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Seed productivity, oil content and accumulation of macronutrients in safflower (*Carthamus tinctorius* L.) genotypes in subtropical region

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Abstract

The objective of this study was to evaluate eighteen genotypes of safflower and their absorption of macronutrients in an experiment conducted in the western region of the state of Paraná. The experiment was conducted under humid subtropical climate on *Typic Hapludox* soil with very clayey texture. The treatments were carried out in randomized blocks with four replications. The following traits were evaluated: shoot dry mass production, seed yield, shoot and seed macronutrient accumulation, and oil production. Data were submitted to analysis of variance and the means compared by Scott-Knott test at 5%. The mean seed yield was 4,531.8 kg ha^{-1} and the mean oil content was 26%. The descending order of safflower macronutrient uptake was N > K > Ca > P > Mg > S, in all genotypes, and macronutrient export was N > P > K > Mg > S > Ca. Mobility of macronutrients extracted from seeds was low for K and Ca, medium for Mg and S, and high for N and P. The genotypes with higher average yield were less efficient in their utilisation of nutrients.

Keywords: biodiesel, *Carthamus tinctorius* L., nutritional efficiency.

Introduction

Safflower (*Carthamus tinctorius* L.) belongs to the Asteraceae family, the same as sunflower. This plant has been cultivated for more than two thousand years, and today it is present on all continents. It can be used in human alimentation and in various industrial processes, including the production of biofuels (Giayetto et al., 1999; Dordas and Sioulas, 2008). It is an annual plant native to Asia and Africa, with high resistance to adverse conditions and dry climates (Oelke et al., 1992). The main producers of this oleaginous plant are India, Argentina, Kazakhstan, Mexico and the United States. With regards to productivity, the ranking changes to Mexico, Tajikistan, China, USA and Turkey.

In Brazil, this crop has little importance compared to other countries (Silva, 2013). Cultivated during the winter or off-season in tropical regions, safflower can be used in the process of obtaining biodiesel or animal feed without negative effects on the main cash crops cultivated during the summer production season. Safflower produces around 3000 kg ha^{-1} of seed, which varies with the degree of technology and investments. The shoot yield varies from 4 to 6 tons per hectare (Mündel and Bergman, 2009). It is worth mentioning that this oleaginous plant has high seed yield (Camas et al., 2007) with high oil production capacity of up to 40% (Ghamarnia and Sepehri, 2010). It is a tough plant as it easily adapts and develops well in tropical climates, such as the western region of Paraná. Thus, it represents an economically viable option for crop rotation. Safflower studies generally emphasize increased productivity through genetic improvement (Ekin, 2005). However, the available information regarding this crop still needs further research, especially in regards to the existing varieties and nutritional needs. Seed yield is directly related to the efficiency of nutrient utilisation in the plant. The nutritional requirement of a plant is determined by the amount of nutrients that the plant is able to uptake (extract) from the soil and removes from the field (export). Nutrient extraction by plants is equivalent to the nutrient content absorbed by the aerial part of the plant, while nutrient export is equivalent to the nutrient content in the produced seeds (Fageria, 2008). The capacity of nutrient uptake or extraction and export is influenced by several factors, such as climate, genotype and planting system (França and Coelho, 2001). Studies on the uptake and efficiency of nutrient utilisation in safflower genotypes will broaden knowledge about their nutritional requirements, as well as more rational use of fertilizers. Therefore, the objective of this work, conducted in the western region of the state of Paraná, Brazil, was to evaluate the extraction and efficiency of macronutrient utilisation in different safflower genotypes.

Results and Discussion

Dry mass production

All variables were influenced by safflower genotypes (Tables 2 to 5). Regarding shoot dry mass production (kg ha^{-1}), it ranged from 7,126.4 to 11,840.3 kg ha^{-1}, with a general average of 9,134.17 kg ha^{-1}. The genotypes with the highest production, above 10,000 kg ha^{-1}, were: CIPL 04406, PECI93.4.P, PECI81.2.L, PECI81.1.L, and PECI54.1.P (Table 2). Silva (2013) evaluated 20 genotypes and found shoot dry mass production from 2,900 to 10,367 kg ha^{-1}, with an average value of 5.443 kg ha^{-1}. According to the author, this trait is relevant for genetic improvement when the genotypes are to be selected for use as animal feed.

