

Effect of row spacing and plant density on grain yield and yield components of *Crambe abyssinica* Hochst

Diferentes espaçamentos entrelinhas e densidades de plantas na produtividade de grãos e componentes de produção de *Crambe abyssinica* Hochst

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Abstract

Understanding the influence of row spacing and plant density on grain yield and yield components of crambe is critical in order to obtain higher grain yields. Therefore, the objective of this study was to evaluate the effects of row spacing and plant density on grain yield and its components in crambe in two distinct regions of Brazil (Marechal Candido Rondon-PR, MCR-PR, and Botucatu-SP, BTU-SP). Narrow and wide row spacing (0.20 and 0.40 m) combined with four plant densities (15, 25, 35, and 45 plants m⁻¹) were evaluated in a randomized block layout with four replications in a 2 × 4 factorial design. The experiment at BTU-SP was run under rainfed conditions with supplementary irrigation, whereas the experiment at MCR-PR was run under rainfed conditions without supplementary irrigation. Both experiments were run in soils classified as Oxisols. There was no interaction between row spacing and plant density. Highest grain yield with supplementary irrigation was observed at 0.20 m row spacing. Without irrigation, row spacing did not affect grain yield owing to the plasticity of crop. The highest grain yield was observed with approximately 30 plants m⁻¹ at both experimental locations. A strong negative correlation was observed between final plant population and number of grains per plant. There was high plant mortality, particularly at high plant densities cultivated under irrigation. Higher mortality occurred because of high intraspecific competition and a larger disease incidence due to the higher humidity in the irrigated experiment. A mechanism of self-adjustment by plant density was observed in crambe, with its intensity dependent on plant density and environmental conditions, such as water and nutrient availability and light incidence.

Key words: Plant plasticity, plant mortality, intraspecific competition.

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Resumo

A compreensão da influência do espaçamento e densidade de plantas na produtividade de grãos de crambe e seus componentes de produção é fundamental para alcançar maior produtividade de grãos. Objetivou-se com este estudo avaliar a produtividade de grãos e os componentes de produção de crambe como resposta a variação do espaçamento entrelinhas e densidades de plantas em duas regiões distintas. Dois ensaios a nível de campo foram realizados em duas regiões do Brasil (Marechal Cândido Rondon-PR - MCR-PR e Botucatu-SP - BTU-SP) para estudar a influência do espaçamento e densidade de plantas na produção de grãos de crambe e seus componentes de produção. Dois espaçamentos entre linhas (0,20 e 0,40 m) e quatro densidades de plantas (15; 25; 35 e 45 plantas m⁻¹) foram avaliados em delineamento de blocos casualizados com quatro repetições, em esquema fatorial 2x4. O ensaio em BTU-SP foi executado em sequeiro, com irrigação suplementar e o ensaio em MCR-PR foi conduzido em condições de sequeiro sem irrigação suplementar. Ambos os experimentos foram conduzidos em Latossolo Vermelho eutroférico. Não houve interação entre espaçamento e densidade de sementeira. Com irrigação, o maior rendimento de grãos foi observado com espaçamento de 0,20 m entre linhas. Sem irrigação, o espaçamento entre linhas não influencia o rendimento de grãos devido à plasticidade da cultura. O maior rendimento de grãos foi observado com cerca de 30 plantas m⁻¹ em ambas as regiões. Foi observada uma grande correlação negativa entre a população final de plantas e número de sementes por planta. Houve alta mortalidade das plantas, principalmente em altas densidades de sementeira com irrigação. A maior mortalidade ocorreu por causa da alta competição intraespecífica e uma maior incidência de doenças devido à maior umidade no ensaio irrigado. Um mecanismo de auto-ajuste para densidade de plantio em crambe foi observado com a sua intensidade, dependendo da densidade de plantas e das condições ambientais, tais como água, nutrientes disponíveis, e incidência de luz.

Palavras-chave: Plasticidade da planta, mortalidade das plantas, competição intraespecífica.

Currently in Brazil, soybean is the main feedstock for biodiesel production; however, the use of soybean for biodiesel production entails a problem because it competes with food production. In contrast, crambe (*Crambe abyssinica* Hochst) is a non-food plant whose grain yield ranges from 1,500 to 1,900 kg ha⁻¹ and the oil content of the species is approximately 38%, which makes it an ideal alternative crop for biodiesel production (MARTINS et al., 2012).

