Effects of Planting Density and Organic Fertilizer on Stand Growth and Yield Components of Castor Bean in Subei Coastal Tidal Flats: Postprint

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Abstract

This study conducted a castor bean planting density and organic fertilizer experiment for three consecutive years from 2013 to 2015 at the coastal tidal flat experimental base of Jinhai Farm in Dafeng City, Jiangsu Province, to investigate the effects of continuous organic fertilizer application and planting density on castor bean population growth and yield components in the coastal tidal flats of Jiangsu. The experiment was designed as a field plot factorial experiment with three planting densities: high (18,000 plants·ha^{-1}), medium (15,000 plants·ha^{-1}), and low (12,000 plants·ha^{-1}), combined with three organic fertilizer application levels (12,000 kg·ha^{-1}, 6,000 plants·ha^{-1}, and 0 kg·ha^{-1}). During each growth period of castor bean, indicators including aboveground dry matter accumulation and distribution, leaf area index, functional leaf chlorophyll content, spike characteristics, and grain yield were investigated. The results showed that continuous application of organic fertilizer for three years significantly improved soil nutrient status. Under medium density, application of 12,000 kg·ha^{-1} organic fertilizer increased total soil nitrogen, available phosphorus, available potassium, and organic matter content at the flowering stage by 47.37%, 169.21%, 54.65%, and 13.77%, respectively, compared with the no organic fertilizer treatment, reaching a significant level ($P<0.05$). Organic fertilizer application increased the leaf area index and functional leaf chlorophyll content during the late growth stage of castor bean under medium and low densities, enhanced the population growth rate, and enabled the aboveground dry matter accumulation of the medium-density population to reach the level of the high-density population. For the medium-density population, increased organic fertilizer application also promoted the proportion of dry matter allocated to reproductive organs after anthesis, and effective spikes per plant, grains per plant, and 100-grain weight increased with increasing organic fertilizer application rate, effectively compensating for the yield reduction in castor bean population caused by decreased density. Ultimately, castor bean under the medium-density treatment with 12,000 kg · ha^{-1} organic fertilizer application achieved the highest yield (3,943.77 kg · ha^{-1}), which showed no significant difference from the high-density population (P<0.05). Thus, appropriately reducing planting density and increasing organic fertilizer application can effectively and reasonably regulate castor bean population growth, promote rational distribution and translocation of dry matter, and achieve the goal of maintaining spikes, increasing weight, and boosting yield.

Full Text

Preamble

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Effect of Organic Fertilizer on Growth and Yield Components of Castor Under Different Planting Densities

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Abstract: A 3-year field experiment was conducted from 2013 to 2015 during summer castor growing seasons at the coastland of Jiangsu Province to analyze the effects of organic fertilizer and planting densities on population growth and yield components of castor. The interactive test of three planting densities [18,000 plant · hm^{-2} (D1), 15,000 plant · hm^{-2} (D2) and 12,000 plant · hm^{-2} (D3)] and three organic fertilizer application rates [12,000 kg · hm^{-2} (O1), 6,000 kg · hm^{-2} (O2) and 0 kg · hm^{-2} (O3)] were conducted with a castor cultivar of 'Zibi 8' as tested material. The investigated items included dry matter accumulation and distribution, leaf area index, chlorophyll content, spike characters and yield components. The results showed that the soil fertility could be improved significantly by using organic fertilizer for three years. With the application of organic fertilizer of 12,000 kg · hm^{-2} under planting density of 15,000 plant · hm^{-2} (D2O1), the contents of soil total nitrogen, available phosphorus, available potassium and organic matter significantly increased by 47.37%, 169.21%, 54.65% and 13.77% respectively compared with that without organic fertilizer treatment (D2O3). Both leaf area index (LAI) and relative content of chlorophyll at the late growth stage was maintained at a high level under planting densities of 15,000 plant · hm^{-2} and 12,000 plant · hm^{-2} with the application of organic fertilizer. Total dry matter production at filling and ripening stages under medium planting density (15,000 plant · hm^{-2}) plus 12,000 kg · hm^{-2} organic fertilizer (D2O1) significantly improved to almost similar level to that under high planting density of 18,000 plant $\cdot$ hm^{-2} (D1O1). In addition, the distribution of dry matter in spike and crop growth rate (CGR) under planting density of 15,000 plant $\cdot$ hm^{-2} both improved after anthesis with the application of organic fertilizer. The effective panicles per plant, grain number per plant and 100-grain weight increased with the increased rate of organic fertilizer application, which effectively compensated for low spike number at lower planting density. In this study, the crop yield under medium density (15,000 plant $\cdot$ hm^{-2}) with 12,000 kg $\cdot$ hm^{-2} organic fertilizer (D2O1) was 3,943.77 kg $\cdot$ hm^{-2}, which was similar to that under high planting density (D1O1). It was concluded that suitable planting density in combination with the application of organic fertilizer effectively improved population growth and the reasonable distribution of dry matter, delayed leaf senescence, increased dry matter accumulation and grain yield at mature stage of caster.

