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Original Research

Plant Density Differentially Influences Seed Weight in Different Portions of the Raceme of Castor

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Abstract

Castor (*Ricinus communis* L.) is an oilseed crop, that is cultivated in arid and semi-arid region. Seed yield per plant of castor significantly effective by different environmental factors, but planting density also influence on seed yield. A field experiments were conducted in 2016 and 2017 to investigate the effects of in-row plant spacing (30, 40, 50 and 60 cm) on seed yield and weight in different portions of the raceme under drip irrigation along with mulching. The results indicating reduction in-row spacing, significantly reduced seed yield and weight per plant. Reduction percentage were greater in secondary and tertiary racemes as compared to primary racemes. Seed weight and yield in basal portion of raceme was also decreased by reducing in-row spacing. In comparison to raceme portion, seed weight was more reduced in the middle portion and showed no change in the upper portion of the raceme as compared to basal portion. Seed yield and weight per unit area was increased owing to the larger plant population with decreasing in-row spacing, but below the threshold value of in-row spacing (30 cm), seed fresh weight yield were decreased. Therefore, it was concluded, higher planting density by reducing the in-row spacing may increase castor fresh weight yield. Yield may be increased further by increasing the seed weight in the basal portion of the raceme, especially for primary racemes, while maintaining the seed weight in the upper and middle portions of the raceme. Further studies needed to explore different planting density effect on seed yield under different environmental factors within different portions of raceme.

Keywords: castor, in-row spacing, yield components, raceme position, seed position

Introduction

Castor (*Ricinus communis* L.) is an industrial crop cultivated for the oil contained in its seed [1]. Castor oil is largely used in the chemical industries worldwide. Castor oil consumption is limited by insufficient and unreliable feedstock supply rather than by demand [2].

In most regions producing castor, seed yield can be rapidly increased with implementation of improved agronomic practices, such as optimization of the plant density [3]. Plant density arrangements for castor crop have been studied previously with different combination [3-5]. In castor crop growth, plant density is the important component because its effect seed yield

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and plant growth [6, 7]. It is very difficult to define best plant density for castor because it depends many factors such as soil properties, role of fertilizers, plant architecture, genotype, other environmental factors (humidity, temperature and rainfall) along with cropping season [3, 6, 8, 9]. Therefore, an optimal individual plant density cannot be broadly recommended for castor.

Total castor seed yield is depended on the seed weight in different portions of the raceme. Castor racemes are born only at the shoot apices. A primary raceme is the inflorescence that develops at the primary stem apex, secondary racemes are born at the apex of secondary branches, and so on. Development of new branches and racemes can continue indefinitely owing to the indeterminate growth habit of castor [10].

Developmental differences among racemes are likely to be associated with environmental and physiological conditions that change during the growing season [10, 11]. For example, the contribution of primary racemes to the total seed yield varies from 14% to 69% [3, 6, 12]. Thus, the contribution of each raceme to seed yield seems not to be a fixed trait, but rather a consequence of the growing conditions that each raceme experiences. Longer and favorable growing conditions are associated with a higher contribution of secondary and tertiary racemes [13]. Thus, the variation in growth among primary, secondary and tertiary racemes were differ under different plant densities, but little information on this variability is presently available [14, 15]. The raceme of castor includes many capsules (for example, more than 200 capsules, and >40 cm long for a primary raceme) in a typical castor plant, male flowers are located at the bottom of the raceme, and female flowers are located in the middle and top portions [16]. Thus, capsule development is dependent on the floral type and position within a raceme and is potentially influenced by environmental factors. The response of Castor to different plant density is complex and involves many eco-physiological aspects, because it creates changes in growth and development [10]. The influence of plant density on seed yield of the different raceme types of castors is poorly understood, and it is unknown if manipulation of plant density will influence the seed weight in different portions of the castor raceme. The objective of this study was to explore the influence of plant density, by adjusting the in-row plant spacing, on the seed yield and weight of each raceme type and different portions of the raceme of castor.

Materials and Methods

Experimental Design

The field experiment was carried out at the Xiaoguai Experimental Station of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences Urumqi, Xinjiang, China, in the 2016 and 2017 cropping seasons. The site has an arid climate with average annual rainfall of 105.3 mm, annual evaporation of 2692 mm, annual insolation of 2705 h, annual accumulated temperature ≥10ºC of 3760ºC, and 232 frost-free days per annum.

