Revista Ciência Agronômica, v. 54, e20218174, 2023
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Burndown herbicides in *Crambe abyssinica* crops: seed yield and quality[1]

Dessecantes na cultura do *Crambe abyssinica*: produtividade e qualidade de sementes

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ABSTRACT - The application of burndown herbicides to crambe crops is important for production of quality seeds. The objective of this work was to evaluate the effect of burndown herbicides applied at pre-harvest, using different spray volumes, on seed yield and quality of crambe plants (*Crambe abyssinica* cv. FMS Brilhante). A randomized block experimental design was used, with four replications, in a 2 × 5 factorial arrangement consisted of two burndown herbicides [glyphosate (Roundup Original 360 g L^{-1}) and diquat (Reglone 200 g L^{-1})] and five spray volumes (0.0, 0.5, 1.0, 1.5, and 2.0 L ha^{-1}). The burndown herbicides were applied at 74 days after sowing, when the plants presented 80% brown seeds, based on visual evaluation of the seed maturation stage. After harvest, the seeds were processed and evaluated for water content, one-thousand seed weight, seed yield, oil contents, germination, and vigor (first germination counting, emergence speed index, accelerated aging, and electrical conductivity). The pre-harvest desiccation of crambe with the herbicide diquat, using spray volumes between 1.3 and 1.5 L ha^{-1}, resulted in seeds with better physiological quality. The seed vigor was low when using desiccation of plants with glyphosate. The crop yield was not affected by the herbicides nor by the different spray volumes.

Key words: Abyssinian kale. Desiccation. Germination. Glyphosate. Vigor.

RESUMO - A aplicação de herbicidas dessecantes na cultura do crambe é importante para produção de sementes de qualidade. Objetivou-se avaliar o efeito de herbicidas dessecantes e diferentes volumes de calda aplicadas em plantas de crambe, cultivar FMS Brilhante, na fase de pré-colheita sobre a produtividade e qualidade de sementes. O delineamento experimental foi em blocos casualizados em esquema fatorial 2 x 5, sendo dois herbicidas dessecantes (Glyphosate – Roundup Original 360 g L^{-1} e Diquat – Reglone 200 g L^{-1}) e cinco volumes de calda (0,0; 0,5; 1,0; 1,5; e 2,0 L ha^{-1}), com quatro repetições. A aplicação dos dessecantes ocorreu aos 74 dias após a semeadura, baseada no estádio de maturação das sementes, verificado a partir da observação visual da porcentagem de sementes marrons (80%). Após a colheita, as sementes foram beneficiadas e avaliadas quanto ao teor de água, peso de mil sementes, produtividade, teor de óleo, germinação e vigor (primeira contagem de germinação, índice de velocidade de emergência, envelhecimento acelerado e condutividade elétrica). A dessecação na fase de pré-colheita das plantas de crambe com o herbicida Diquat, nos volumes de calda entre 1,3 e 1,5 L ha^{-1}, proporcionou sementes de melhor qualidade fisiológica. O vigor das sementes foi reduzido pela dessecação das plantas com Glyphosate. A produtividade da cultura não foi afetada pelos herbicidas e nem pelos diferentes volumes de calda.

Palavras-chave: Crambe. Dessecação. Germinação. Herbicidas. Vigor.

DOI: 10.5935/1806-6690.20230018
Editor-in-Article: Prof. Salvador Barros Torres - sbtorres@ufersa.edu.br
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Received for publication on 25/08/2021; approved on 07/05/2022
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INTRODUCTION

Crambe (*Crambe abyssinica* Hochst; Brassicaceae) is native to Mediterranean regions (SILVA *et al*., 2019). Seeds of this species are approximately 38% oil; erucic acid is the main constituent, with approximately 60% (TAVARES *et al*., 2018), which is used to produce erucamide, a key ingredient in the plastic industry.