Seed Yield

The average seed yield varied between 3,668.8 and 5,322.7 kg ha^{-1}, with an overall average of 4,531.8 kg ha^{-1}. The following genotypes all reached seed yield close to 5,000 kg ha^{-1}: CIPL 04406, PECI 98.1.P, PECI 93.4.P, PECI 81.2.L, PECI 81.1.L, and PECI 54.1.P (Table 2). Statistically, the results indicated three ranges of significance, the lowest range with six genotypes, the average range with five genotypes, and the highest range with seven genotypes. Yields obtained in this study were higher than an average yield of 2,900 kg ha^{-1} reported by Arantes (2011) in Nova Odessa, SP, and the maximum yield of 1,974.2 kg ha^{-1} observed by Zoz (2012) in Botucatu, SP.

Oil content

Oil content in the seeds ranged from 23.1 to 29.4%, with an overall average of 26%. Eight of the 18 evaluated genotypes produced seeds with more than 26% oil (Table 2). Ambrosano (2012) and Arantes (2011) found average oil content of 24.0 and 24.1% in safflower seeds, respectively. Gerhardt (2014) found figures that reached 30.2%, while Zoz (2015) found oil content in safflower seeds of 29.3–39.5% across 12 genotypes, with mean value of 34.2%. According to Ekin (2005) and Silva (2013), in addition to productivity, oil content is one of the most relevant traits of safflower crop, and cultivars with higher oil content should be sought-after in harvest programs to best meet market requirements. Coronado (2010) evaluated 22 safflower cultivars of Mexican origin, all of which had oil content higher than 35%, and the one with the highest yield produced 41.9% of oil.

Amounts of extracted macronutrients

The genotypes varied regarding the amounts of extracted nutrients. All genotypes extracted macronutrients in the following descending order: N > K > Ca > P > Mg > S (Table 3), at the following quantities: 250 kg ha^{-1} of N, 144 kg ha^{-1} of K, 99 kg ha^{-1} of Ca, 48 kg ha^{-1} of P, 38 kg ha^{-1} of Mg, and 22 kg ha^{-1} of S. Ravi et al. (2008) found nutrient extraction order of N > K > S > P, with no data for Ca and Mg. Kumar et al. (2015), evaluating extraction of N, P, K, confirmed that safflower extracted more K than N, followed by P. However, the soil in which the experiment was conducted had low levels of N and high levels of K. Anicésio et al. (2015) observed that the accumulation of N in the plants increased linearly with the application of this nutrient into the soil, which varied from 0 to 480 kg ha^{-1} of N. The extraction and export of macronutrients, and requirements for macronutrients varied with genotype (Tables 3, 4 and 5). According to Borges et al. (2009) and Sanes et al. (2013), the variation in the kinetic parameters of nutrient absorption and the morphological differences of the root system make the differentiated absorption of nutrients quite common among cultivars of the same species, as verified by Erdal and Baydar (2005) and Murthy (2006) in safflower, by Jardini et al. (2014) in sunflower, and Ludwig et al. (2013) in gerbera—both species of the Asteraceae family, the same as safflower. The extraction of N differed statistically among genotypes (Table 3). The average N extraction value was 250 kg ha^{-1}, ranging from 193 kg ha^{-1} (PECI 70.1.P genotype) to 336 kg ha^{-1} (PECI 93.4.P genotype). Two groups of genotypes were statistically identified with intermediate levels of extraction: CIPL 1302, CIPL 04406, PECI 8.2.L, PECI 98.1.P, PECI 81.2.L, PECI 81.1.L, and PECI 54.1.P, which accumulated in their shoots 257 to 288 kg ha^{-1} of N; and CIPL 1301, PECI 100.3.P, PECI 95.1.L, PECI 91.4.P, PECI 93.3.P, PECI 14.2.L, and PECI 81.3.P, which accumulated 223 to 242 kg ha^{-1} of N. The lowest extraction of N was observed for PECI 70.1.P, PECI 9.2.L and CIPL 04407, which extracted 193, 200 and 205 kg ha^{-1} of N, respectively (Table 3). For the extraction of P, values between 40 kg ha^{-1} (genotype CIPL 04407) and 61 kg ha^{-1} (PECI 54.1.P genotype) were observed, with an average value of 48 kg ha^{-1} (Table 3). The following genotypes: CIPL 04406, PECI 98.1.P, PECI 93.4.P, PECI 81.2.L, and PECI 54.1.P, were the ones that extracted the most (from 52 to 61 kg ha^{-1}), others accumulated less (from 40 to 50 kg ha^{-1}) and did not differ statistically among themselves. Singh and Singh (1980) observed P extraction of 40 kg ha^{-1} by safflower crops. Kumar et al. (2015) verified that safflowers extracted 18 kg ha^{-1} of P in a soil with average levels of P, and Shillode et al. (2016) found P extraction levels of 17 kg ha^{-1}.

