhibitors	Flumioxazin	Sumisoya®	20
Auxin mimics	Fluroxypyr	Truper®	230
PPO inhibitors	Fomesafen	Flex®	225
ALS inhibitors	Foramsulfuron + iodosulfuron	Equip Plus®	36 + 24
ACCase inhibitors	Haloxyfop	Verdict® R	36
ALS inhibitor	Imazethapyr	Pivot® 100 SL	80
ALS inhibitor	Iodosulfuron	Hussar®	3.5
PPO inhibitors	Lactofen	Cobra®	150
Carotene synthesis inhibitors	Mesotrione	Callisto®	144
ACCase inhibitor	Nicosulfuron	Sanson® 40 SC	50
Carotene synthesis inhibitors	Tembotrione	Soberan®	75.6
ACCase inhibitor	Tepraloxydim	Aramo® 200	70
	Late POST – experiment 4		
PSII	Bentazon	Basagran® 600	720
PSII + ALS inhibitors	Bentazon + imazamox	Amplo®	600 + 28
ACCase inhibitors	Clethodim + fenoxaprop	Podium® S	40 + 40
ACCase inhibitors	Clethodim	Select® 240 EC	84
PPO inhibitors	Flumiclorac	Radiant® 100	40
ACCase inhibitors	Fluazifop	Fusilade® 250 EW	125
PPO inhibitors	Flumioxazin	Sumisoya®	20
ACCase inhibitors	Haloxyfop	Verdict® R	36
ALS inhibitors	Nicosulfuron	Sanson® 40 SC	50
Carotene synthesis inhibitors	Tembotrione	Soberan®	75.6
ACCase inhibitors	Tepraloxydim	Aramo® 200	70

PSII, photosystem II; DOXP,1-deoxy-d-xylulose-5-phosphate; ALS, acetolactate synthase; PPO, protoporphyrinogen oxidase; ACCase, acetyl-CoA carboxylase inhibitors.

3. Results and Discussion

According to the data obtained in the PPI experiment (Table 3), the herbicide diclosulam caused low crop injury at 28 DAA, differing from the other treatments. However, when assessing plant dry matter, a reduction of 79.4% was observed compared to the control. The herbicides metribuzin, pendimethalin, and trifluralin differed from the other treatments, with the highest injury scores from 7 to 28 DAA, leading to plant death at 28 DAA. Because of plant death, it was not possible to measure dry matter in these treatments. For application in PRE, all of the tested herbicides reduced plant biomass production, although the results of some specific herbicides are highlighted (Table 4).

Table 3. Crop injury of linseed plants at 7, 14, 21, and 28 days after application (DAA) of herbicides in pre-plant and incorporated (PPI), as well as the fresh and dry mass of plants at 28 DAA (experiment 1).

Herbicides	Crop injury (%)				Fresh mass (g)	Dry mass (g)
	7 DAA	14 DAA	21 DAA	28 DAA		
Control	0.0 a	0.0 a	0.0 a	0.0 a	4.9 a	0.7 a
Diclosulam	0.0 a	4.0 ab	9.3 b	20.8 b	0.2 b	0.2 b
Metribuzin	4.3 a	8.5 b	95.8 c	100.0 c	0.0 c	0.0 c
Pendimethalin	100.0 b	100.0 c	100.0 c	100.0 c	0.0 c	0.0 c
Trifluralin	97.5 b	97.0 c	100.0 c	100.0 c	0.0 c	0.0 c
Mean	40.4	42.0	61.0	64.2	1.0	0.2
CV (%)	5.8	6.1	5.2	1.1	7.5	14.8

Means with the same letters in the same column do not differ according to Tukey's test at the 5% probability level.

Table 4. Crop injury of linseed plants at 7, 14, 21, and 28 days after application (DAA) of herbicides in pre-emergence (PRE), as well as the fresh and dry mass of plants at 28 DAA (experiment 2).