Crambe has been recognized as a very interesting option for Brazilian agriculture, because it is a drought and cold tolerant species (FALASCA et al., 2010; TOEBE et al., 2010; MAUAD et al., 2013) with a short life cycle of approximately 95 days (COSTA et al., 2012a, b). Crambe may be produced as a second crop, following the soybean harvest, using the same equipment used in soybean and wheat production, and its production cost is lower than that of other oilseeds (JASPER et al., 2010).

Another interesting aspect is that in Brazil, no-tillage is commonly adopted by farmers. Heinz et al. (2011) found that crambe produces approximately 2,688 kg ha⁻¹ of dry biomass, which releases approximately 64.3 kg ha⁻¹ of nitrogen, 8.7 kg ha⁻¹ of phosphorus, 94.4 kg ha⁻¹ of potassium, 14.7 kg ha⁻¹ of calcium, 6.5 kg ha⁻¹ of magnesium, and 12.6 kg ha⁻¹ of sulfur back to the soil after harvest. Recent studies also indicate that the dry biomass of crambe helps to reduce soil infestation with weeds (CONCENÇO et al., 2012, 2013; PACHECO et al., 2013).

Crambe oil is an important erucic acid source with several industrial uses, such as in production of plastics, cosmetics, synthetic rubber, lubricants, corrosion inhibitors, adhesives and for electrical isolation (FALASCA et al., 2010; ROGÉRIO et al., 2013). This oil contains between 50% and 60% of the erucic long chain fatty acid, which is a long-chain fatty acid (FALASCA et al., 2010;

WAZILEWSKI et al., 2013) and it may also be used as a biodiesel feedstock (ADAMSEN; COFFELT, 2005; SANTOS et al., 2013).

After oil extraction, the meal can be used as a protein supplement for animals (LAGHETTI et al., 1995). Indeed, some studies indicate that crambe can be used in the composition of cattle feed (CARRERA et al., 2012); and crambe flour has already been approved for dairy feed in the United States (OPLINGER et al., 1991).

In Brazil, there is just one crambe cultivar, FMS Brilhante, released by the MS Foundation (LARA-FIOREZE et al., 2013). Crambe studies in Brazil began in 1995 (PILAU et al., 2011), but until now, it has not really been accepted by farmers, mainly because of lack of information about crop management. For example, technical recommendations on appropriate row spacing and plant density are unavailable. There are a few studies about row spacing and plant density (WHITE et al.,

1966; LAGHETTI et al., 1995; WANG et al., 2000; PITOL et al., 2010), but for Brazilian growers, these results are only incipient. Therefore, the objective of this study was to evaluate the effects on grain yield and its components in *Crambe abyssinica* Hochst. in response to row spacing and plant density in two distinct regions of Brazil.

Two experiments were conducted in 2011. The first experiment was conducted in Marechal Cândido Rondon (MCR-PR), in the state of Parana, Southern Brazil, at the experimental farm of the West State University of Parana (24°33'S; 54°03'W, at 400 m a.s.l.). The second experiment was conducted in Botucatu (BTU-SP), in the state of Sao Paulo, Southwestern Brazil, at the experimental farm of Sao Paulo State University (22°58'S; 48°23'W, at 765 m a.s.l.). Both experiments were conducted on Oxisols following a conventional sowing system (Table 1). Soil tillage was performed in the layer from 0 to 20 cm with an intermediate grade followed by mild grade.

Table 1. Soil chemical properties of experiment areas in the layer of 0.0-20.0 cm.

P	OM	pH _{CaCl}	H+Al	Al ³⁺	K ⁺	Ca ²⁺	Mg ²⁺	SB	CEC	BS	Al
mg dm ⁻³	g dm ⁻³		----- cmol _c dm ⁻³ -----				-----			----- % -----	
Marechal Cândido Rondon (MCR-PR)											
15.14*	28.02	4.93	5.62	0.05	0.48	4.19	2.26	6.93	12.55	55.22	0.72
Botucatu (BTU-SP)											
9.00**	28.00	4.60	5.32	0.30	0.49	1.90	1.40	3.79	9.11	41.60	7.33

OM - organic matter; SB - sum of bases; CEC - cationic exchange capacity; BS - base saturation. *Mehlich extractor, **Resin extractor.

The experiments were carried out in a randomized block design with four replications in a 2 × 4 factorial scheme. The main factor was row spacing, with two levels (0.20 m and 0.40 m); the secondary factor was plant density, with four levels (15, 25, 35, and 45 plants m⁻¹). The crambe cultivar sown was FMS Brilhante, developed in Brazil by MS Foundation from Maracaju - MS.