Regarding the extraction of K, it was found that PECI 54.1.P and PECI 93.4.P accumulated the highest amounts of this nutrient, from 208 to 213 kg ha^{-1} of K, respectively (Table 3), without significant difference. Statistically, three other groups were significant—two intermediate groups consisting of four genotypes (CIPL 04406, PECI 95.1.L and PECI 98.1.P and PECI 81.1.L)—another group consisting of eight genotypes (PECI 8.2.L, PECI 93.3. P, PECI 14.2.L, PECI 81.3.P, CIPL 1302, PECI 100.3.P, CIPL 1301, and PECI 81.2.L)—and four genotypes (CIPL 04407, PECI 9.2.L, PECI 70.1.P, and PECI 91.4.P) forming a group with low extraction levels, which varied from 101 to 118 kg ha^{-1} of K. The average K extraction value was 144 kg ha^{-1} (Table 3). Ravi et al. (2008) and Kumar et al. (2015) found K extraction by safflowers of 66 and 75 kg ha^{-1}, respectively. This difference shows a variation in K extraction behaviour, mainly depending on soil and yield. Those authors obtained safflower yields well below yields observed in this study and in soils with low fertility. The extraction of Ca varied from 65 kg ha^{-1} for genotype CIPL 04407 to 133 kg ha^{-1} for genotype PECI 81.1.L (Table 3). The genotypes PECI 95.1.L, PECI 81.2.L, PECI 54.1.P, PECI 98.1.P, PECI 93.4.P, CIPL 04406, and PECI 81.1.L accumulated the highest amounts of Ca, which ranged from 110 to 133 kg ha^{-1} and were not statistically different from one another. In contrast, the genotypes CIPL 04407, PECI 9.2.L, PECI 93.3.P, and PECI 70.1.P extracted the smallest amounts of Ca, ranging from 65 to 77 kg ha^{-1}.

On average, the accumulation of Ca in the shoots of the genotypes was 99 kg ha^{-1} of Ca. Zobiole et al. (2010) found Ca extraction of 116 kg ha^{-1}. Vafaie et al. (2013) reported that Ca extraction in safflower increased with K doses and decreased with increasing Mg doses. However, the authors presented only Ca contents in the shoots, without reporting K extraction by the plants. When it comes to the extraction of Mg, the genotypes PECI 93.4.P, CIPL 04406, PECI 81.1.L, PECI 81.2.L, PECI 54.1.P, extracted the highest quantities of this macronutrient, from 40 to 51 kg ha^{-1} (Table 3). and PECI 98.1.P, and did not differ statistically from one another. The genotypes PECI 93.3.P,

Table 1. Safflower genotypes used in the experiment and their origin.

Genotype	Origin
CIPL 1302	CIANO - Mexico
CIPL 04407	CIANO - Mexico
CIPL 1301	CIANO - Mexico
CIPL 04406	CIANO - Mexico
PECI 100.3.P	IAPAR - Brazil
PECI 95.1.L	IAPAR - Brazil
PECI 91.4.P	IAPAR - Brazil
PECI 8.2.L	IAPAR - Brazil
PECI 93.3.P	IAPAR - Brazil
PECI 98.1.P	IAPAR - Brazil
PECI 93.4.P	IAPAR - Brazil
PECI 14.2.L	IAPAR - Brazil
PECI 70.1.P	IAPAR - Brazil
PECI 9.2.L	IAPAR - Brazil
PECI 81.2.L	IAPAR - Brazil
PECI 81.1.L	IAPAR - Brazil
PECI 81.3.P	IAPAR - Brazil
PECI 54.1.P	IAPAR - Brazil

Table 2. Height, shoot dry mass yield, seed yield, and seed oil content of safflower genotypes in subtropical region. Santa Tereza do Oeste, PR, Brazil, 2015.