Herbicides	Crop injury (%)				Fresh mass (g)	Dry mass (g)
	7 DAA	14 DAA	21 DAA	28 DAA		
Control	0.0 a	0.0 a	0.0 a	0.0 a	4.9 a	0.7 a
2,4-D	89.0 bc	91.3 d	95.0 e	100.0 d	0.0 f	0.0 f
Ametryn + clomazone	52.5 b	90.3 d	100.0 e	100.0 d	0.0 f	0.0 f
Atrazine	4.0 a	10.8 abc	87.50 e	100.0 d	0.0 f	0.0 f
Carfentrazone + sulfentrazone	57.0 b	83.8 d	92.0 e	100.0 d	0.0 f	0.0 f
Carfentrazone	100.0 d	100.0 d	100.0 e	100.0 d	0.0 f	0.0 f
Clomazone	89.0 cd	85.0 d	100.0 e	100.0 d	0.0 f	0.0 f
Diclosulam	3.8 a	10.5 abc	48.8 d	66.3 c	0.2 ef	0.1 e
Flumioxazin	100.0 d	100.0 d	100.0 e	100.0 d	0.0 f	0.0 f
Imazaquin	0.0 a	8.8 abc	50.0 d	100.0 d	0.0 f	0.0 f
Imazethapyr	5.5 a	6.8 abc	23.8 bc	50.0 bc	0.2 ef	0.1 e
Isoxaflutole	57.5 b	85.0 d	90.0 e	100.0 d	0.0 f	0.0 f
Lactofen	100.0 d	100.0 d	100.0 e	100.0 d	0.0 f	0.0 f
Mesotrione	6.0 a	23.8 bc	16.0 abc	5.8 a	0.7 d	0.1 de
Metribuzin	4.3 a	7.0 abc	8.8 ab	12.0 a	0.3 e	0.1 de
Metsulfuron	0.5 a	4.8 ab	22.50 bc	46.3 b	0.4 e	0.1 d
Pendimethalin	0.0 a	11.0 abc	46.3 d	100.0 d	0.0 f	0.0 f
Saflufenacil	5.5 a	5.0 ab	3.0 ab	0.3 a	2.3 b	0.4 b
S-metolachlor	3.5 a	22.50 ab	32.50 cd	41.3 b	1.3 c	0.3 c
Sulfentrazone	7.5 a	25.0 c	37.50 cd	45.0 b	0.2 ef	0.1 d
Trifluralin	0.0 a	8.3 abc	36.3 cd	100.0 d	0.0 f	0.0 f
Mean	32.1	41.9	56.7	69.9	0.5	0.1
CV (%)	16.5	17.6	14.5	10.6	18.6	18.0

Means with the same letters in the same column do not differ according to Tukey's test at the 5% probability level.

Regarding visual crop injury, saflufenacil treatment did not differ from the control at 28 DAA. There was a dry matter reduction of approximately 44%, which differed from that of the control and the other herbicides. Mesotrione and metribuzin also did not differ from the control in relation to crop injury symptoms, but they presented a marked reduction in dry matter. Treatments consisting of applications of imazethapyr, metsulfuron, S-metolachlor, sulfentrazone, and diclosulam during the pre-emergence stage of the crop showed an injury level of around 50%, differing from the control and the other herbicides. These treatments also resulted in a significant reduction in plant dry matter. All other treatments led to plant death (100% crop injury) at 28 DAA, making it impossible to measure the plant dry matter.

In POST, the herbicides bentazon, clethodim, fluazifop, flumiclorac, flumioxazin, haloxyfop, nicosulfuron, tembotrione, and tepraloxydim, in addition to the mixtures of bentazon + imazamox and clethodim + fenoxaprop (ready-mixes), presented potential for selectivity, with less visual injury at 28 DAA, similar to the control without herbicide application. None of the herbicides mentioned above differed from the control in the evaluation of plant dry matter (Table 5).

