

# Growth, yield, and oil content of Brassica species under Brazilian tropical conditions

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**ABSTRACT:** *Brassica* oilseed species are becoming increasingly popular for industrial uses, with emphasis on biodiesel. It is of importance to evaluate the yield and oil production potential of nontraditional oilseeds for use as feedstock in Brazil. In this study, growth, yield, and oil content and their correlations were determined for eight accessions of *B. juncea* and *B. rapa* in two years under tropical conditions of southeastern Brazil. Significant variation was observed between *B. juncea* and *B. rapa* accessions for yield components and oil content. *B. rapa* was the earliest maturing and had the highest oil content, whereas *B. juncea* had the highest number of pods and the highest yield and oil yield. *Brassica rapa* accessions flowered early, with an average cycle of 97 days, whereas *B. juncea* reached maturation after 110 days on average. Accessions were grouped according to the oil content of each species, with the most promising accessions having an oil content of 45–47%. Accessions of *Brassica* species had high oil yields, reaching 910 kg ha<sup>-1</sup> of oil yield for *B. juncea* PI 180266. There was a linear correlation between oil content and thousand seed weight, pod length, and seeds per pod of the *Brassica* species accessions. Considering oil content and oil yield across years, *Brassica* species show promise as alternative oilseed crops for biodiesel production in tropical conditions.

**Key words:** vegetable oils, biodiesel, *Brassica*, germplasm.

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## INTRODUCTION

The genus *Brassica* has attracted interest in the industrial and food sectors because it comprises species that are the third-largest source of oil in the world (McVetty and Duncan 2015). *Brassica napus* is the only *Brassica* species cultivated in Brazil due to its ability to adapt to tropical conditions. The species is grown in autumn and winter in order to produce high-quality oil in the colder regions of southern Brazil. The cultivation of this species is still insufficient to meet the demand for oil for human consumption.

Due to environmental concerns in recent years and the potential of replacing petroleum-derived fuel sources with renewable products, there has been growing interest in utilizing *Brassica* species in nonfood applications (Hossain et al. 2019). For large-scale industrial applications, raw materials should compete minimally with food production (Johnson et al. 2007). An example of such competition is canola quality *B. napus* oil, which if grown for biofuel would compete directly with food-related production (Hossain et al. 2019).

Other oilseed species in the Brassicaceae family, such as *B. juncea* and *B. rapa*, have shown potential for biofuel production and other industrial uses in several regions (Hossain et al. 2019). These species generally have a high content (22:1) of erucic acid, which has several industrial applications. Erucic acid has a low flash point, good combustion, and lubricating qualities, all of which makes it a valuable component for biodiesel (Zanetti et al. 2009). Thus, there is great market potential for the expansion and development of new sources of erucic acid, mainly for export (Bhardwaj and Hamama 2000).



In addition to oil yield, oilseed species must also be able to grow in various environments if they are to be useful for industrial production. In this sense, *B. juncea* can tolerate various types of abiotic and biotic stresses and has been the subject of recent studies in Canada (Gan et al. 2016; Hossain et al. 2019) and in the United States, (Enjalbert et al. 2013; Gesch et al. 2015) as well as in low rainfall areas in India (Kumar et al. 2016) and Australia (Gunasekera et al. 2006a; Wilkes et al. 2013).

The *Brassica* oilseed species mentioned above have been promising sources of oil (Pavlista et al. 2011; Hossain et al. 2019), but little is known about the cultivation of these oilseeds in Brazil. Thus, a thorough characterization of oil content and oil yield will be useful in identifying new sources of raw material for industrial use in Brazil. Phenotypic variations in yield, flowering, and oil content are essential for the improvement of these species through plant breeding. The hypothesis is that oil content and oil yield vary among *Brassica* accessions and that these species have the potential for fall-winter cultivation in Brazil. The objective of the study was to determine the growth, yield, and oil content and their correlations for eight accessions of *B. juncea* and *B. rapa* in two years under tropical conditions in southeastern Brazil.