Environmental conditions during the period that seeds remain in the field, after their physiological maturity, until the harvest are among factors that affect the physiological quality of crambe seeds (GUIMARÃES *et al*., 2012). Thus, the risks of losses caused by the permanence of seeds in the field due to climate variations (air relative humidity and temperature oscillations), attacks of insects and pathogens and, consequently, the seed pre-harvest deterioration, have been serious concerns of crambe growers (MARCOS-SON, 2015).

The application of burndown herbicides at pre-harvest is an alternative for reducing the exposure time of physiologically mature seeds to unfavorable environmental conditions, as it allows an early harvest (LAMEGO *et al*., 2013). In addition, they reported that it assists in maturation uniformity and determination of harvest times without compromising the seed physiological quality, when the application is caried out adequately.

The use of burndown herbicides results in drying and fall of leaves and in a rapid seed water loss, enabling the harvest of seed lots with low moisture in periods closer to the maturity physiological point, when the seed vigor, germination, and dry matter are high (SILVA *et al*., 2016). Positive results of pre-harvest desiccation have been reported for crambe (CANGUSSÚ *et al*., 2018), soybean (COMIN *et al*., 2018), and cowpea crops (ASSIS *et al*., 2019; RAISSE *et al*., 2020).

Nonetheless, the use of herbicides for pre-harvest desiccation requires studies on some important aspects, mainly on the adequate choice of products, herbicide rate, and application time, and their effect on seed quality. Diquat and glyphosate are among herbicides available in the market; diquat is a contact herbicide of fast action that dries plant tissues within few days after application and has low translocation in plants (RAISSE *et al*., 2020). Glyphosate is a systemic herbicide of relatively slow action used to control annual late-emergence weed plants and acts as a burndown herbicide (MC NAUGHTON *et al*., 2015).

Researches with crambe are scarce, mainly evaluating the effect of herbicide application at pre-harvest on seed physiological quality. The use of herbicides for pre-harvest desiccation of crambe can be an alternative to uniformize seed maturation without harming seed quality**.**

In this context, the objective of this work was to evaluate the effect of burndown herbicides applied at pre-harvest, using different spray volumes, on seed yield and quality of crambe plants (*Crambe abyssinica* cv. FMS Brilhante).

MATERIAL AND METHODS

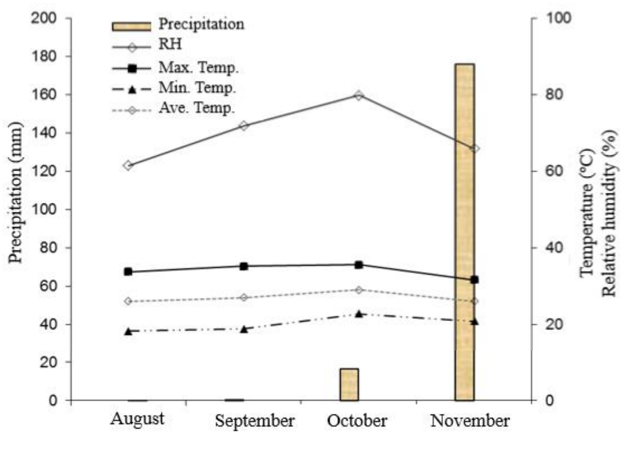
The experiment was conducted in the experimental area of the State University of Montes Claros (UNIMONTES), Janaúba, Minas Gerais, Brazil (15°49'44.26''S, 43°16'09.11''W, and altitude of 540 m), with analyses carried out in the Laboratory of Seed Analysis of the UNIMONTES, from August 2018 to January 2019.

The climate of the region is Aw, tropical with dry winter, according to the Koppen classification (ALVARES *et al*., 2013). The soil of the experimental area was classified as a Typic Udifluvent (Neossolo Fluvico; Santos *et al*., 2018). Data of monthly rainfall depth, relative air humidity, and air temperature in the area during the experimental period are presented in Figure 1.

A randomized block experimental design with four replications was used, in a 2 × 5 factorial arrangement consisted of two burndown herbicides [glyphosate (Roundup Original 360 g L^{-1}) and diquat (Reglone 200 g L^{-1})] and five spray volumes (0.0, 0.5, 1.0, 1.5, and 2.0 L ha^{-1}), applied to the plants at pre-harvest.