The herbicides carfentrazone, chlorimuron, clodinafop, imazethapyr, iodosulfuron, and mesotrione, in addition to the ready-mix foramsulfuron + iodosulfuron, had a lower potential for selectivity than the herbicides mentioned above, since even with mild crop injury there was a reduction in plant dry matter after their application. Atrazine, fluroxypyr, fomesafen, lactofen, and mixtures of ametryn + clomazone and fluazifop + fomesafen did not show any potential for selectivity. All these herbicides caused the plants to die, and due to severe injury, it was not possible to evaluate the dry matter of these treatments.

Table 5. Crop injury of linseed plants at 7, 14, 21, and 28 days after application (DAA) of herbicides in post-emergence (POST), as well as the fresh and dry mass of plants at 28 DAA (experiment 3).

Herbicides	Crop injury (%)				Fresh mass (g)	Dry mass (g)
	7 DAA	14 DAA	21 DAA	28 DAA		
Control	0.0 a	0.0 a	0.0 a	0.0 a	19.6 a	2.8 a
Ametryn + clomazone	100.0 f	100.0 e	100.0 d	100.0 d	0.0 h	0.0 f
Atrazine	97.5 f	100.0 e	100.0 d	100.0 d	0.0 h	0.0 f
Bentazon	2.0 a	2.8 ab	2.5 a	1.0 a	16.4 abc	2.4 ab
Bentazon + imazamox	6.3 a	1.0 a	0.3 a	0.0 a	12.4 cde	2.3 ab
Carfentrazone	36.3 c	75.0 d	62.20 c	53.8 c	4.1 gh	0.6 ef
Chlorimuron	3.8 a	18.0 b	13.8 a	8.8 ab	5.1 gh	0.8 def
Clethodim + fenoxaprop	2.8 a	1.5 a	1.5 a	1.3 a	15.9 abcd	2.3 ab
Clethodim	3.3 a	2.3 ab	0.8 a	0.3 a	17.0 abc	2.8 a
Clodinafop	70.0 e	37.5 c	31.3 b	17.5 b	6.5 fg	0.6 ef
Fluroxypyr	65.0 de	100.0 e	98.5 d	100.0 d	0.0 h	0.0 f
Fluazifop + fomesafen	100.0 f	100.0 e	100.0 d	100.0 d	0.0 h	0.0 f
Fluazifop	6.3 a	2.8 ab	1.3 a	0.8 a	19.7 a	2.8 a
Flumiclorac	4.3 a	3.8 ab	0.5 a	0.3 a	17.0 abc	2.5 ab
Flumioxazin	11.0 ab	2.23 ab	2.3 a	1.0 a	13.9 bcd	2.1 abc
Fluroxypyr	66.3 de	95.3 e	100.0 d	100.0 d	0.0 h	0.0 f
Fomesafen	96.3 f	98.8 e	100.0 d	100.0 d	0.0 h	0.0 f
Foramsulfuron +	3.8 a	7.3 ab	3.0 a	2.3 a	6.5 fg	1.0 de
Haloxyfop	5.3 a	6.0 ab	1.3 a	0.8 a	17.4 abc	2.2 abc
Imazethapyr	4.3 a	11.3 ab	8.8 a	6.3 a	6.8 fg	1.2 de
Iodosulfuron	3.3 a	1.3 a	1.3 a	0.3 a	7.9 efg	1.4 cde
Lactofen	52.5 d	85.8 de	93.8 d	100.0 d	0.0 h	0.0 f
Mesotrione	25.0 bc	18.0 b	11.3 a	5.8 a	10.7 def	1.6 bcd
Nicosulfuron	5.8 a	4.3 ab	1.3 a	1.0 a	16.7 abc	2.2 abc
Tembotrione	4.8 a	1.5 a	0.8	0.0 a	19.1 ab	2.6 a
Tepraloxydim	5.0 a	2.3 ab	1.8 a	0.8 a	17.1 abc	2.6 a
Mean	30.0	33.7	32.2	30.8	9.6	1.4
CV (%)	18.6	17.7	17.3	11.5	20.7	23.0

Means with the same letters in the same column do not differ according to Tukey's test at the 5% probability level.