A gray desert soil from the study area, was analyzed before sowing. The chemical properties of the 0-30 cm soil layer was as follows: total available nitrogen (N) 16.7 mg kg^{-1}, pH (H_2O) 8.1, soil bulk density 1.33 g cm^{-3}, Olsen phosphorus (P) 3.1 mg kg^{-1}, NH_4OAc-extracted potassium (K) 208.9 mg kg^{-1}, and organic matter 5.3 g kg^{-1}.

Seeds of the castor hybrid 'Nongfeng commercial producer of the hybrid seed' were sown on 23 April 2016 and 20 April 2017. Two rows (40 cm apart) were sown on either side of the irrigation drip line. The distance between two drip lines was 160 cm (Fig. 1). The treatments comprised four in-row plant spacings (60, 50, 40, and 30 cm) and four plant densities (20,833, 25,000, 31,250 and 41,667 plants ha^{-1}). A randomized block design with three replicates was used. Thus, there were 12 plots in total, each 16 m × 11 m in size.

The total volume of water supplied by drip irrigation (DI) under mulch film was 4000 m^3 ha^{-1}. Urea was applied as a fertilizer at the rate of 250 kg N ha^{-1}, of which 20% (50 kg N ha^{-1}) was applied before sowing as a basal dressing in 10 cm soil depth, and the remainder (200 kg N ha^{-1}) was applied with the drip irrigation in seven individual applications (Table 1). In addition, 150 kg P_2O_5 ha^{-1} (as superphosphate) and 150 kg K ha^{-1} (as potassium sulfate) were applied before sowing as a basal dressing [17].

Measurements

Yield-related agronomic traits were measured by randomly selected 10 adjacent plants in two rows of both sides of drip line at maturity stage of plants in 139 and 137 days in 2016 and 2017 cropping seasons respectively.

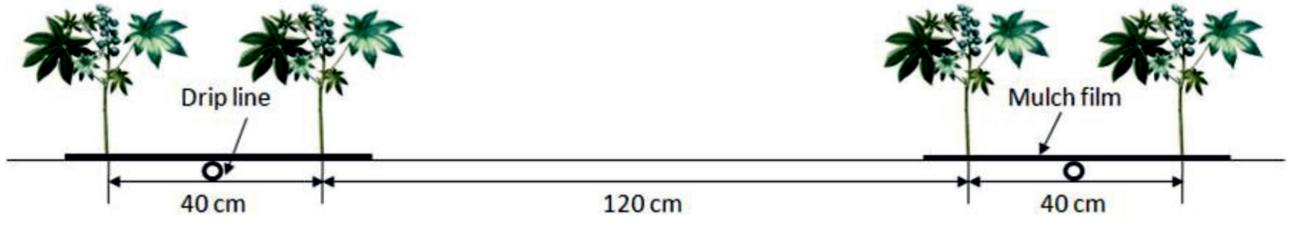

Fig. 1. Schematic diagram illustrating the plant row spacing and irrigation system used in the experiment.

Table 1. Amount of water and nitrogen fertilizer applied by drip irrigation.

Total water and nitrogen			Date of application										
		2016	5 May	17 May	29 May	10 Jun	22 Jun	4 Jul	14 Jul	24 Jul	4 Aug	14 Aug	26 Aug
		2017	29 April	12 May	24 May	6 Jun	17 Jun	1 Jul	12 Jul	20 Jul	1 Aug	12 Aug	23 Aug
Water (m^3 ha^{-1})	4000		200	200	300	400	400	500	500	500	400	300	300
Nitrogen (kg N ha^{-1})	200		–	–	–	20	20	30	40	40	30	20	–

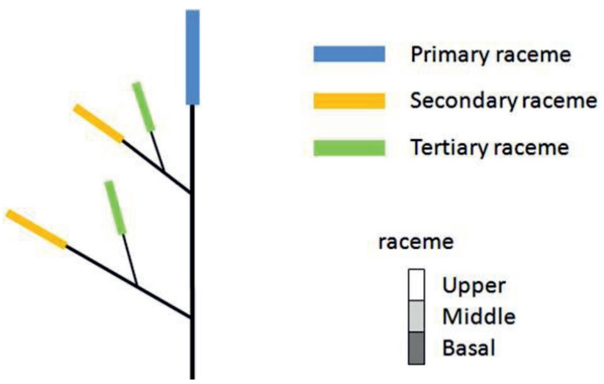

Fig. 2. Schematic diagram illustrating specific raceme portions. Each raceme is divided into three equal portions, termed ‘Upper’, ‘Middle’ and ‘Basal’, representing the seed position in the raceme.