## MATERIALS AND METHODS

### Site description

The experiment was conducted in Botucatu, state of São Paulo, Brazil (48°25' W, 22°51' S, 777 m above sea level), over a period of two years: 2015 and 2016. The soil was Rhodic Acrudox (Soil Survey Staff 2014). Chemical analysis showed pH 5.1 in  $\text{CaCl}_2$  (0.01 mol·L<sup>-1</sup>); 27 g·dm<sup>-3</sup> organic matter; 34 mg·dm<sup>-3</sup> P (Resin-P); 7 mmol<sub>c</sub>·dm<sup>-3</sup> K<sup>+</sup>; 48 mmol<sub>c</sub>·dm<sup>-3</sup> Ca<sup>2+</sup>; 17 mmol<sub>c</sub>·dm<sup>-3</sup> Mg<sup>2+</sup>; 105 mmol<sub>c</sub>·dm<sup>-3</sup> of cation exchange capacity (CEC); and 68% saturation basis. The soil consisted of 630 g·kg<sup>-1</sup> sand, 90 mg·kg<sup>-1</sup> silt, and 280 g·kg<sup>-1</sup> clay.

The climate was Cwa, according to the Köppen climate classification system; tropical with dry winters and hot, rainy summers. Long-term (1956–2013) mean annual maximum and minimum temperatures were 26.1 and 15.3 °C, respectively, with a mean annual precipitation of 1358 mm. Precipitation and temperature were measured between May and August during this study (Fig. 1).

### Experimental setup

A randomized complete block design with three replications was applied. Eight accessions of each of *B. juncea* and *B. rapa* were evaluated in 2015 and 2016 (Table 1). All *Brassica* accessions are of industrial type, which is high in erucic acid and glucosinolates. Accessions were obtained from the North Central Regional Plant Introduction Station (NCRPIS-USDA-USA).

Accessions were sown by hand May 8, 2015 and April 27, 2016, in five rows in 3 m long plots with 0.45 m spaces between rows. Each plot consisted of 20 plants per square meter. The size of the plot was 6.75 m<sup>2</sup>. Fertilizer was applied as 30 kg·ha<sup>-1</sup> N, 84 kg·ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and 48 kg·ha<sup>-1</sup> K<sub>2</sub>O. Weeds were manually controlled during the cultivation period.

### Agronomic measurements

Flowering time was recorded for each plot as the date when 50% of the plants had flowered. The cycle was determined by comparing the date of seedling emergence to that of harvest (when 80% of plants had dry pods) in number of days. Plant height was determined for five randomly selected plants per plot when 50% of the plants had flowered. Five plants were randomly taken from each plot at full maturity to estimate the seed number per pod and the thousand seed weight. The thousand seed weight was determined by counting subsamples of 100 seeds per plot. The number of seeds per pod and the pod length of each plant were measured across ten pods, taken from the middle part of the terminal raceme. The pod length was measured using a graduated ruler. Yield was estimated by manually harvesting the central useful portion with subsequent threshing, cleaning, and correction to 90 g·kg<sup>-1</sup>. Oil content was determined by TD-NMR in an SLK-SG-200 spectrometer (Malagueno, Cordoba, Argentina). Oil yield was calculated as the product of oil content and seed yield.