The experimental area was seeded with crambe (*Crambe abyssinica* cv. FMS Brilhante) seeds from the Mato Grosso do Sul Foundation. The soil was prepared using conventional system, consisting of one plowing and two harrowing. The seeds were manually sown in an area

Figure 1 - Data of monthly rainfall depth, relative air humidity, and air temperatures in the area during the experimental period, recorded by the Brazilian National Institute of Meteorology



of 600 m^2 at 3 cm depth, using a spacing of 0.45 m between rows and 0.05 m between plants, for approximately 450,000 plants ha^{-1}. Each plot consisted of four planting rows; and the evaluation area was 3.6 m^2, consisting of the two central rows of plants, considering two rows as border. A thinning was carried out after seedling emergence, leaving approximately 20 plants per linear meter.

Little information is found on application of soil fertilizers to crambe, but it is known that these plants absorb great amounts of nitrogen due to their significant grain protein contents (SOUZA *et al*., 2009). Thus, 45 kg ha^{-1} of nitrogen was applied, as soil fertilizer, at 23 days after sowing, using urea as source. Technical recommendations for the ideal development of the crop were followed during the crop cycle, including control of weed plants through manual weeding, and irrigation using a micro sprinkler system.

The burndown herbicides were applied at 74 days after sowing, when 80% of the seeds presented a brown color. A backpack sprayer with capacity for 20 L was used. A protection made of aluminum and plastic tarpaulin was used between plots to avoid drift of herbicides.

Seeds from plants desiccated using the burndown herbicide diquat were harvested at one day after the herbicide application (75 days after sowing), whereas seeds from plants desiccated using glyphosate were harvested at 7 days after the herbicide application (82 days after sowing), as it is a systemic herbicide and requires a longer action time. The racemes were manually harvested, placed in plastic bags, and taken to the laboratory. The seeds were then manually extracted, processed, and subjected to determination of water content. Seeds from non-desiccated plants were harvested at 75 days after sowing.

Seed water contents were determined by the oven method at 105 ± 3 °C for 24 hours, using four replications of 5 g of seeds; the results were expressed as percentages (BRASIL, 2009).

After the water content stabilization, the seeds were weighed to obtain the seed yield; the results were expressed as kg ha^{-1} by adapting the equation proposed by Santos *et al*. (2005).

One-thousand seed weight was determined using 8 replications of 1,000 seeds weighed in a precision balance (0.001 g); the results were expressed as grams (BRASIL, 2009).

The seed oil was extracted using the methodology adapted and described by the Instituto Adolfo Lutz (2008). Approximately 2 g of crambe seeds were ground and transferred to a Soxhlet extraction device, then, an organic solvent (petroleum ether) was added and the mixture was maintained under constant warming for 8 hours at 65 ºC. The solvent was distilled under low pressure in a rotary evaporator. The oil yield was expressed as the average of four extractions.

The germination test was conducted in transparent acrylic boxes (11 × 11 × 3.5 cm); seeds were sown on blotter paper and moistened with distilled water at a volume equivalent to 2.5-fold the paper weight. The boxes containing the seeds were maintained in a digital germinator set at temperature of 25 °C and constant light. The evaluations were carried out at the fourth and seventh day after sowing, and the results were expressed as percentages of normal seedlings, according to criteria established by Brasil (2009).

Emergence speed index was determined under laboratory conditions (approximately 25 °C); seeds were sown to a depth of two centimeters in transparent acrylic boxes containing washed and sterilized sand moistened with water at a volume equivalent to 50% of the retention capacity (BRASIL, 2009), and the moisture was maintained through daily waterings. The evaluations were carried out by daily counts of the number of normal seedlings that emerged and presented cotyledons above the substrate, until emergence stabilization. The emergence speed index was calculated at the end of the test using the formula proposed by Maguire (1962).