Raceme effective length per plant is measured with ruler, raceme number per plant, seed number per raceme, are counting manually [1]. Furthermore, each plant was divided into primary, secondary and tertiary raceme, after that same parameters are mention above measured with same procedure. 100-seed weight of primary, secondary and tertiary racemes at different portions (upper, middle and basal) of each raceme are measured with weight balance (Fig. 2). Some castor plants produced quaternary racemes, but these carried no mature seed and consequently were not measured. Seed yield was determined by harvesting an area of about 51.2 m^2, randomly selected four rows with from each plot.

Data Analysis

Assumptions of parametric statistics were tested to verify normality and homogeneity of variance using the Shapiro-Wilk normality test and Levene’s test before further analysis. To determine the main effect and interaction effects of each growth trails ($P<0.05$), data were analyzed using one-way analysis of variance (ANOVA) with row spacing as main factor. Furthermore, a posthoc Tukey test $P<0.05$ was performed to determine significant difference within treatments (SAS Institute, 1998). Origin 2015 software (OriginLab Corporation, Northampton, MA, USA) was used for correlation analysis and graphs making.

Results and Discussion

Seed Yield

Castor seed yield increased by more than 34% with decrease of in-row plant spacing from 60 to 30 cm in 2016 and 2017 (Table 2). However, the extent of yield increase was gradually reduced with decreasing in-row spacing. For example, in 2016, the yield increase was 667 kg ha^{-1} (15.1%) with decrease of in-row spacing from 60 to 50 cm, 503 kg ha^{-1} (9.9%) with decrease in spacing from 50 to 40 cm, and 347 kg ha^{-1} (6.1%) for the change in spacing from 40 to 30 cm. Similar results were obtained in 2017 experiment. It was also observed that castor seed yield increased with increasing plant density [7, 13] but beyond the threshold level of plant in-row spacing (30 cm) seed yield and weight was reduced [1, 16]. Therefore, according to the results, there is an optimum plant density dependent on genotype, soil properties, fertilizer effects, environmental conditions, and agricultural practices [18]. In the present study, the seed yield under the lowest in-row spacing of 30 cm was higher among other spacing. This finding suggests that increasing the planting density through decreased in-row plant spacing using a wide-narrow row-spacing

Table 2. Castor seed yield attained between different in-row plant spacings.

In-row plant spacing (cm)		60		50		40		30
2016	Yield (kg ha^{-1})	4419.3a		5080.4b		5643.0c		5990.1c
	Yield increase (kg ha^{-1})		661.1a		562.6a		347.1b	
2017	Yield (kg ha^{-1})	4610.4a		5290.6b		5798.1c		6179.7c
	Yield increase (kg ha^{-1})		680.2a		507.5b		381.6c	

Table 3. Yield and its components per castor plant under different in-row plant spacings.

Year	In-row plant spacing (cm)	Raceme number per plant	Effective raceme length (cm)	Seed number per raceme	100-seed weight (g)	Seed weight per plant (g)
2016	60	5.1a	38.3a	804.8a	30.2a	246.6a
	50	4.9a	31.3ab	733.4ab	30.7a	228.1ab
	40	5.0a	29.0b	671.7b	28.9a	197.3b
	30	4.8a	25.1b	561.9c	27.8a	159.0c
2017	60	5.1a	32.9a	845.5a	30.7a	262.4a
	50	5.0a	28.9ab	766.9ab	30.8a	237.6a
	40	5.0a	27.0ab	668.2b	29.6a	201.4b
	30	4.9a	23.6b	526.8c	29.4a	156.4c

Note: "Effective raceme length" indicates the length of the raceme that bore seeds. Means followed by the same letter(s) for each parameter within a year are not significantly different at $P<0.05$ ($n = 3$).

pattern is a favourable method to increase castor yield under DI [6].