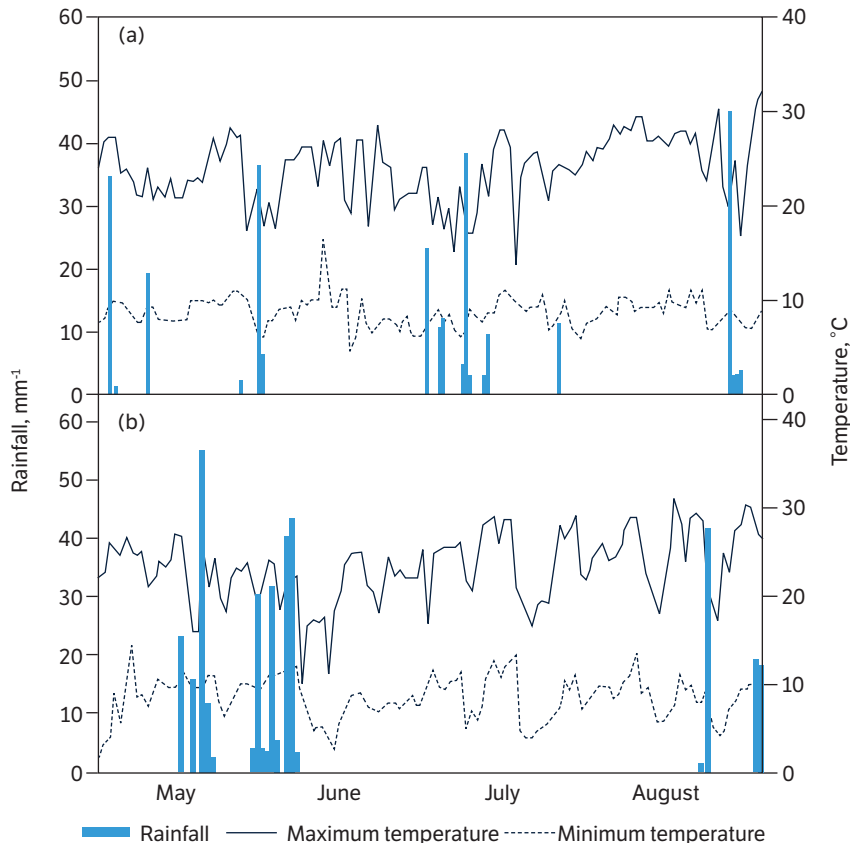
## Statistical analyses

Data were evaluated for normality and homogeneity of variances using Kolmogorov–Smirnov and Levene’s tests, respectively. The data were evaluated using ANOVA; means were compared using the Scott-Knott test ( $p \leq 0.05$ ) and application of simple linear correlation with oil content ( $p \leq 0.05$ ). Data was subjected to principal component analysis (PCA) to reduce the number of variables in the original data set to a more significant set of variables, while maintaining maximum information. For this analysis, data from all agronomic traits were standardized, resulting in a mean equal to zero and variance equal to unit. All statistical analyses were performed using Minitab 17 Statistical Software (Minitab Inc., State College, PA).

## RESULTS AND DISCUSSION

### Climatic conditions

Total precipitation during the experiment (May–August) was 268 and 353 mm in 2015 and 2016, respectively, which is higher than the historical average of 208 mm. However, despite the high average annual rainfall (1358 mm), precipitation before flowering in 2015 was only 63 mm, distributed almost exclusively within 30 days of its emergence (Fig. 1). In contrast, in 2016, more than 70% of the annual precipitation occurred prior to the flowering stage, which resulted in higher vegetative growth. However, there was no precipitation in July 2016 and only 80 mm of rainfall in August 2016. July is historically the driest month (37 mm), followed by August (38 mm). Maximum and minimum daily temperatures were similar in both years, although lower temperatures occurred in 2016 during the early stages of growth, falling as low as 2 °C. Higher temperatures (30 °C) were observed in 2016 during the flowering stage (Fig. 1).



**Figure 1.** Rainfall, minimum temperature and maximum daily temperature between May and August of 2015 (a) and 2016 (b).

**Table 1.** Description of the *Brassica* species accession used in 2015 and 2016.

<i>Brassica</i> species accessions	Plant name	Origin
<b><i>Brassica juncea</i></b>		
PI 432386	BAU M/23	Bangladesh
PI 432384	BAU M/19	Bangladesh
PI 180266	-	India, Gujarat
PI 449438	-	Pakistan
PI 649105	IB 391	India
PI 426394	K 759	Pakistan
PI 180421	-	India, Rajasthan
PI 432379	BAU M/9	Bangladesh
<b><i>Brassica rapa</i></b>		
PI 6841	Sampad	Bangladesh
PI 6838	Tori 7	Bangladesh
PI 603026	K 656	Pakistan
PI 6839	Kalyania	Bangladesh
PI 352789	Sarson	India
PI 432373	BAU M/39	Bangladesh
PI 340199	IB 115	India
PI 347597	BCb 9	India

All *Brassica* species accessions are of industrial type, which is high in erucic acid and glucosinolates.

## Yield components

On average, the accessions of *B. juncea* and *B. rapa* flowered in 52 and 39 days, respectively. The range was 39 to 66 days for *B. juncea* and 31 to 56 days for *B. rapa* (Tables 2 and 3). A similar average was observed by Enjalbert et al. (2013) in a study of 94 accessions in Colorado, USA, under irrigation (52 days) and dryland conditions (50 days). The accessions of *B. rapa* had early flowering in tropical conditions. Padilla et al. (2005) were also able to group accessions of *B. rapa* by early flowering (44 days) in the northwest region of Spain. Khan et al. (2013) observed an interval of 30 to 36 days for full flowering of the accessions in Bangladesh.

On average, *B. juncea* reached maturation after 112 days and *B. rapa* after 70 days. The range was 77 to 122 days for *B. juncea* and 88 to 112 days for *B. rapa* (Tables 2 and 3). Gesch et al. (2015), when comparing species of oilseeds sown in May in Minnesota, USA, reported 97 to 113 days between planting and harvest, with a short crop cycle for *B. rapa*, which tended to have a lower yield due to early maturation, as observed in the present study. The access of *B. juncea* PI 426394 included one of the latest cycles in 2015 and the latest cycle in 2016 (122 days). This cycle should not be a problem in the regions of Brazil, as corn and wheat that are grown in winter have similar or longer cycles.