Genotype	Shoot dry mass yield kg ha^{-1}	Seed yield kg ha^{-1}	Seed oil content %
CIPL 1302	8633.3 b	4626.2 b	27.8 a
CIPL 04407	7250.6 b	4009.5 c	29.4 a
CIPL 1301	8156.1 b	4136.0 c	24.9 b
CIPL 04406	10009.2 a	4931.1 a	23.1 b
PECI 100.3.P	8729.5 b	4466.5 b	25.5 b
PECI 95.1.L	9475.9 b	4128.5 c	24.3 b
PECI 91.4.P	8137.3 b	4718.4 a	24.7 b
PECI 8.2.L	8328.7 b	4553.2 b	26.3 a
PECI 93.3.P	8278.6 b	4162.1 c	26.8 a
PECI 98.1.P	9041.3 b	4917.6 a	24.0 b
PECI 93.4.P	11443.8 a	5322.7 a	26.1 a
PECI 14.2.L	9089.3 b	4317.2 b	24.7 b
PECI 70.1.P	7633.9 b	3668.8 c	29.0 a
PECI 9.2.L	7126.4 b	3944.4 c	25.3 b
PECI 81.2.L	10697.0 a	5075.2 a	28.3 a
PECI 81.1.L	11840.3 a	5183.7 a	27.8 a
PECI 81.3.P	8789.3 b	4463.6 b	25.0 b
PECI 54.1.P	11755.0 a	4948.4 a	24.5 b
Average	9134	4532	26
CV%	13.24	10.3	7.56

Averages followed by different letters in the column differ from each other by 5% according to the Scott-Knott test.

Table 3. Extraction of nitrogen, phosphorus, potassium, calcium, magnesium and sulphur in safflower genotypes in subtropical region. Santa Tereza do Oeste, PR, Brazil, 2015.

Genotype	N	P	K	Ca	Mg	S
	----------	----------	---------- kg ha^{-1}	----------	----------	----------
CIPL 1302	261 b	47 b	138 c	99 b	38 b	22 b
CIPL 04407	205 d	40 b	101 d	65 c	29 c	17 b
CIPL 1301	223 c	45 b	141 c	83 b	34 b	20 b
CIPL 04406	283 b	57 a	169 b	127 a	46 a	27 a
PECI 100.3.P	232 c	41 b	138 c	97 b	36 b	21 b
PECI 95.1.L	242 c	41 b	166 b	110 a	37 b	24 a
PECI 91.4.P	234 c	48 b	118 d	90 b	38 b	21 b
PECI 8.2.L	257 b	48 b	125 c	102 b	38 b	23 a
PECI 93.3.P	224 c	42 b	125 c	77 c	32 c	19 b
PECI 98.1.P	280 b	52 a	158 b	120 a	40 a	26 a
PECI 93.4.P	336 a	60 a	208 a	124 a	51 a	29 a
PECI 14.2.L	232 c	49 b	129 c	91 b	37 b	21 b
PECI 70.1.P	193 d	41 b	112 d	77 c	30 c	17 b
PECI 9.2.L	200 d	38 b	105 d	76 c	28 c	17 b
PECI 81.2.L	288 b	53 a	142 c	114 a	44 a	25 a
PECI 81.1.L	288 b	50 b	179 b	133 a	46 a	26 a
PECI 81.3.P	229 c	48 b	129 c	86 b	36 b	19 b
PECI 54.1.P	286 b	61 a	213 a	117 a	42 a	25 a
Average	250	48	144	99	38	22
CV%	6.28	12.64	9.30	9.54	12.36	12.82

Averages followed by different letters in the column differ from each other by 5% according to the Scott-Knott test.

Table 4. Export of nitrogen, phosphorus, potassium, calcium, magnesium and sulphur in safflower genotypes in subtropical region. Santa Tereza do Oeste, PR, Brazil, 2015.