The accelerated aging test was carried out based on the method proposed by Marcos-Filho (1999). Approximately 300 seeds of each sample were uniformly distributed on an aluminum screen coupled to the inside of transparent acrylic boxes containing 40 mL of distilled water. The boxes were then covered and transferred to an incubator at 41 °C for 72 hours. Four replications of 50 seeds were then subjected to the germination test, in the same conditions previously described, and the number of normal seedlings was counted at the fourth day after sowing; the results were expressed as percentages.

The electrical conductivity test was carried out using four replications of 50 seeds per treatment, with known weights. The seeds were placed in plastic cups containing 75 mL of distilled water, and the cups were maintained in a germinator set at 25 °C for 24 hours. The solutions were subjected to readings using a conductivity meter (DM 31); the results were expressed as $\mu S\ cm^{-1}\ g^{-1}$ of seeds, dividing the results by the weight of the seeds (VIEIRA *et al*., 2002).

The data were tested for assumptions of normality and homogeneity of variances by the Shapiro-Wilk and Bartlett tests, respectively, at 5% significance level. These assumptions were met and the results were subjected to analysis of variance; the means found for the herbicides were subjected to the F test at 5% probability level. The means found for the herbicide spray volumes were subjected to regression analysis, estimating the parameters evaluated by the t test at 5% significance level, choosing the most adequate models based on the biological results and the value of the coefficient of determination.

RESULTS AND DISCUSSION

The results of the analysis of variance showed that only water content, accelerated aging, and electrical conductivity were significantly affected ($p < 0.05$) (Table 1). Water content was affected only by the herbicide spray volumes. The interaction between the sources of variation (burndown herbicide and spray volumes) was significant ($p < 0.05$) for the accelerated aging and electrical conductivity; thus, statistical breakdown of the interaction was use to assess the data.

The water content means fitted to a quadratic regression model (Figure 1). Seeds from non-desiccated plants (spray volume of 0.0 L ha^{-1}) presented an estimated water content of 9.33%. However, it decreased as the spray volumes of burndown herbicides was increased, reaching the lowest water (7.18%) when using the spray volume of 1.53 L ha^{-1}.

The application of burndown herbicides accelerated water loss processes in plants and seeds, thus decreasing the exposure period to biotic and abiotic factors after the physiological maturity (RAISSE *et al*., 2020).

The seed water content defines the temperature and time of the seed drying process and seed packaging for storage or grinding in the industry, i.e., a greater seed water content implies longer time and greater energy at the drying stage and leads to the growth of pests and fungi, damaging the seeds.

One-thousand seed weight was not affected by the burndown herbicides and spray volumes, presenting a mean of 6.79 g. This information is important because it estimates the size of the seeds and their maturity and health status.

The treatments presented no differences for seed oil content and seed yield. Oil content presented values between 26.8% and 30.3% and mean of 28.55% (Table 1), which is below the Brazilian national mean (38%) (PITOL *et al*., 2010). The low oil contents found can be connected to the occurrence of high temperatures during the crop cycle (Figure 1), which may have affected the seed production. These are similar results to those found by Costa *et al*. (2019), who attributed the low crambe seed oil contents to climate conditions, mainly high temperatures during the crop cycle.

The mean seed yield found corresponded to 2,218.9 kg ha^{-1}, which is above the Brazilian national mean (1,500 kg ha^{-1}), according to Pitol *et al*. (2010), compensating the mean oil yield of 633.5 L ha^{-1}.

Table 1 - Analysis of variance for water content (WC), one-thousand seed weight (1000SW), oil content (OC), seed yield (SY), germination (GER), first germination counting (FGC), emergence speed index (ESI), accelerated aging (AE), and electrical conductivity (EC) of crambe (*Crambe abyssinica* cv. FMS Brilhante) seeds from plants subjected to pre-harvest application of different spray volumes of burndown herbicides