In the *B. juncea* accessions plant height was higher by 12%, on average. This species is characterized by vigorous growth, which is why it is used as a cover crop. The range was 59 to 155 cm for *B. juncea* and 49 to 130 cm for *B. rapa* (Tables 2 and 3). Similar results were observed by Chauhan et al. (2007) (158 to 179 cm) for *B. juncea*. On average, the accessions of *B. juncea* and *B. rapa* reached a height of 109 and 97 cm, respectively (Tables 2 and 3), which was substantially lower than the values reported by Iqbal et al. (2008) (> 200 cm) but higher than those observed by Enjalbert et al. (2013) (65 cm). There was a slight increase of 8% for *B. juncea* and 7% for *B. rapa* in 2016 compared to 2015, respectively. This demonstrates uniform plant growth. Thus, the physical characteristics of the analyzed accessions are in agreement with the literature and the results indicate that

**Table 2.** Flowering, cycle, height, pods, pod length (PL), seeds per pod, thousand seed weight (TSW), oil content, yield and oil yield of *Brassica* species in 2015.

Species	Flowering (days)	Cycle (days)	Height (cm)	Pods	PL (cm)	Seeds per pod	TSW (g)	Oil content (%)	Yield (kg·ha <sup>-1</sup> )	Oil yield (kg·ha <sup>-1</sup> )
<i>Brassica juncea</i>										
PI 432386	51 a	103 b	106 a	231 b	3.3 e	13.5 c	2.2 d	42.2 b	1017 a	430 a
PI 432384	39 c	104 b	82 c	331 a	3.1 e	9.9 c	1.7 d	37.7 c	1123 a	423 a
PI 180266	48 b	104 b	110 a	228 b	3.8 d	13.4 c	3.1 c	44.2 a	1108 a	490 a
PI 449438	51 a	108 a	121 a	168 c	3.8 d	10.6 c	2.4 d	44.3 a	743 b	328 b
PI 649105	47 b	104 b	97 b	304 a	3.5 e	11.9 c	2.1 d	41.5 b	1093 a	452 a
PI 426394	46 b	110 a	115 a	279 a	3.7 d	12.3 c	2.4 d	44.0 a	1060 a	466 a
PI 180421	49 b	107 a	120 a	183 c	3.9 d	11.5 c	3.0 c	42.2 b	838 b	354 b
PI 432379	41 c	97 c	83 c	284 a	3.3 e	12.2 c	2.2 d	41.1 b	987 a	404 a
<i>Brassica rapa</i>										
PI 6841	36 d	88 e	69 d	70 d	5.5 b	24.8 a	7.3 a	44.8 a	686 b	311 b
PI 6838	33 e	88 e	53 e	164 c	4.5 c	18.5 b	4.2 b	40.8 b	625 b	253 b
PI 603026	48 b	104 b	109 a	251 b	3.4 e	13.0 c	3.0 c	42.2 b	1123 a	475 a
PI 6839	31 e	88 e	52 e	161 c	5.3 b	18.9 b	3.9 b	43.7 a	799 b	348 b
PI 352789	42 c	97 c	72 d	67 d	6.3 a	25.6 a	7.8 a	44.3 a	661 b	292 b
PI 432373	37 d	92 d	72 d	190 c	5.6 b	20.9 b	4.1 b	44.9 a	668 b	300 b
PI 340199	42 c	106 a	93 b	199 c	4.1 d	13.4 c	3.1 c	39.3 c	982 a	388 a
PI 347597	36 d	88 e	71 d	123 d	5.5 b	19.9 b	3.4 c	44.4 a	648 b	287 b

Same letter indicates no difference by Scott–Knott test ( $p < 0.05$ ).

**Table 3.** Flowering, cycle, height, pods, pod length (PL), seeds per pod, thousand seed weight (TSW), oil content, yield and oil yield of *Brassica* species in 2016.