In MCR-PR, precipitation totaled 467.8 mm (Figure 1a). The temperature varied from -0.9°C

to 37.1°C and on June 28, 2011 there was a frost (Figure 1b), but it did not affect the experiment because the plants were in the early stages of growth. In BTU-SP, on the other hand, precipitation totaled only 98.2 mm (Figure 1c) and temperature varied from 2.4°C to 33.4°C (Figure 1d).

In BTU-SP, sprinkle irrigation was applied on the same day that crambe was sown and continued for 70 days after sowing (DAS). The total water sheet applied by irrigation was 300 mm. The frequency of

irrigation was adjusted based on precipitation and crop development.

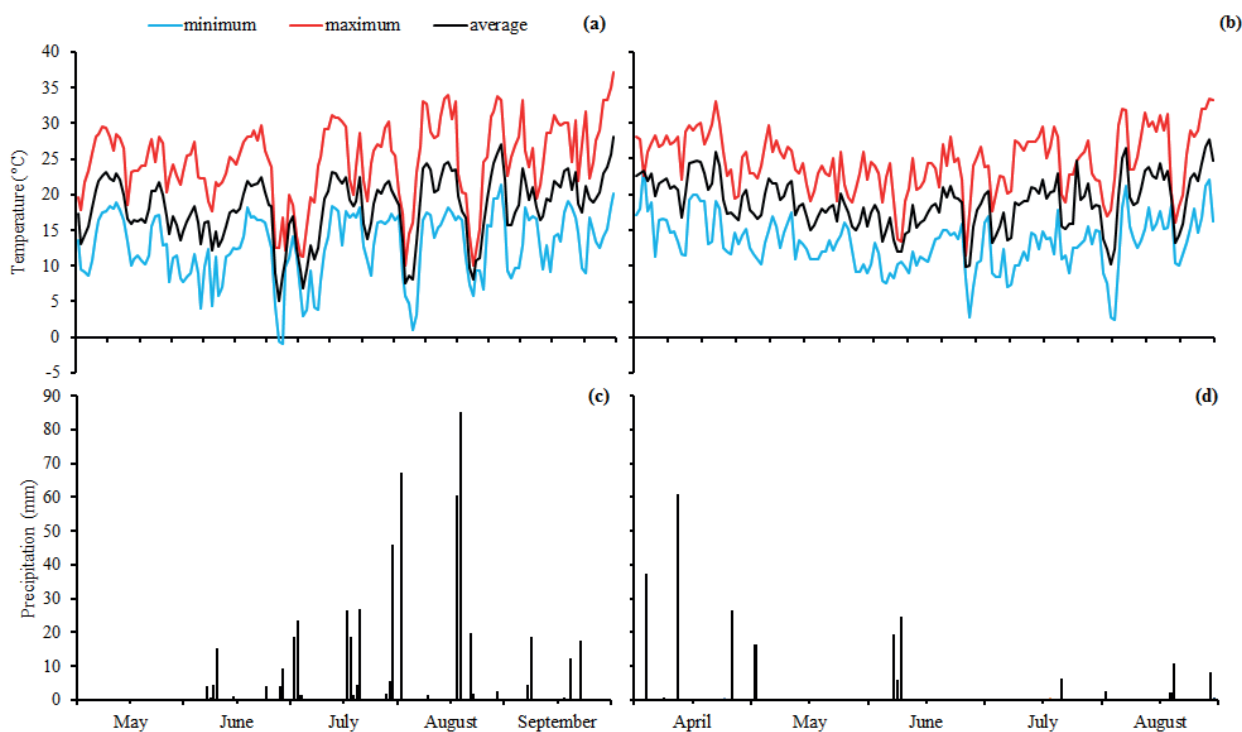
The experimental plants were sown manually on May 28 and April 27 in MCR-PR and BTU-SP, respectively. In both cases, 50% more seed than necessary for each plant density treatment was sown. Three days after plant emergence, plants in excess were pulled out to achieve the desired plant densities to be tested.

Experimental plots were 2×2 m for a total area of 4.0 m^2 . Narrow (0.20 m) and wide spacing (0.40 m) between rows allowed for 10 and 5 rows,

respectively. Data was collected only from the central rows, thus excluding 1 and 2 lateral rows in narrow and wide and spacing, respectively. Plants in the upper and lower edges (0.5 m into the row), were also excluded for data collection purposes.