Source of variation	Degree of freedom	Probability				
		WC	1000SW	OC	SY	GER
Burndown herbicide (BH)	1	0.59^{ns}	0.08^{ns}	0.30^{ns}	0.61^{ns}	0.57^{ns}
Spray volumes (SV)	4	0.00*	0.10^{ns}	0.70^{ns}	0.50^{ns}	0.18^{ns}
BH × SV	4	0.67^{ns}	0.21^{ns}	0.19^{ns}	0.88^{ns}	0.89^{ns}
Blocks	3	0.36^{ns}	0.57^{ns}	0.15^{ns}	0.10^{ns}	0.21^{ns}
Means		7.95	6.79	28.55	2.218.9	65.05
CV (%)		7.88	4.15	6.40	19.89	38.14

Source of variation	Degree of freedom	Probability			
		FGC	ESI	AE	EC
Burndown herbicide (BH)	1	0.58^{ns}	0.76^{ns}	0.00*	0.00*
Spray volumes (SV)	4	0.38^{ns}	0.32^{ns}	0.82^{ns}	0.15^{ns}
BH × SV	4	0.95^{ns}	0.42^{ns}	0.00*	0.00*
Blocks	3	0.25^{ns}	0.24^{ns}	0.22^{ns}	0.14^{ns}
Means		50.75	11.45	63.77	343.68
CV (%)		53.25	28.10	15.63	10.48

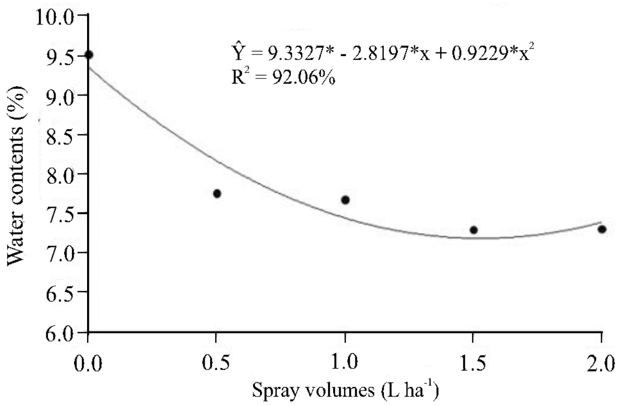
^{ns} not significant; * significant at 5% probability level by the F test

The results of germination presented no significant differences between treatments, with no effects of herbicides and spray volumes on seed germination capacity. This result denotes the positive action of herbicides with the spray volumes tested. Similar results were reported by Comin *et al.* (2018), who found that pre-harvest desiccation of soybean crops at the R7 stage does not negatively affect the physiological quality of seeds.

However, the seeds presented a mean germination percentage of 65%, regardless of the treatment (Table 1). This result is explained by the uneven maturation of crambe crops (OLIVEIRA *et al.*, 2014), which results in different degrees of seed dormancy over harvests (COSTA *et al.*, 2011). The values obtained in the germination test classified the found crambe production found in all treatments as adequate for marketing as seed, as the minimum percentage required for standard seeds of this species is 60%, according to Brasil (2013).

The seed vigor evaluated by the first germination counting and emergence speed index was not affected by the treatments, presenting an overall mean of 51% and 7.27, respectively (Table 1). The obtaining of vigorous seeds is essential for the establishment of crambe crops, enables a higher uniformity of plants and, consequently, affects the seed yield (ABATI *et al.*, 2017).

Figure 2 - Water contents in crambe (Crambe abyssinica cv. FMS Brilhante) seeds from plants subjected to pre-harvest desiccation



When seeds have a decreased vigor, the negative effects of using burndown herbicides can be higher after some time of storage. In the present study, the seeds were not stored, and all evaluations were carried out soon after harvest. Therefore, the seeds were vigorous, maintaining their capacity to produce normal seedlings after being subjected to non-controlled environmental conditions, considering the test of emergence speed index.

The accelerated aging of seeds presented no differences between the burndown herbicides at the lowest spray volumes (0.0 and 0.5 L ha^{-1}) (Table 2). However, the herbicide diquat stood out with a higher percentage of normal seedlings after the accelerated aging when using the highest spray volumes (1.0; 1.5, and 2.0 L ha^{-1}), indicating a higher seed vigor.