In the case of late POST application, none of the herbicides tested differed from the control in terms of plant height, number of capsules, and grain mass per plant, and it can be considered that all tested herbicides have the potential for selectivity in late POST application (Table 6). A major characteristic of herbicides used for weed management in crops is selectivity, which is the ability of the plant to survive without injury or reduced yield.

The selective effect results from the interaction between the plant, herbicide, and environment, such that species exhibit different responses of selectivity to herbicides (Negrisoli et al., 2004; Devine et al., 1993). Factors such as the herbicide dose, position (site where the molecule is found in the environment), temporal location (time of application), and weed characteristics influence the selectivity of molecules (Oliveira Júnior and Inoue, 2011). In the application of herbicides in PPI, spraying is carried out directly onto the soil, and there must be incorporation to avoid losses by physical-chemical processes (photodegradation and volatilization) of molecules (Mendes et al., 2017).

Herbicides in this mode of application act by inhibiting cell division (trifluralin and pendimethalin), inhibiting the production of amino acids (diclosulam), or inhibiting electron flow in photosystem II (metribuzin), and are absorbed by the roots, thereby acting quickly on plants (Cudney, 1996). It can be concluded that linseed crops do not have mechanisms for survival and maintenance of productivity after exposure to these herbicides, since the treatments caused plant death.

Regarding herbicides applied pre-emergence, without incorporation, the evaluated molecules have several mechanisms of action. In such applications, position selectivity can occur, so that the herbicide is positioned in the topsoil and the seed is usually positioned below this area. Factors such as the vertical movement of herbicides due to rainfall, irrigation, or contact with the area treated by the herbicide after germination at the beginning of seedling development can cause phytotoxicity and, in some cases, plant death (Oliveira Júnior and Inoue, 2011).

These factors are dependent on the physical and chemical characteristics of the herbicide, such as solubility, Koc, half-life, soil characteristics, and the evaluated dose (Mendes et al., 2017). Subsequent experiments can be conducted to investigate potentially selective herbicides for the pre-emergence stage in linseed crops and evaluate these characteristics to determine the ideal dose and sowing time. In the case of dose adjustment, the ability to control species should also be assessed. However, such alternatives can be incorporated into a productive system seeking integrated weed management. The literature presents results that express this consideration in the face of the necessary adjustments. For example, in cotton crops the herbicide flumioxazin is used approximately 21 days before sowing so that there is selectivity (Rodrigues and Almeida 2011).

Table 6. Height, number of capsules and linseed grains under herbicide application at late post-emergence herbicides (late POST) at the full flowering stage.

Herbicides	Height (cm)	Number of capsules*	Grain mass plant^{-1} (g)*
Control	95.0	12.3	0.33
Bentazon	100.0	12.3	0.27
Bentazon + imazamox	93.6	10.3	0.31
Clethodim + fenoxaprop	95.7	11.0	0.28
Clethodim	91.0	13.2	0.29
Flumiclorac	93.0	10.6	0.27
Fluazifop	91.3	13.3	0.29
Flumioxazin	92.1	10.3	0.25
Haloxyfop	98.9	11.8	0.29
Nicosulfuron	95.8	11.0	0.27
Tembotrione	97.7	12.2	0.31
Tepraloxydim	100.2	12.6	0.32
Mean	95.4	11.7	0.30
CV (%)	5.8	18.8	21.5

Means do not differ in the same column by F-test ($p > 0.05$).
* Grain mass and number of capsules from the four plants.