Keywords: Castor; Organic fertilizer; Planting density; Population growth; Yield components

Introduction

Planting density is a fundamental factor affecting crop growth, development, and yield formation. Numerous studies have investigated the effects of density on castor (*Ricinus communis* L.) yield [1-5]. Within a certain range, castor plant height, leaf area index (LAI), and net photosynthetic assimilation rate increase with increasing density [2]. However, excessive density advances the peak LAI appearance time and reduces its duration, which is unfavorable for photosynthate assimilation and leads to decreased panicles per plant, 100-grain weight, and economic yield [3]. Rational close planting helps coordinate the contradiction between population and individual plants, enabling robust individual development without premature senescence while maintaining a certain population size, thereby achieving coordinated development of panicles per unit area and grain weight for high castor yield [4]. In the coastal shoal areas of Jiangsu Province, the typical castor planting density ranges from 12,000 to 16,000 plants $\cdot$ hm^{-2}. Further increasing density often leads to vigorous vegetative growth, poor ventilation and light penetration, insufficient net photosynthetic productivity [5], premature population senescence during the reproductive growth stage, conflicts between population and individual growth, and increased lodging risk [6-7]. Conversely, low density favors individual plant development but compromises population function, ultimately hindering yield formation [2,7]. Ensuring both population quantity and quality are two fundamental aspects that must be addressed in constructing high-yield castor populations, and they represent significant challenges.

Current approaches to ensuring population quantity and improving population quality in castor production mainly include topping and pruning, density adjustment, and water-fertilizer regulation [3,8]. While topping and pruning can artificially control branch numbers and fruit panicles to avoid excessive growth and promote dry matter transport to grains, the limitation on grain number risks reducing grain weight per unit area [8] and increases labor intensity in agricultural production, making large-scale promotion difficult. Adjusting planting density through row spacing configuration can only regulate ventilation and light conditions to a limited extent and cannot fundamentally solve the conflict between population and individual growth caused by vigorous vegetative growth in the early stage [3]. Fertilizer management is a crucial factor in constructing high-yield optimized populations [9-10], with previous research focusing primarily on the effects of mineral nutrients such as N, P, and K on castor growth and development [11-13]. However, in the coastal shoal areas of Jiangsu with poor soil fertility and concurrent rainfall and heat during the castor growth season, applying quick-release fertilizers to regulate population structure carries certain risks. It may cause excessive vegetative growth during the nutritional growth stage, poor population ventilation and light penetration, leading to lodging and delayed maturity [7,13]. Combining quick-release fertilizers with slow-release fertilizers is a more reliable approach for constructing optimized high-yield crop populations [14-16]. As a high-quality slow-release fertilizer, organic fertilizer has the characteristics of nutrient slow-release and long-lasting fertility effects. Its application can improve soil physical and chemical properties, increase soil organic matter content, enhance soil fertility, and improve crop yield [17-18]. Adjusting planting density and selecting appropriate fertilization strategies may be a simple, low-risk approach to achieving castor yield increase and stability.

Research on the interactive effects of planting density and fertilization on castor yield is scarce and mostly concentrated on the interaction between planting density and nitrogen fertilizer [2,5,19]. Density and nitrogen application rate exhibit complementary interactive effects within a certain range, regulating the leaf area coefficient and photosynthetic productivity of castor populations [3]. However, excessive nitrogen application causes excessive early growth [7] and low utilization efficiency due to ammonia volatilization losses, leading to atmospheric pollution, soil environmental degradation, water eutrophication, and decreased crop quality [20-21]. This study aims to improve soil fertility through increased organic fertilizer application and investigate the effects of organic fertilizer application under different densities on castor population leaf function, population structure, and yield components, with the goal of extending the functional duration of castor leaves, maintaining leaf area index and crop growth rate at high levels, enhancing castor population material production capacity, and ultimately obtaining an optimized castor population structure suitable for the coastal shoal areas of Jiangsu Province, providing theoretical and technical basis for high and stable castor yield.

Materials and Methods

1.1 Experimental Site Conditions

The experiment was conducted at the Jinhai Farm in Dafeng City, Jiangsu Province (32°59 30 -33°0 21 N, 120°49 40 -120°51 4 E), a typical reclaimed area in the coastal shoal region of northern Jiangsu. The experimental site is located approximately 4 km east of the Yellow Sea and west of the Dafeng Milu National Nature Reserve, reclaimed in 1999. The region belongs to the north subtropical monsoon climate zone, with an average annual precipitation of 1,058.4 mm, mainly concentrated in the rainy season from June to August, an average annual temperature of 13.5°C, and a frost-free period of 212.3 days. The soil is classified as alluvial saline soil, sub-classified as tidal saline soil, with the surface layer mostly moderately salinized and slightly alkaline (pH 8.4). The basic physicochemical properties of the soil before the experiment are shown in .