Fertilizer was applied at a rate of 100 kg ha^{-1} of phosphorus, 60 kg ha^{-1} of potassium, and 40 kg ha^{-1} of nitrogen, 10 days after plant emergence. Then, 30 days after plant emergence, an additional supply of 50 kg ha^{-1} of potassium and 45 kg ha^{-1} of nitrogen were applied. Hand weeding was carried out as required, and no pest control was needed during the study period.

Figure 1. Temperature and precipitation in Marechal Candido Rondon (MCR-PR) (a and c) and Botucatu (BTU-SP) (b and d) during the experimental period.



At the end of the growing season (101 and 102 days after plant emergence in MCR-PR and BTU-SP, respectively) the following parameters were measured:

a) 1000-grain weight in four replicates;

b) Final plant population was determined by counting all plants in each plot;

c) Number of grains per plant, counted on ten plants in each plot;

d) Plant height, determined as the distance

between soil surface and top of the plant canopy;

e) Grain yield, estimated by harvesting the grain from all plants in each plot, adjusting for 13% humidity and converting into kg ha^{-1} .

Data on final plant population and number of grains per plant were transformed to square root to meet normality test statistical requirement. Data were submitted to analysis of variance and means from row spacing were compared by the F test ($p \leq 0.05$). Means of plant densities were analyzed by polynomial regression. The slope significance was tested by Student's t-test, and the significance was presented.

There was no significant interaction between

row spacing and plant density. In MCR-PR, the row spacing did not influence crambe grain yield, 1000-grain weight (W1000) or plant height (PHE) (Table 2).

Final plant population (FPP) and grain number per plant (NGP) were influenced by row spacing. FPP at the narrow spacing was approximately 50% higher than at the wide spacing. However, NGP in the wider row spacing was approximately 50% higher than that in the narrow row spacing. This suggests plasticity in crambe plants, because in the wider row spacing, crambe plants produced more grains (Table 2). However, there was no statistical yield difference between narrow and wide row spacing tested here.

Table 2. Yield, 1000-grain weight (W1000), final plant population (FPP), number of grains per plant (NGP), and plant height (PHE) of crambe at narrow and wide row spacing in Marechal Candido Rondon (MCR-PR) and Botucatu (BTU-SP), 2011.

Row spacing	YIELD	W1000	FPP ($\times 1000$)	NGP	PHE
m	kg ha^{-1}	g	plant ha^{-1}	No./plant	cm
----- Marechal Candido Rondon (MCR-PR) -----					
0.20	1245.9	6.00	1164.82 a	174.10 b	95.19
0.40	1176.7	6.16	625.69 b	365.51 a	94.00
C.V. (%)	14.77	7.37	10.61	15.81	10.52
----- Botucatu (BTU-SP) -----					
0.20	1760.7 a	6.76	854.84 a	333,86 b	117.69 a
0.40	1276.6 b	6.58	439,48 b	458.78 a	108.94 b
C.V. (%)	23.58	6.45	8.79	12.63	8.93

Means followed by different letters within columns are different by the F test at 5% of probability.

The negative correlation observed between FPP and NGP also suggests plasticity in plants of *Crambe abyssinica* Hochst. For every 10% increase in FPP, there was a concomitant decrease of 5.44 and 3.94% in NGP at MCR-PR and BTU-SP, respectively.

In BTU-SP, yield responded to row spacing (Table 2). Grain yield in the narrower row spacing was 38% higher than that in the wider row spacing. The row spacing effect on FPP was the same in the experiment established in MCR-PR. There were

approximately 50% more plants in the narrow than in the wide row spacing. However, NGP in the wide row spacing was only 27% higher than that in the narrow row spacing (Table 2). In this experiment, crambe plasticity was not enough to compensate for the free space. Plant height was on average 8.75 cm higher in the narrow than in the wide row spacing. The 1000-grain weight was not influenced by row spacing (Table 2).