The results of germination after accelerated aging were, in general, higher than the mean percentage obtained by the germination test, regardless of the treatment. These results denote that the crambe seeds were exposed to conditions that favored the overcoming of primary dormancy during the accelerated aging test, thus improving their germination performance. These results are consistent with those reported by Cruz *et al*. (2013), who found higher germination percentage after accelerated aging, compared to the germination test.

Considering the statistical breakdown of the spray volumes within each burndown herbicide, the results of accelerated aging of both herbicides fitted to quadratic regression equations (Figure 3). The seed germination by accelerated aging increased as the spray volume of the herbicide diquat was increased, reaching a maximum estimated percentage of 77% for the spray volume of 1.9 L ha^{-1}.

The herbicide glyphosate resulted in the maximum estimated germination percentage (62%) for the spray volume of 0.6 L ha^{-1}, representing a 6.7% increase when compared to the control (0.0 L ha^{-1}). Nonetheless, the highest spray volumes affected the seed vigor, with a 32.8% decrease when using 2.0 L ha^{-1} of glyphosate, compared to the maximum point. These results confirm the negative effect on the seeds by the systemic action of glyphosate at high spray volumes, denoting the need for an adequate rate for desiccation of plants to preserve the seed quality.

Table 2 - Mean results of the accelerated aging test (%) for crambe (*Crambe abyssinica* cv. FMS Brilhante) seeds as a function of pre-harvest application of different spray volumes of burndown herbicides

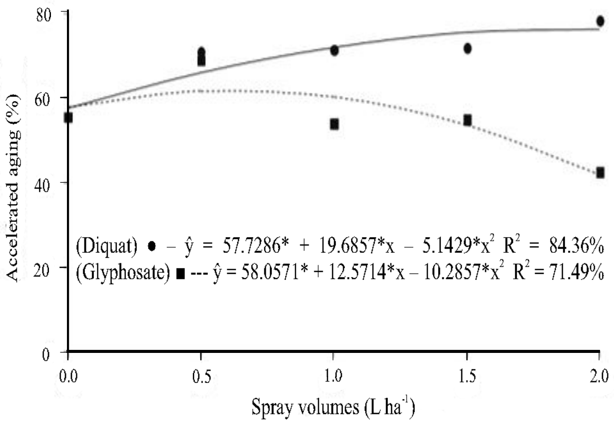
Burndown herbicide	Spray volume (L ha^{-1})				
	0	0.5	1.0	1.5	2.0
Diquat	55.50 a	71.00 a	71.50 a	72.00 a	78.50 a
Glyphosate	55.50 a	69.00 a	54.00 b	55.00 b	42.50 b

Means followed by the same letter in the columns are not different from each other by the F test at 5% probability level

Herbicides used for pre-harvest desiccation have characteristics that result in a fast drying of plants, preserving their normal characteristics, and are not translocated to plant parts and, mainly, are not accumulated in the harvested product (Sediyama, 2013). Diquat is a contact herbicide of fast action that inhibits the photosystem I and, after absorbed, it acts as a false acceptor, deflecting the flow of electrons, which rapidly reduces the plant water contents, drying plant tissues within few days after its application, thus causing a rapidly plant death and limiting its translocation in the plants. Higher seed vigor was found when using desiccation with diquat, compared to glyphosate, at spray volumes equal to or higher than 1.0 L ha^{-1}, confirming the findings of Santos *et al*. (2005) and Sediyama (2013).

Seeds can be contaminated by application of systemic herbicides such as glyphosate, as these herbicides can be translocated in the whole plant and directed and concentrate in reserve accumulation regions, mainly at the grain filling stage (RAÍSSE *et al*., 2020). This risk is increased when using glyphosate due to the metabolization of its molecules, which probably generates toxic compounds. Therefore, the systemic translocation of glyphosate in the plant enables its molecules to be transported to the seeds, resulting in physiological changes that affect seed vigor.