Species	Flowering (days)	Cycle (days)	Height (cm)	Pods	PL (cm)	Seeds per pod	TSW (g)	Oil content (%)	Yield (kg·ha <sup>-1</sup> )	Oil yield (kg·ha <sup>-1</sup> )
<i>Brassica juncea</i>										
PI 432386	57 d	109 d	131 b	312 c	3.9 e	13.5 c	2.9 d	42.6 c	955 e	406 d
PI 432384	58 c	116 c	129 b	549 a	3.4 e	11.5 c	2.2 d	37.7 f	1296 d	488 c
PI 180266	61 b	115 c	134 b	388 b	4.2 d	14.8 c	3.4 d	44.2 b	2057 a	910 a
PI 449438	66 a	119 b	155 a	331 c	3.8 e	11.9 c	2.7 d	42.6 c	1433 d	611 b
PI 649105	54 e	109 d	93 c	325 c	4.1 d	13.0 c	3.5 d	41.1 e	1586 c	653 b
PI 426394	56 d	122 a	131 b	362 b	3.9 e	13.4 c	3.1 d	43.9 b	1612 b	707 b
PI 180421	59 c	110 d	133 b	239 c	4.4 d	12.6 c	3.1 d	41.8 c	1560 c	652 b
PI 432379	44 f	106 e	59 e	541 a	3.7 e	12.6 c	2.9 d	43.1 c	1436 d	619 b
<i>Brassica rapa</i>										
PI 6841	34 i	92 f	49 f	101 d	5.6 b	26.1 a	8.1 b	46.8 a	1203 d	563 c
PI 6838	34 i	93 f	41 f	294 c	4.9 c	18.3 b	4.5 c	44.1 b	1214 d	536 c
PI 603026	56 d	112 d	130 b	377 b	3.7 e	12.6 c	3.3 d	40.6 e	1338 d	542 c
PI 6839	35 i	93 f	49 f	303 c	4.9 c	14.3 c	4.2 c	45.3 b	1346 d	610 b
PI 352789	41 g	106 e	59 e	119 d	6.6 a	27.1 a	9.6 a	46.9 a	1365 d	641 b
PI 432373	39 g	106 e	73 d	450 b	5.6 b	20.5 b	2.3 d	46.0 a	871 e	400 d
PI 340199	43 f	106 e	65 e	356 b	4.1 d	11.9 c	3.0 d	40.7 e	1433 d	583 c
PI 347597	38 h	93 f	61 e	251 c	5.6 b	18.5 b	4.7 c	42.6 c	1219 d	523 c

Same letter indicates no difference by Scott–Knott test ( $p < 0.05$ ).

these species can be cultivated in different environments. This is important because the architecture of the plant determines the properties of the primary branches and thus, also the number of pods and consequently the yield of the plant.

The number of pods per plant varied among species and accessions. In the first year, five promising accessions of *B. juncea* were grouped together, containing more than 251 pods per plant (Table 2). *Brassica juncea* species yielded on average 64% more pods than *B. rapa* species, even though the accession PI 603026 (*B. rapa*) presented 250 pods per plant in 2015 (Table 2). The range of pods per plant was 168 to 549 pods for *B. juncea* and 67 to 450 cm for *B. rapa* (Tables 2 and 3). The accessions with the smallest number of pods per plant, PI 6841 (70 pods) and PI 352789 (67 pods), belonged to the species *B. rapa*. In the second year, accession PI 432373 and PI 432384 had more than 500 pods (Table 3). This difference in pod yield per plant from the first to the second year may have occurred mainly due to climatic conditions, including differences in rainfall and temperature. In general, *B. juncea* accessions had more pods per plant than *B. rapa* (46%), which is in accordance with Gunasekera et al. (2006 a).

Pod length and the number of seeds per pod, contrary to the number of pods per plant, were higher in *B. rapa* accessions, especially in the accessions PI 6841 and PI 352789 (Tables 2 and 3). The range of pod length was 3.9 to 4.4 cm for *B. juncea* and 3.4 to 6.6 cm for *B. rapa*, while the range of seeds per pod was 9.9 to 14.8 cm for *B. juncea* and 13.0 to 27.1 cm for *B. rapa* (Table 2 and 3). Such accessions had an average pod length of 6 cm and 26 seeds per pod, whereas the average for the *B. rapa* species was 5 cm and 19 seeds per pod (Tables 2 and 3), which is within the interval of seeds per pod (12 to 24) and pod length (4 to 7 cm) proposed by Khan et al. (2013). Pods of *B. juncea* accessions had an average length of 3.6 cm and 13.5 seeds per pod, which is close to the ranges proposed by Sharma and Sardana (2013) for pod length (4.4 to 6.3 cm) and seeds per pods (9.3 to 13.1 seeds) of *B. juncea* cultivated in India. On average over the years, pod length and number of seeds per pod were 36 and 53% higher in *B. rapa* in relation to *B. juncea*, respectively (Tables 2 and 3).