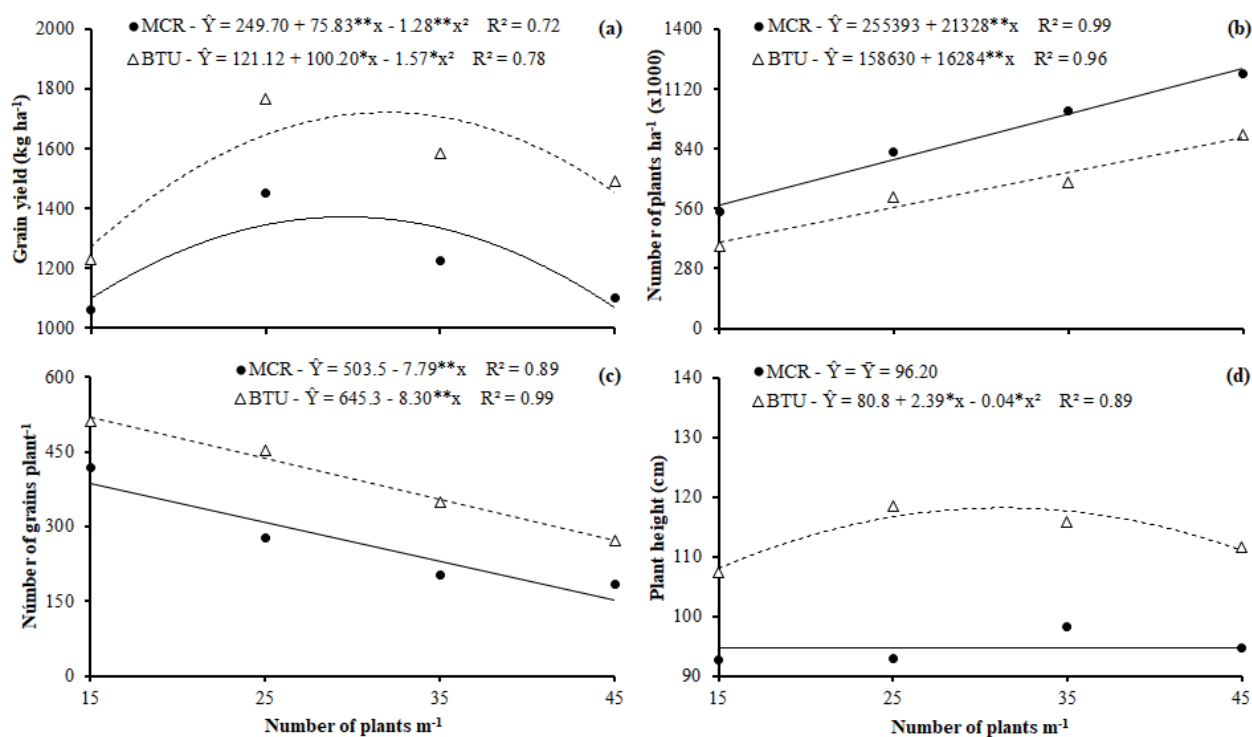
Plants were able to occupy the free space in the

wide row spacing, where they produced as much as plants in the narrow row spacing, without irrigation. However, under irrigation, plants grown with the wide row spacing were not as efficient as plants grown at the narrow row spacing, thus yielding less product. Some studies recommend growing *Crambe abyssinica* Hochst. at wide row spacing and without irrigation; or, alternatively, under irrigation at a narrower row spacing to maximize yield (LAGHETTI et al., 1995; WHITE et al., 1966). Studying different narrow (0.21 m) and wide (0.45 m) row spacing, other researchers concluded that crambe shows a good ability to compensate for the variation in row spacing, which would be the reason why they fail to observe a significant effect of row spacing on yield (PITOL et al., 2010).

Highest yield was observed at densities of 30 and 32 plants m^{-1} in MCR-PR and BTU-SP, respectively (Figure 2a). Yield increased with plant number up to approximately 30 plants m^{-1} due to the more efficient use of free space along and between rows. Plant populations of more than 30 plants m^{-1} showed a decrease in yield owing to the higher competition for water, nutrients, and light.

There was a linear increase in FPP together with a linear decrease in NGP with increasing plant density, in both experiments (Figure 2b and 2c). Maximum plant height at BTU-SP was estimated in populations of 30 plants m^{-1} . In contrast, plant height was not affected by plant density at MCR-PR (Figure 1d).

Figure 2. Grain yield (a), final plant population (b), number of grains per plant (c), and plant height (d) of crambe at different plant densities in Marechal Candido Rondon (MCR-PR) and Botucatu (BTU-SP), 2011. ** and * mean significant effect at 1% and 5% probability as per Student's t-test.