Yield Components

Deduction in-row spacing, the raceme number per plant and 100-seed weight showed decreasing trends, but the differences among treatments were not significant (Table 3). Seed number per raceme was the main determinant of seed yield per plant [12, 19]. The effective raceme length and seed number per raceme showed significant decreases with the reduction of in-row plant spacing (60 to 30 cm). While decreased in-row spacing from 60 to 30 cm, the seed yield per plant decreased from 246.6 to 159.0 g plant^{-1} (35.5%), and from 262.4 to 156.4 g plant^{-1} (41.2%), in 2016 and 2017, respectively (Table 3). Instead of decreased raceme number per plant and 100-seed weight, but overall yield were increased in narrow (Table 2) spacing because its increased number of plants per ha, that added more seed number per plant and more raceme number per plant [20]. It was also observed that the number of seeds per raceme decreased linearly as castor plant density increased [21]. It was observed decreased seed yield per

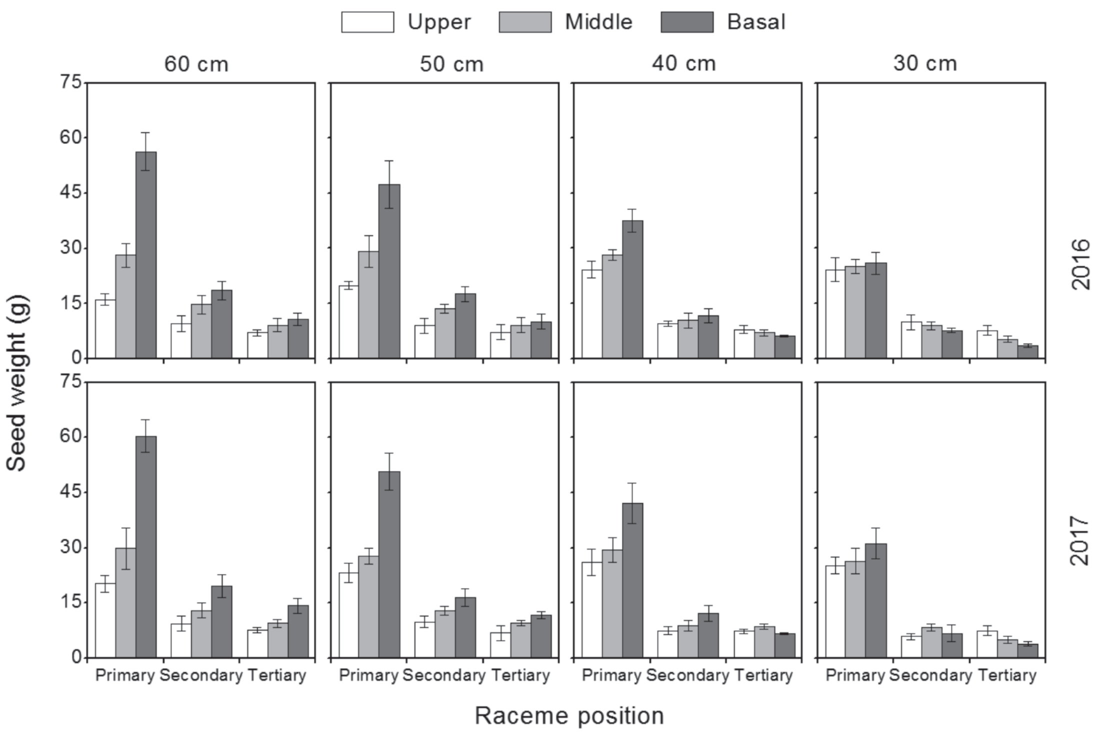

Fig. 3. Seed weight in different portions of primary, secondary and tertiary castor racemes. Error bars represent the standard error of the mean (n = 3).

castor raceme with increased plant density within a row [6]. However, neither study examined changes in seed yield under different portions of the raceme. In this study raceme was divided into three portions (Fig. 2) and found more reduction in basal, middle portion and very less in the upper portion (Fig. 3).

The present study showed that the number of seeds per raceme decreased, in the order tertiary/secondary/primary racemes, with the decreased of in-row spacing, (Table 4). For example, in 2016 within in-row spacing reduction from 60 to 30 cm, the seed number of primary racemes decreased from 312.8 to 253.6 (18.9%), that of secondary racemes from 139.0 to 95.7 (31.1%) and tertiary racemes from 98.0 to 63.1 (35.6%). Higher plant density within narrow row spacing creates higher competition among plants and causing decline in seed yield per plant [22-24]. In narrow spacing every plant try to capture resources under competition with other neighbour plant [24, 25]. For this process every plant trying to capture resources by increasing their below ground growth as compared to above ground growth [23], due to this seed yield of per plant was reduced.

Seed Weight in Different Portions of Raceme

The seed weight in different portions of the primary raceme showed the trend basal>middle>upper (Fig. 3). However, the differences in seed weight among the raceme portions differed from those observed with the decreased of in-row spacing. The seed weight in the upper portion decreased significantly, almost no change was observed in the middle portion, and the basal portion showed a gradual decreased with reduction of in-row spacing. This result explained that reduction

Table 4. Yield and its components for different raceme types of castor under different in-row plant spacings.