Genotype	N	P	K	Ca	Mg	S
	$kg\ ha^{-1}$					
CIPL 1302	180 a	37 a	29 a	7 a	19 a	13 a
CIPL 04407	154 b	33 b	25 b	6 a	17 b	10b
CIPL 1301	147 b	35 b	26 b	7 a	18b	10 b
CIPL 04406	181 a	45 a	35 a	9 a	25 a	14 a
PECI 100.3.P	158 b	34 b	25 b	7 a	18 b	11 b
PECI 95.1.L	148 b	31 b	26 b	7 a	17 b	11 b
PECI 91.4.P	169b	40 b	27 b	8 a	18 b	11 b
PECI 8.2.L	179 a	39 a	28 b	7 a	20 a	13 a
PECI 93.3.P	154 b	34 b	26 b	7 a	18 b	10 b
PECI 98.1.P	194 a	42 a	33 a	9 a	23 a	14 a
PECI 93.4.P	222 a	44 a	33 a	8 a	23 a	14 a
PECI 14.2.L	156 b	35 b	27 b	8 a	18 b	11 b
PECI 70.1.P	132 b	31 b	24 b	7 a	16 b	9 b
PECI 9.2.L	143 b	32 b	23 b	7 a	16 b	10 b
PECI 81.2.L	184 a	43 a	31 a	8 a	22 a	13 a
PECI 81.1.L	185 a	39 a	32 a	9 a	21 a	13 a
PECI 81.3.P	164 b	38 b	27 b	7 a	19 b	11 b
PECI 54.1.P	176 a	41 a	33 a	9 a	20 a	13 a
Average	168	37	27	8	19	12
CV%	13.75	12.28	12.17	9.26	12.27	12.76

Averages followed by different letters in the column differ from each other by 5% according to the Scott-Knott test.

Table 5. Nitrogen, phosphorus, potassium, calcium, magnesium and sulphur utilisation efficiency by safflower genotypes at Subtropical region. Santa Tereza do Oeste, PR, Brazil, 2015.

Genotype	N	P	K	Ca	Mg	S
	kg seeds kg^{-1} nutrient					
CIPL 1302	17.7 b	98.4 b	33.5 b	46.7 b	121.7 b	210.3 b
CIPL 04407	19.6 a	115.7 a	45.8 a	71.2 a	159.5 a	272.1 a
CIPL 1301	18.5 a	102.8 a	32.8 b	55.7 a	136.1 a	231.3 a
CIPL 04406	17.4 b	81.2 c	27.4 b	36.4 b	100.6 b	171.3 b
PECI 100.3.P	19.3 a	112.8 a	33.5 b	47.7 a	128.5 a	220.3 a
PECI 95.1.L	17.1 b	112.8 a	27.9 b	42.1 b	125.0 a	192.8 b
PECI 91.4.P	20.2 a	96.4 b	39.2 a	51.4 a	121.7 b	220.3 a
PECI 8.2.L	17.7 b	96.4 b	37.0 b	45.4 b	121.7 b	201.1 b
PECI 93.3.P	18.6 a	110.1 a	37.0 b	60.1 a	144.6 a	243.5 a
PECI 98.1.P	17.6 b	90.0 b	30.4 b	38.6 b	115.7 b	177.9 b
PECI 93.4.P	15.8 b	77.1 c	22.2 c	37.3 b	90.7 b	159.5 b
PECI 14.2.L	18.6 a	94.4 b	35.9 b	50.8 a	125.0 a	220.3 a
PECI 70.1.P	19.0 a	112.8 a	41.3 a	60.1 a	154.2 a	272.1 a
PECI 9.2.L	19.7 a	121.7 a	44.1 a	60.9 a	165.2 a	272.1 a
PECI 81.2.L	17.6 b	87.3 b	32.6 b	40.6 b	105.1b	185.0 b
PECI 81.1.L	18.0 b	92.5 a	25.8 c	34.8 b	100.6 b	177.9 b
PECI 81.3.P	19.5 a	96.4 a	35.9 b	53.8 a	128.5 a	243.5 a
PECI 54.1.P	17.3 b	75.8 c	21.7 c	39.5 b	110.1 b	185.0 b
Average	18.3	98.5	33.6	48.5	125.3	214.3
CV%	13.28	12.64	9.30	9.54	12.36	12.82

Averages followed by different letters in the column differ from each other by 5% according to the Scott-Knott test.

PECI 70.1.P, CIPL 04407, and PECI 9.2.L accumulated less Mg in their shoots, with amounts varying from 28 to 32 kg ha^{-1}, and did not differ statistically. A group of eight other genotypes with intermediate extractions was identified, accumulating between 34 and 38 kg ha^{-1} of Mg. No data on the export of Mg were found in other safflower experiments. Zobiole et al. (2010) found Mg extraction of 42 kg ha^{-1} by sunflower—the closest oilseed crop to safflowers.