Studies have shown that weed control in periods longer than 14 days between application and sowing of the crop is reduced (Jaremtchuk, et al., 2009). Jensen and Permin (1992) observed that the herbicides trifluralin, linuron, and lenacil did not cause injury to linseed, and the herbicides cyanazine and pendimenthalin caused severe damage to plants during pre-emergence. In post-emergence, the authors mentioned that bentazon, chlorsulfuron, and clopyralid were selective to the crop. Wall (1994) evaluated the depth of sowing and the influence of trifluralin and pendimethalin on linseed crops, and reported that the herbicides did not influence productivity when sown at shallower depths (3 cm).

Some herbicides act on grasses (acetyl-CoA carboxylase [ACCase] inhibitors), such as eudicotyledonous plants, because of the differences between eukaryotic and prokaryotic ACCase among species (Agostinetto et al., 2002). Linseed is classified as a broadleaf plant, so the herbicides with this mechanism of action showed potential for selectivity to the linseed crop, except for clodinafop, under the conditions of this experiment (Millam et al., 2005). The selectivity of other mechanisms of action, applied in post-emergence of the crop, are related to the metabolism of the herbicide by the plant, and reduced absorption or translocation (Oliveira Júnior and Inoue, 2011).

Bentazon, a herbicide inhibitor of electron flow in photosystem II, is an alternative for weed management in linseed crops, presenting mild crop injury, and is potentially selective in evaluating plant yield. The protoporphyrinogen oxidase (PPO)-inhibiting herbicides flumiclorac and flumioxazin are also potential tools for the evaluation of yield in POST applications. These herbicides have low translocation in plants, and are absorbed by the roots, stems, and leaves (Cudney, 1996). Possibly for this reason, selectivity occurs post-emergence, and herbicides are not selective in PRE. Flumioxazin had a higher injury score in linseed, and Kurtenbach et al. (2019) reported that the combination of pyroxasulfone and sulfentrazone proved to be a safe alternative that was selective to the linseed crop.

In the present study, the following herbicides showed potential for selectivity during post-emergence, be it initial or late: bentazon, bentazon + imazamox, clethodim + fenoxaprop, cletodim, flumiclorac, fluazifop, flumioxazin, haloxyfop, nicosulfuron, tembotrione and tepraloxydim. However, none of the herbicides evaluated in the pre-emergence stage, whether incorporated or not, provided an indication of selectivity, given the conditions tested. Thus, it is inferred that golden linseed has low tolerance to herbicides, especially to pre-emergent and most POST latifolicides.

The results presented in this exploratory study provide strong indications that will help in the development of future research and practices for the identification of herbicides that have selectivity for crops in different modes of application. Different positioning, varying doses, types of soil, and times of application may present more varied responses compared to the use of pre-emergent herbicides. Some herbicides, such as bentazon, have some potential for post-emergent use in golden linseed. Field experiments evaluating plant yields should be conducted to propose management recommendations based on solid criteria.

4. Conclusions

Various herbicides were found to have low selectivity in pre-emergence of linseed, whether incorporated or not, and bentazon, bentazon + imazamox, clethodim + fenoxaprop, clethodim, flumiclorac, fluazifop, flumioxazin, haloxyfop, nicosulfuron, tembotrione, and tepraloxydim had potential selectivity in post-emergence, whether early or late. Linseed is susceptible to or has low tolerance to various herbicides.

Authors' Contribution

Mateus Dalpubel Mattiuzzi contributed to the execution of the experiment, data collection, analysis and interpretation of results, writing of the manuscript and final correction of the manuscript. Alfredo Junior Paiola Albrecht contributed to the conceptualization of the study, supervision, and final correction of the manuscript. Luisa Carolina Baccin contributed to the analysis and interpretation of results, writing of the manuscript and final correction of the manuscript. André Felipe Moreira Silva contributed to the analysis and interpretation of results, writing of the manuscript and final correction of the manuscript. Leandro Paiola Albrecht contributed to the conceptualization of the study, supervision, and final correction of the manuscript. Willian Felipe Larini contributed to the execution of the experiment, data collection, and final correction of the manuscript.

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