Depending on row spacing and plant density, a high rate of plant mortality was observed. At MCR-PR, plant mortality varied from 2.59 to 32.35% in row spacing, with 15 and 45 plants m^{-1} , respectively (Table 3).

Table 3. Initial plant population, final plant population and variation between initial and final plant population of crambe at different plant densities in Marechal Candido Rondon (MCR-PR) and Botucatu (BTU-SP), 2011.

Row spacing	Plant density	IPP	FPP				
			MCR-PR		BTU-SP		
m	seeds m^{-1}	plants m^{-2}	plants ha^{-1}	plants ha^{-1}	var (%)	plants ha^{-1}	var (%)
0.20	15	75.0	750,000	730,556	-2.59	499,375	-33,42
	25	125.0	1,250,000	1,103,704	-11,70	782,500	-37,40
	35	175.0	1,750,000	1,302,778	-25,56	897,500	-48,71
	45	225.0	2,250,000	1,522,222	-32,35	1,240,000	-44,89
0.40	15	37.5	375,000	361,111	-3,70	275,625	-26,50
	25	62.5	625,000	545,833	-12,67	442,708	-29,17
	35	87.5	875,000	733,333	-16,19	464,583	-46,90
	45	112.5	1,125,000	862,500	-23,33	575,000	-48,89

Plant mortality was greater at BTU-SP than at MCR-PR, varying from 26.50 to 48.89% in rows 0.40 m apart with 15 and 45 plants m^{-1} , respectively (Table 3).

Higher plant density resulted in higher plant mortality, probably due to the higher competition between plants for water, nutrients and light. The less vigorous plants died. In addition, it was verified that higher plant mortality occurred under irrigation. With a large enough water supply, the more vigorous plants expressed their genetic potential and they developed faster than less vigorous plants. The crambe cultivar FMS Brilhante is not totally uniform; there is genetic variation among plants.

Plants with less vigor died overcome by plants of higher vigor. This effect is stronger in crambe because it is an early and fast developing species. We propose that crambe exhibits a mechanism whereby its plant population is self-adjusting, according to plant density and environmental conditions.

There was a highly significant negative correlation between NGP and FPP in both experiments. At BTU-SP, there were significant positive correlations between yield and PHE; and between yield and FPP. There were also significant, positive correlations between FPP and PHE; and between FPP and W1000 (Table 4).

Table 4. Correlations between plant height (PHE), number of grains per plant (NGP), final plant population (FPP), 1000-grain weight (W1000) and grain yield of *Crambe abyssinica* Hochst., grown in Marechal Candido Rondon (MCR-PR) and Botucatu (BTU-SP), 2011.

Traits	Place	Traits			
		NGP	FPP	W1000	Yield
PHE	MCR-PR	-0.04	-0.11	-0.29	-0.13
	BTU-SP	-0.09	0.42*	0.00	0.52**
NGP	MCR-PR	-	-0.69**	-0.19	0.33
	BTU-SP	-	-0.61**	-0.34	0.18
FPP	MCR-PR	-	-	0.03	0.21
	BTU-SP	-	-	0.48**	0.57**
W1000	MCR-PR	-	-	-	0.25
	BTU-SP	-	-	-	0.33

** and * mean significant effect at 1% and 5% of probability as per Student's t-test.

Maximum plant height in BTU-SP was measured with 30 plants m⁻¹, the same plant density at which the highest grain yield was observed. In BTU-SP, a positive correlation was observed between plant height and grain yield. Taller plants had a higher number of branches and, consequently, a higher number of grains per plant, resulting in a higher grain yield. In their study, Dalchiavon et al. (2012) verified that crambe plants grown at higher density are taller and, for plant densities of up to 65 plants m⁻¹, an increase in the number of branches per plant was recorded. Silva et al. (2014) observed a positive correlation between plant height and the number of tertiary branches.

In addition, higher plant density associated with higher humidity—as observed in BTU-SP—increased incidence of fungal diseases like anthracnose, a finding already highlighted by other authors (PITOL et al., 2010). The incidence of disease, mainly in the early stages of growth, may reduce final plant population. This is what we believe may have caused the higher plant mortality observed in BTU-SP during these studies.

Under conditions of optimum water availability, the highest yield is obtained with 0.20 m row spacing. In contrast, under conditions of low water availability, plants at wider row spacing may

compensate by an increase in the number of grains per plant, thus sustaining yield. Sowing densities of approximately 30 plants m⁻¹ resulted in higher crambe grain yield.

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