Two groups were statistically significant when analysing the extraction of S by safflower genotypes. The first group was formed by the genotypes PECI 93.4.P, CIPL 04406, PECI 98.1.P, PECI 81.1.L, PECI 81.2.L, PECI 54.1.P, PECI 95.1.L, and PECI 8.2.L, which extracted larger amounts of S. They did not differ statistically among themselves and accumulated between 23 and 29 kg ha^{-1} of this nutrient. The other group, formed by the remaining ten genotypes, accumulated smaller amounts of S, varying from 17 to 22 kg ha^{-1}. The average extraction of S by safflowers was 22 kg ha^{-1} of S. Ravi et al. (2008) found S extraction by safflower of 12 kg ha^{-1}; however, they obtained low seed yield.

Amounts of exported macronutrients

The genotypes differed in the exported quantities of macronutrients and all presented the following descending order of macronutrient exportation: N > P > K > Mg > S > Ca (Table 4). The same order of exportation was also found by Zobiole et al. (2010) in sunflower. On average, safflower exported 168 kg ha^{-1} of N, 37 kg ha^{-1} of P, 27 kg ha^{-1} of K, 8 kg ha^{-1} of Ca, 19 kg ha^{-1} of Mg and 12 kg ha^{-1} of S, with an average seed yield of 4,532 kg ha^{-1}. Kumar et al. (2015) found export of 20 kg ha^{-1} of N, 10 kg ha^{-1} of P and 30 kg ha^{-1} of K, and seed yield of 1,295 kg ha^{-1}. Rastgou (2013) observed values of Ca export between 11.2 and 15.7 kg t^{-1} of seed. The difference in exportation capacity depends on the evaluated genotype, soil nutritional status and fertilization, as well as on seed yield.

The following genotypes exported high amounts of N, P, K, Mg, and S: PECI 93.4.P, PECI 98.1.P, PECI 81.1.L, PECI 81.2.L, CIPL 04406, CIPL 1302, PECI 8.2.L, PECI 54.1.P, and did not differ statistically from one another. The other ten genotypes exported lower amounts of these nutrients, and also did not differ statistically from one another (Table 4). There was no difference among the genotypes in relation to the export of Ca. Nitrogen exports ranged from 132 to 222 kg ha^{-1}, P from 31 to 44 kg ha^{-1}, K from 24 to 33 kg ha^{-1}, Ca from 6 to 9 kg ha^{-1}, Mg from 16 to 25 kg ha^{-1}, and S from 9 to 14 kg ha^{-1}.

Nutrient export represents the amount of nutrients that is accumulated in the seeds; therefore, it represents a loss of nutrients through the harvested seeds, which must be replenished by future fertilization. The export of nutrients in relation to total nutrient absorption (i.e. nutrients accumulated in the shoots) occurred in the following percentages: N = 67%; P = 77%; K = 19%; Ca = 8%; Mg = 50% and S = 54% (Tables 3 and 4). Thus, when the crop remains on the field, the mean percentages of possible nutrient return to the soil are: N = 33%, P = 23%, K = 81%, Ca = 92%, Mg = 50% and S = 46%.

Higher percentages of N and P in seeds, in detriment of stems and leaves, can be explained by high mobility of these nutrients within the plant and their participation in the production of lipids and proteins. Zobiole et al. (2010) also observed high N and P mobilization in sunflower achenes. Crusciol et al. (2012) also found the same behaviour in castor bean, and Mauad et al. (2015), in niger (*Guizotia abyssinica*)—an oilseed crop of the Asteraceae family. According to Castro et al. (1999), in oleaginous plants N determines the equilibrium of accumulated protein content and oil production because of its influence on the metabolism and the synthesis of reserve compounds in the seeds. In the case of P, Faquin (2005) states that increasing P doses commonly favour lipid content in seeds. Almeida Júnior et al. (2009) observed increased oil content in castor bean seeds in response to the application of P. According to Penning de Vries (1974), oleaginous plants require more P, since lipid production requires more of this nutrient than the production of carbohydrates.

Low export of Ca by safflower (about 10%) was also verified for peanuts, sunflower, and niger crops by Feitosa et al. (1993), Zobiole et al. (2010), and Mauad et al. (2015), respectively. According to Marschner (1995) and Maathuis (2009), Ca presents low mobility in the phloem, thus limited redistribution in the plant, and consequently reduced translocation to fruits and storage organs.