The *B. rapa* accessions PI 6841 and PI 352789, respectively, had the highest thousand seed weight regardless of growth conditions, with weights ranging from 7 to 9 g (Tables 2 and 3). The accessions of *B. juncea* were grouped (Scott-Knott test) according to the smallest thousand seed weight; 2.5 g on average, in accordance with studies by Enjalbert et al. (2013) (1.09 to 3.20 g) and Gunasekera et al. (2006 a) (2.3 to 3.1 g). On average over the years, thousand seed weight was 78% higher in *B. rapa* species compared to *B. juncea* accessions. The range of thousand seed weight was 1.7 to 3.5 g for *B. juncea* and 2.3 to 9.6 g for *B. rapa* (Tables 2 and 3). Seed size is known to be positively correlated with rapid emergence (Enjalbert et al. 2013). Pod characteristics did not vary significantly between the two years and different climatic conditions, indicating that these traits may be largely controlled by genetic variation.

## Yield

Yield of most *B. juncea* accessions was higher than that of *B. rapa* in 2015. In the first year, despite irregular rainfall, the yield reached up to 1123 kg·ha<sup>-1</sup> (Table 2), which is close to the average yield for *Brassica* oilseeds (1200 kg·ha<sup>-1</sup>) obtained in tropical conditions in India (Kumar et al. 2016) and in the United States (Enjalbert et al. 2013). Yield of *B. juncea* accessions were on average 29 and 19% higher than that of *B. rapa* in 2015 and 2016, respectively (Tables 2 and 3). Gesch et al. (2015) observed that *Brassica* species with early maturation, such as *B. rapa*, tend to have a smaller yield than genotypes with later maturation, which supports the findings of this present study.

In 2016, with regular rainfall, especially before flowering, the *B. juncea* accession PI 180266 had a yield of 2057 kg·ha<sup>-1</sup> (Table 3), which is close to the yield documented for the *B. juncea* accession RBJ-03047 (2222 kg·ha<sup>-1</sup>) cultivated in semi-arid conditions in Pakistan (Iqbal et al. 2008) and in the United States (2011 kg·ha<sup>-1</sup>) (Gesch et al. 2015). The range of yield was 743 to 2057 kg·ha<sup>-1</sup> for *B. juncea* and 625 to 1433 kg·ha<sup>-1</sup> for *B. rapa* (Tables 2 and 3). Wilkes et al. (2013) reported variation in yield from 350 to 1640 kg·ha<sup>-1</sup> of *B. juncea* genotypes in Australia. Variation from 30 to 1800 kg·ha<sup>-1</sup> was also observed in Australia by Gunasekera et al. (2006 a), under conditions of late seeding and water scarcity. The accession of *B. juncea* germplasm (PI 180266) is from Gujarat, India, and this accession stood out in both years of the present study in terms of oil yield. *Brassica juncea* is originally from India and, according to Gan et al. (2007), it is a productive species in semi-arid regions with unreliable rainfall. This increases the potential of the species for cultivation in the dry and warm winter areas of Midwest Brazil. Gunasekera et al. (2006 a, b) reported greater yield stability and short cycle of *B. juncea* species in dry environments and marginal areas in the south of Western Australia.



In 2015, there was greater precipitation after flowering and grain filling (115 mm), which damaged the crop. There is clear evidence that *Brassica* species are negatively affected by excess soil moisture (Gesch and Cermak 2011). In 2016, over 70% of annual rainfall occurred before flowering, which resulted in higher vegetative growth and did not affect the crop cycle. These results indicate that regions with high precipitation in winter (July), as is the case of southern Brazil, may have problems with the cultivation of some *Brassica* species.

The yield obtained for *Brassica* accessions in the present study is interesting, since the medium-low yield of *B. napus* species in Brazil is 1500 kg·ha<sup>-1</sup> (Silva et al. 2017). Improved efforts are needed to increase the yield of *Brassica* species that have high erucic acid content. The yield increase of *Brassica* industrial crops in Brazil may be more effective due to the rusticity characteristics of the species and lower sensitivity to the environment. These *Brassica* species are generally more suited to stressful environments associated with low rainfall, high temperatures, and late sowing (Gunasekera et al. 2006 b).