Year	Raceme position	In-row plant spacing (cm)	Raceme number per plant	Effective raceme length (cm)	Seed number per raceme	100-seed weight (g)	Seed weight per raceme (g)	Seed weight per plant (g)
2016	Primary	60	1a	47.2a	312.8a	32.2a	100.7a	100.7a
		50	1a	41.3ab	297.4ab	32.4a	96.4ab	96.4ab
		40	1a	35.6b	288.6ab	31.1a	89.8ab	89.8ab
		30	1a	34.0b	253.6b	29.7a	75.3b	75.3b
	Secondary	60	2.2a	38.4a	139.0a	30.9a	43.0a	94.5a
		50	2.1a	29.9b	128.5ab	31.2a	40.1ab	84.2ab
		40	2.2a	26.7bc	110.0c	28.7a	31.5bc	69.4bc
		30	2.1a	21.4c	95.7c	27.7a	26.5c	55.7c
	Tertiary	60	1.9a	29.4a	98.0a	27.6a	27.1a	51.4a
		50	1.8a	24.6ab	92.2ab	28.6a	26.4ab	47.5ab
		40	1.8a	22.6b	78.5c	27.0a	21.2bc	38.1bc
		30	1.7a	20.0b	63.1d	26.1a	16.5c	28.0c
2017	Primary	60	1a	45.9a	336.7a	32.8a	110.4a	110.4a
		50	1a	42.9ab	318.7ab	31.9ab	101.7ab	101.7ab
		40	1a	40.8ab	306.2ab	31.9ab	97.7bc	97.7bc
		30	1a	33.0b	272.4b	30.4b	82.8c	82.8c
	Secondary	60	2.2a	32.4a	137.2a	30.6a	42.0a	92.4a
		50	2.1a	25.6ab	127.2ab	30.9a	39.3a	82.5a
		40	2.2a	23.5ab	95.8c	29.6a	28.6bc	63.0b
		30	2.1a	22.5b	71.6d	29.3a	21.0c	44.1c
	Tertiary	60	1.9a	20.4a	108.9a	28.8a	31.4a	59.6a
		50	1.9a	18.2a	95.9ab	29.5a	28.1ab	53.4a
		40	1.8a	16.6a	82.8b	27.3b	22.6bc	40.7b
		30	1.8a	15.2a	57.8c	28.4ab	16.4c	29.5c

Note: "Effective raceme length" indicates the length of the raceme that bore seeds. Means followed by the same letter(s) for each parameter within a year are not significantly different at $P<0.05$ (n = 3).

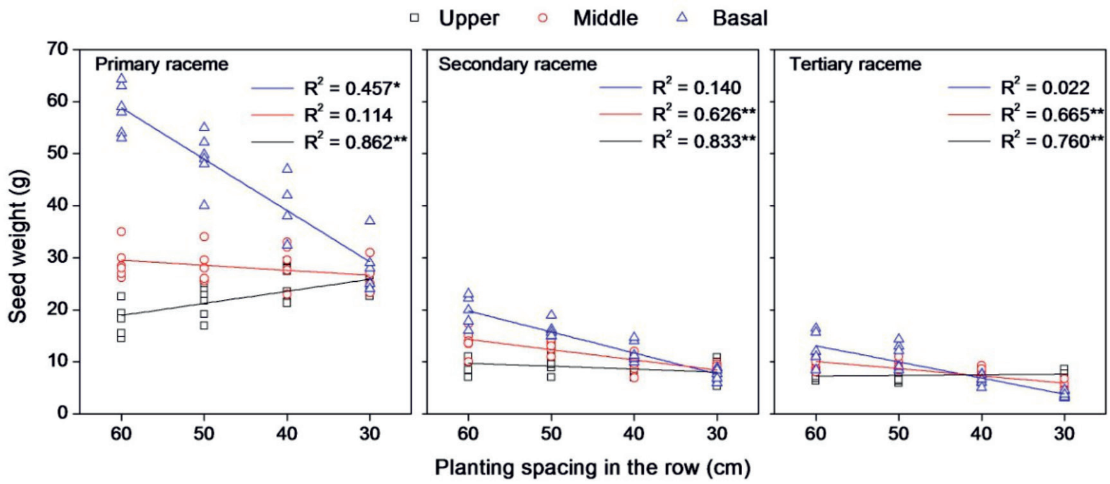

Fig. 4. Linear regression between seed weight in different portions of the raceme and in-row plant spacing for different raceme types. * Significant correlation P<0.05, ** highly significant correlation P<0.01 (n = 24).