In the case of K, approximately 80% of the total accumulated K can be returned to the soil through crop residues, because the export of this nutrient through seeds occurs only at a rate of 20%. This low relative export of K was also observed by Zobiole et al. (2010) in sunflower. The authors report that the redistribution of K in sunflower occurs preferentially to the stem and to the sections, not to the achenes. In this case, the use of safflower as an option for crop rotation may boost K recycling.

Efficiency of macronutrient utilisation

The efficiency of macronutrient utilisation was evaluated by analysing the amount of seed produced per kg of extracted macronutrients. Regarding the efficiency of safflower genotypes in the utilisation of N, it was found that PECI 91.4.P, PECI 9.2.L, CIPL 04407, PECI 81.3.P, PECI 100.3.P, PECI 70.1.P, PECI 93.3.P, PECI 14.2.L, and CIPL 1301 were the most efficient, which produced from 18.5 to 20.2 kg of seed per each kg of N extracted from the soil (Table 5). However, the most efficient genotypes in the utilisation of N were not the most productive ones (Table 5). This shows that they have a lower demand for N.

Regarding P efficiency, the genotypes PECI 9.2.L, PECI 93.3.P, PECI 70.1.P, PECI 95.1.L, PECI 100.3.P, and CIPL 04407 showed the highest efficiency, varying from 103 to 122 kg of seed produced per each kg of this macronutrient extracted from the soil (Table 5). The lowest efficiency in the utilisation of P was observed in the genotypes CIPL 04406, PECI 93.4.P and PECI 54.1.P, which were also the most productive. Thus, these three genotypes require higher P fertilization than the other genotypes to obtain high yields.

The genotypes CIPL 04407, PECI 91.4.P, PECI 70.1.P and PECI 9.2.L showed the highest efficiency in the utilisation of K, with an average of 43 kg of seeds per each kg of K, while PECI 95.1.L, CIPL 04406, PECI 81.1.L, PECI 93.4.P, and PECI 54.1.P were the least efficient genotypes, with an average of 25 kg of seeds per kg of K (Table 5).

Evaluating Ca efficiency, the genotypes CIPL 04407, PECI 9.2.L, PECI 93.3.P, and PECI 70.1.P showed values higher than 60.0 kg seeds per kg of this nutrient (high efficiency), reaching up to 71.2 kg seeds per kg of Ca. Genotypes that presented the lowest efficiency were: PECI 54.1.P, PECI 98.1.P, PECI 93.4.P, CIPL 04406, and PECI 81.1.L, all of which showed values below 40.0 kg seeds per kg Ca (Table 5).

When it comes to Mg efficiency, it was found that the genotypes PECI 9.2.L, CIPL 04407, PECI 70.1.P, and PECI 93.3.P presented high values, while the genotypes PECI 98.1.P, PECI 81.1.L, CIPL 04406 and PECI 93.4 .P presented low values, and were also the least efficient ones in the utilisation of Mg.

In the case of S efficiency, the genotypes CIPL 04407, PECI 70.1.P, PECI 9.2.L, PECI 93.3.P and PECI 81.3.P presented values between 272.1 and 243.5 kg seeds per kg of S. These were the ones with high efficiency, while the genotypes PECI 81.1.L, PECI 98.1.P, CIPL 04406, and PECI 93.4.P showed low values, which were no higher than 177.9 kg seeds per kg of S. (Table 5).

In general, genotypes with the highest yields (5,014 kg ha^{-1} on average) are less efficient in the utilisation of nutrients, and those with lower yields (4,416 kg ha^{-1} on average) have shown to be more efficient in the utilisation of nutrients. Therefore, the choice of genotype should be based on this information. If more fertilizer is available to obtain higher yields, genotypes from the first group should be chosen, and if the resources are limited, genotypes from the second group should be chosen. There was a group formed by the genotypes PECI 100.3.P, PECI 81.3.P, and PECI 14.2.L that presented intermediate yields, varying from 3,669 to 4,162 kg ha^{-1}, but which showed overall high efficiency in the utilisation of the majority of nutrients.

Materials and Methods

Conduction of the experiment

The experiment was conducted under humid subtropical climate at the Experimental Station of the Agronomic Institute of Paraná (25° 04 '57.22” S and 53° 35 '03.33” W) located in the municipality of Santa Tereza do Oeste, PR, at an average altitude of 757m. The soil in the area is classified as *Typic Hapludox,* with very clayey texture.