## Oil content and oil yield

Accessions of both species were grouped according to oil content, with the most promising accessions having an oil content of 45–46%. The range of oil content was 37.7 to 44.3% for *B. juncea* and 39.3 to 46.9% for *B. rapa* (Tables 2 and 3). Despite these similar values, the environment, seeding date and temperature play a key role in seed oil content (Gunasekera et al. 2006 b; Pavlista et al. 2011). Such variation in seed oil content in both *Brassica* species demonstrates a potential for improvement with future research and corroborates the conclusions of Iqbal et al. (2008). These accessions can be used for a breeding program to begin to increase oil content.

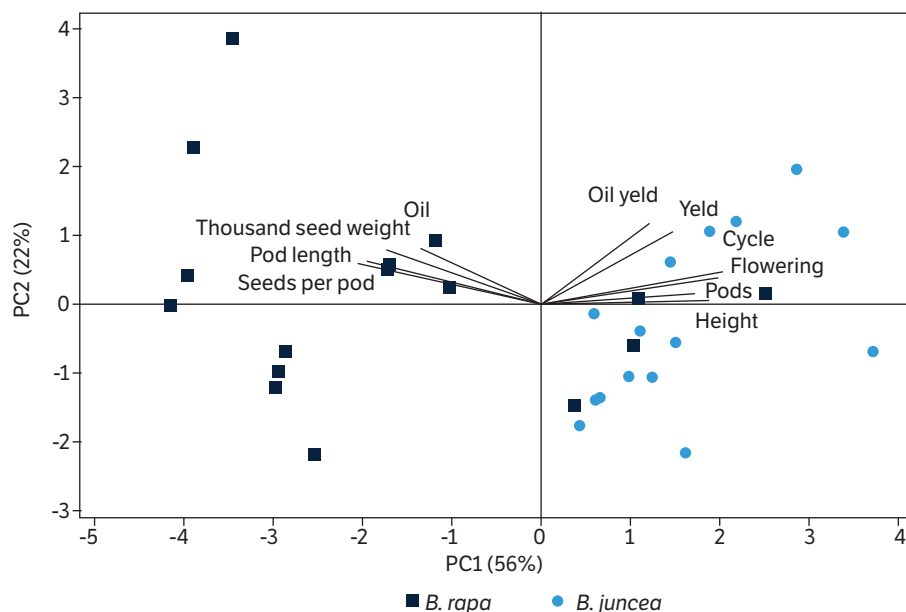
On average, *B. rapa* accessions showed 3% higher oil content than that of *B. juncea* species, reaching 46.9% for *B. rapa* accessions PI 352789 (Tables 2 and 3). This result was similar to that of Gesch et al. (2015), who found the oil content to be between 44–48%. However, some accession had a low oil content in both years, such as PI 432384 (37.7%). Slight variation in oil content over the two years for both species was observed. Less than 2% variation on average was observed for oil content in both years for both species. Gunasekera et al. (2006 b) reported that oil content varied from 32–45% in *Brassica* species. In view of the end use of these oils, the positive characteristics are high erucic acid content and good oxidation stability, the latter evaluated by limited amounts of polyunsaturated fatty acids (PUFA) (Erhan et al. 2006). One of the most important attributes of industrial oilseeds is oil content, and it is important to note that large-scale production of raw materials will depend on yield, which will result in oil yield per hectare. However, it is also the case that large-scale commercial production will depend heavily on profitable markets for seed by-product after oil extraction (Gesch et al. 2015).

In 2015, oil yield ranged from 253 to 490 kg·ha<sup>-1</sup>, and in 2016 from 400 to 910 kg·ha<sup>-1</sup> (Tables 2 and 3). Even though *B. juncea* species had a higher yield, the higher average oil content of *B. rapa* accessions reduced the average difference between the species from 26% in yield to just 14% in oil yield, demonstrating the value of accessions with high oil content. Gesch et al. (2015) reported variation from 287 to 1588 kg·ha<sup>-1</sup> and 210 to 885 kg·ha<sup>-1</sup> for several *Brassica* species cultivated in the northern central region of the United States over two years, respectively. This study demonstrated the diversity of yield components responses among different *Brassica* oilseed species when grown in tropical conditions of southeastern Brazil.