in-row spacing along with plant density, effect differently on the rename portions. Some row spacing were affect the upper, someone affect the basal and some were affect the middle portion [5, 16]. A similar trend was observed for secondary racemes with the decreased of in-row spacing from 60 cm to 40 cm; however, the ranking upper>middle>basal was observed under 30 cm in-row plant spacing in 2016, whereas the middle portion attained the highest seed weight in 2017 (Fig. 3). The seed weight in different portions of tertiary racemes showed the trend basal>middle>upper under 60 and 50 cm in-row spacings. However, under 40 cm in-row spacing the rank order was identical to that of secondary racemes under 30 cm in-row spacing, and the trend upper>middle>basal. These results suggested that, regardless of the raceme type, the effect of the decrease of in-row spacing on seed weight was mainly exerted on the basal portion of the raceme.

The correlation between in-row spacing and seed weight in different portions of the raceme was analyzed (Fig. 4). The seed weight in the basal portion of primary, secondary and tertiary racemes declined significantly with the decrease of in-row spacing, but the extent of the decrease differed among the raceme types and showed the trend primary>secondary>tertiary. The seed weight of the middle portion also reduced with decreasing in-row spacing, but the extent of the decrease was smaller than that of the basal portion. The seed weight in the upper portion of the primary raceme increased with decreasing in-row spacing, but no significant change was observed for secondary and tertiary racemes. This finding indicating that decreasing in-row spacing, basal and middle part of the raceme facing interspecific competition to capture resources that's why growth of basal and middle portions were effective more as compared to upper portions [26, 27]. The decreased in seed weight in the different raceme types showed the trend tertiary/secondary/primary with reduction of in-row spacing (Table 4, P<0.05). The smaller decreased in seed weight of the primary raceme with reduction of in-row spacing compared with the other raceme types, mainly reflected the small decreased in seed weight of the middle portion and the increased in the upper position of the primary raceme. The seed weight of the primary raceme decreased more significantly (P<0.05) than that of secondary and tertiary racemes. Therefore, the overall seed weight per plant decreased with the reduction of in-row spacing, and the greatest impact was on the basal portion of primary racemes.

In castor, the number of seeds per capsule is defined during raceme development, and little variation from the typical three-seeded capsules is observed [13]. The average number of seeds per capsule varies from 2.5 to 2.9, and is not influenced by plant density [3, 7-9]. Therefore, in the present experiment, the decreased seed weight in the basal portion of the raceme with decreased of in-row spacing could reflect a decrease in the number of capsules.

In a typical castor plant, male (staminate) flowers are located in the basal portion of the raceme, and female (pistillate) flowers are located in the middle and upper portions [19]. A castor raceme usually does not develop all of the female flowers to capsules, that it potentially could because some female flowers are lost by abscission [28]. Flower abscission can be caused by carbohydrate shortage in relation to the source-sink ratio [5], as observed in *Capsicum annuum* [29], *Citrus sinensis* [30] and *Olea europaea* [31], although the different species involved prevent direct comparisons. Accordingly, a source reduction (defoliation) applied after initiation of the raceme reduced the number of seeds production [3]. Therefore, removing some secondary or tertiary ineffective raceme may be more effective to the improvement of castor yield.

Conclusions

Seed weight and yield per castor plant decreased significantly with the increase of in-row plant spacing but overall yield was increased because of higher number of plants. Below 30 cm plant spacing overall yield was also reduced. Seed yield with 60 cm in-row spacing decreased about 35% compared with 30 cm in-row spacing. The percentage decrease was greater for secondary and tertiary racemes than primary racemes. Regardless of raceme type, the effect of reduction in-row spacing on seed weight was mainly exerted on the basal portion of the raceme, which showed a significant decreased, especially in primary racemes. While, seed weight decreased less markedly in the middle portion, and increased (in primary racemes) or showed no change (in secondary and tertiary racemes) in the upper portion. Furthermore, seed weight in the basal portion of the raceme was increased, while maintaining seed weight in the upper and middle portions. This study, give direction, different plant density significantly effects seeds yield and weight on different portion of raceme. Further studies needed to explore raceme seeds yield under different plant densities along with different environmental factors for better understanding of raceme, seed yield.

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Conflict of Interest

The authors declare no competing interests.

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