In December 2013, soil samples from a depth of 0.00–0.20m were collected in the experimental site in order to quantify the soil chemical properties, which were: pH ($CaCl_2$)

= 4.59, C (Walkley-Black) = 30.23 g dm^{-3}, K (Mehlich-1) = 0.62 cmolc dm^{-3}, Ca (1 mol KCl L^{-1}) = 4.99 cmol dm^{-3}, Mg (1 mol KCl L^{-1}) = 2.82 cmolc dm^{-3}, Al (1 mol KCl L^{-1}) = 0.5 cmolc dm^{-3}, V = 47%, and P (Mehlich-1) = 10 mg dm^{-3}.

Safflower genotypes used in this experiment came from Centro de Investigacion Agricola del Noroeste (CIANO) in México and from Agronomic Institute of Paraná (IAPAR) in Brazil, as described in table 1. The sowing was carried out in June 2014. Fertilization during the sowing was done by applying 300 kg ha^{-1} of NPK 04-30-10, providing 12 kg ha^{-1} of N, 90 kg ha^{-1} of P_2O_5 and 30 kg ha^{-1} of K_2O. Thirty days after the emergence, 60 kg ha^{-1} of N and 66 kg ha^{-1} of S were broadcast-applied without incorporation using ammonium sulphate as the source.

The treatments of the crops were made according to the specific needs.

Measured traits

The evaluated traits included shoot dry mass yield, seed yield, seed oil content, the extraction and export of macronutrients (N, P, K, Ca, Mg and S), and nutrient utilisation efficiency.

To determine yield, the plants were harvested at ground level, and the collected seeds were sent to the laboratory for processing, weighing and humidity determination. Then, the yield (kg ha^{-1}) was adjusted to 13% of humidity level.

After harvesting, the shoots (stems, leaves, and fruits without seeds) were washed with distilled water and dried in forced-air circulation oven at 65ºC until reaching constant mass and subsequently weighed to determine shoot dry mass yield. Thereafter, the material was milled in a Willey-type mill with a 0.84 mm mesh sieve. A 300g sample of seeds underwent the same procedure.

The ground dry mass from the shoots and seeds was mineralized by the nitric-perchloric mixture (3:1 v/v), to determine Ca and Mg contents by atomic absorption spectrophotometry. The content of K was determined by flame emission photometry and the content of P and S by colorimetry. To determine N content, the Kjeldahl semi-micro method was used, with sample mineralization by sulphuric acid.

Nutrient extraction was calculated using the shoot dry mass yield and the nutrient content in the shoots; nutrient export was calculated using seed yield and the nutrient content in the seeds. The efficiency of nutrient utilisation was obtained using the ratio between seed yield and nutrient extraction. The results are given in kg of seeds per kg of each extracted nutrient.

Oil content was determined according to the methodology adapted from the Institute Adolfo Lutz (2008), using the Soxhlet oil extractor.

Experimental design and statistical analysis

Eighteen safflower genotypes were evaluated in a randomized block design with four replications. The experimental plot was composed of two 4-m long rows with 0.45-m spacing between the rows, totalling 3.6m^2. Obtained data were submitted to analysis of variance, and the averages were compared by the Scott-Knott test at 5% probability, using the Assistat application.

Conclusion

The average safflower yield was 9,134.2 kg ha^{-1} of shoots and 4,531.8 kg ha^{-1} of seeds, with oil content of 26%, depending on the genotype. Nutrient extraction by safflower genotypes showed the following descending order: N > K > Ca > P > Mg > S, with respective averages of 250, 144, 99, 48, 38 and 22 kg ha^{-1}. The genotypes differed in terms of the exported amounts of nutrients, and the following is the descending order of macronutrient exportation: N > P > K > Mg > S > Ca. The genotypes that presented high yields (PECI 93.4.P, PECI 81.1.L, PECI 81.2.L, PECI 54.1.L, CIPL 04406, PECI 98.1.P, and PECI 91.4.P), which amounted to an overall average of 5,014 kg ha^{-1}, are less efficient in the utilisation of nutrients, and those that showed lower yields (PECI 93.3.L, CIPL 04407, CIPL 1301, PECI 95.1.L, PECI 9.2.L, and PECI 70.1.P), with an average of 4,008 kg ha^{-1} were more efficient in the utilisation of nutrients.

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