Figure 3 - Accelerated aging of crambe (*Crambe abyssinica* cv. FMS Brilhante) seeds as a function of different rates of the herbicides diquat and glyphosate



The evaluation of electrical conductivity showed that the herbicide diquat resulted in lower leaching of solutes from seeds than glyphosate, in all spray volumes studied, except for the control (Table 3), denoting more vigorous seeds. Lower electrical conductivities denote higher integrity of cell membranes and low release of solutes (PRADO *et al*., 2019), which can stimulate the development of microorganisms that are harmful to the emergence of seedlings under field conditions (MARCOS-SON, 2015). Contrastingly, a high electrical conductivity is a result of a high output of seed cell constituents, resulting in seed deterioration and loss of seed vigor (ZUCARELI *et al*., 2016).

The result of the spray volumes within each burndown herbicide showed no significant effect for the herbicide glyphosate (Figure 4). Contrastingly, the electrical conductivity of seeds from plants subjected to desiccation with diquat fitted to a quadratic regression model. The highest value (385.51 µS cm g^{-1}) was found for the spray volume 0.0 L ha^{-1} (control), decreasing as the diquat spray volume was increased up to 1.3 L ha^{-1}, which presented the lowest electrical conductivity (289.66 µS cm g^{-1}). Higher spray volumes showed increases in electrical conductivity as the spray volume was increased, reaching 321.27 µS cm g^{-1} when using the spray volume of 2.0 L ha^{-1}.

The reorganization capacity of seed cell membranes at the beginning of the immersion process directly affects the amount and nature of solutes released to the external medium. These solutes modify the electrical conductivity of the immersion water according to the amount of the leachate material, resulting in a direct relationship to the state of the seed cell membrane system (LIMA *et al*., 2015).

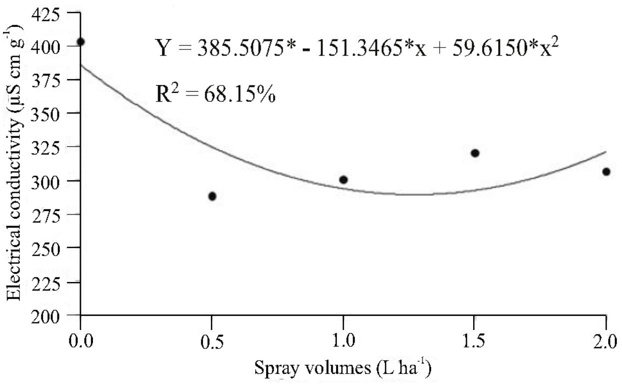
Information on application time, burndown herbicide type, and spray volume is essential to obtain high quantity of viable seeds and to avoid negative effects on seed quality and yield. In addition, information about the products to be applied to this crop and their mechanism of action and effect on seed production, germination, and vigor are needed, as well as assessments on possible presence of residues in the harvested material (TAVARES *et al*., 2016). Regarding the crambe crops, little technical information is found on the use of burndown herbicides at pre-harvest and their effect on seed quality.

Table 3 - Electrical conductivity (µS cm g^{-1}) of crambe (*Crambe abyssinica* cv. FMS Brilhante) seeds as a function of pre-harvest application of different spray volumes of burndown herbicides

Burndown herbicide	Spray volume (L ha^{-1})				
	0.0	0.5	1.0	1.5	2.0
Diquat	402.00 a	288.20 b	300.46 b	320.23 b	306.35 b
Glyphosate	402.00 a	416.82 a	481.24 a	455.74 a	442.94 a

Means followed by the same letter in the columns are not different from each other by the F test at 5% probability level

Figure 4 - Electrical conductivity of crambe (Crambe abyssinica cv. FMS Brilhante) seeds as a function of different spray volumes of the herbicide diquat



CONCLUSIONS

1. Pre-harvest desiccation of crambe plants using the herbicide diquat at spray volumes between 1.3 and 1.5 L ha^{-1} results in seeds with better physiological quality;
2. Crambe seed vigor is decreased by desiccation of plants with glyphosate;
3. The crop yield is not affected by the herbicides nor by the different spray volumes.

ACKNOWLEDGEMENTS

The authors thank the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES), the Brazilian National Council for Scientific and Technological Development (CNPq), and the Foundation for Research Support of the State of Minas Gerais (FAPEMIG) for their financial support.

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