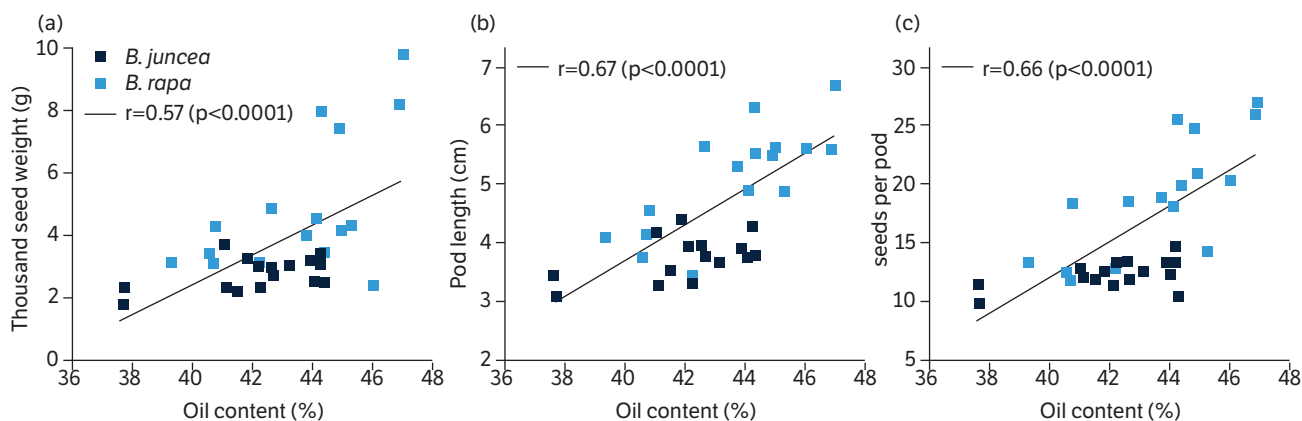
Further studies are needed to determine the causes of these differences to make traditional winter crops in Brazil. The study resulted in the identification of characteristics that will benefit future breeding efforts to further improve genotypes that have shown greater potential for biodiesel and industrial use.

## Principal component analysis and correlation

Principal component biplot demonstrates the correlation between traits average yield components (Fig. 2). In the principal component analysis, the first two PCs accounted for 78% of the variation. Most of *B. juncea* accessions were separated in the right-side quadrants of the biplot as they produced more pods, yield, oil yield, height, cycle, and flowering and were taller than *B. rapa* accessions. On the other hand, *B. rapa* were separated in the left side quadrants of the biplot as they produced heavier seeds, more seeds per pod, pod length, and oil than *B. juncea*. Variables associated with yield and oil yield are situated on the right of PC2 in both years (Fig. 2).



**Figure 2.** Biplot with the projection of the characteristics in the first two main components with the discrimination of *Brassica* species in 2015 and 2016.



**Figure 3.** Simple linear correlation of oil content with thousand seed weight (a), pod length (b) and seeds per pod (c) of *Brassica* species in 2015 and 2016.

Oil content was significantly correlated with the thousand seed weight ( $r = 0.66$ ;  $p < 0.001$ ) (Fig. 3a), pod length ( $r = 0.67$ ;  $p < 0.001$ ) (Fig. 3b) and number of seeds per pod ( $r = 0.57$ ;  $p < 0.001$ ) (Fig. 3c). This means it would be relatively easy to select superior genotypes with high oil content. Currently one of the objectives of the *Brassica* species breeding program is to increase the oil content (Salisbury et al. 2016). Oil content was positively correlated with seeds per pod (Sing and Chowdhury 1983) and seed weight (Gunasekera et al. 2006b) in *B. juncea*. Therefore, considering these traits as selection criteria will be advantageous in improving *B. juncea*.

Although these *Brassica* species show promising performance under other environmental conditions (Enjalbert et al. 2013; Wilkes et al. 2013; Gesch et al. 2015), this success has not yet been widely documented under tropical conditions. Nevertheless, the yield components of the species found in Brazil compared favorably with those documented in the literature. The *Brassica* species, with their ancient and widespread germplasm, have shown potential for future advances in genetic improvement.



## CONCLUSION

Accessions of *Brassica* species cultivated during the two-year study had adequate yield and oil yields, demonstrating that they are promising alternative oilseed crops for the cool seasons in tropical environments. This study revealed that *B. rapa* accessions were short-cycle crops and had a high oil content, whereas *B. juncea* accessions had a high yield and oil yield. On average *B. juncea* had the highest oil yield due to high yield. The positive correlation of thousand seed weight, pod length and seeds per pod with oil content demonstrates the possibility of developing high-oil industrial oilseeds. *Brassica* species are promising alternative oilseed crops for cultivation during the cool seasons in tropical conditions.

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