Table 1 Basic nutrient status of plough-layer soil of the tested field before the experiment

Soil layer	Total nitrogen ($g \cdot kg^{-1}$)	Available phosphorus ($mg \cdot kg^{-1}$)	Available potassium ($mg \cdot kg^{-1}$)	Organic matter ($g \cdot kg^{-1}$)	Electrical conductivity ($dS \cdot m^{-1}$)
15–30 cm					

1.2 Experimental Design

The experiment adopted a two-factor randomized block design with three planting density levels: high (18,000 plants $\cdot$ hm^{-2}, D1), medium (15,000 plants $\cdot$ hm^{-2}, D2), and low (12,000 plants $\cdot$ hm^{-2}, D3); and three organic fertilizer application rates: 12,000 $kg \cdot hm^{-2}$ (O1), 6,000 $kg \cdot hm^{-2}$ (O2), and 0 $kg \cdot hm^{-2}$ (O3). Nine treatment combinations were established with three replications each, totaling 27 plots with a plot area of 4 m $\times$ 6 m = 24 m^2. The tested castor variety was 'Zibi 8' , provided by Zibo Academy of Agricultural Sciences, Shandong Province.

The experiment was conducted as a continuous summer castor-winter fallow positioning planting trial from May 2013 to November 2015. Each year, nitrogen fertilizer (urea, N 46%) was applied at 150 $kg(N) \cdot hm^{-2}$, with 90 $kg \cdot hm^{-2}$ as base fertilizer and 60 $kg \cdot hm^{-2}$ applied during flowering and fruiting stages. Phosphorus (calcium superphosphate) and potassium (potassium sulfate) fertilizers were applied at 120 $kg(P_2O_5) \cdot hm^{-2}$ and 60 $kg(K_2O) \cdot hm^{-2}$, respectively, and incorporated once during the seedling stage. Organic fertilizer (decomposed chicken manure, with dry-base nutrient contents of N 33.5 $g \cdot kg^{-1}$, organic matter 327.6 $g \cdot kg^{-1}$, P_2O_5 22.56 $g \cdot kg^{-1}$, and K_2O 16.7 $g \cdot kg^{-1}$) was applied annually at the squaring stage in furrows 30 cm from the castor row roots. During the three-year experimental period, the total precipitation during the castor growing season (April–November) was 990.7 mm, 1,023.2 mm, and [data missing] mm, respectively. Herbicides were applied for weed control, and other field management measures were consistent across all treatments.

1.3 Measurement Items and Methods

1.3.1 Soil Nutrient Content Determination At the castor flowering stage, soil samples were collected from 0–30 cm depth at 30 cm from plant roots using a soil auger, with three sampling points per plot. Soil samples from the same layer were mixed and brought back to the laboratory for nutrient content determination.

1.3.2 Growth Indicators and Yield Component Determination Fixed plants were selected in each plot (6 plants per plot) for growth stage and yield indicator surveys. Leaf area index (LAI) and functional leaf chlorophyll content (SPAD) were measured at the seedling, squaring, flowering, flowering-fruiting, and grain-filling maturity stages. Chlorophyll content was measured using a handheld SPAD-502 chlorophyll meter (Minolta, Japan) on the third functional leaf below the growth point, with 10 measurement points per leaf and 6 plants per plot, and the average SPAD value was calculated.

At maturity, grain yield was measured through actual harvest, with panicle length, panicle number, and grain number at each level recorded. After grain air-drying, 100-grain weight was determined, theoretical yield calculated, and actual yield measured per plot.

At each growth stage, three representative plants were selected per plot and separated into leaves, stems, and panicles. Samples were killed at 105°C, dried at 75°C, and dry weight was measured.

1.4 Data Processing and Analysis Methods

Leaf area = length × width × k (1)
where k is the castor leaf area correction coefficient, with k = 1.65 for expanded leaves [16].

Leaf area index = green leaf area / land area (2)

The experiment used 2015 data for statistical analysis, with sowing and yield statistics collected from April 27 to November 10, 2015, and grain yield measured through actual harvest.

Harvest index (HI) = yield / aboveground total dry weight (3)

Crop growth rate (CGR, $kg \cdot kg^{-1} \cdot d^{-1}$) = ($W_2$ - W_1) / A × (t_2 - t_1) (4)
where W_2 and W_1 are the dry weights measured at times t_2 and t_1, respectively, and A is the land area.

All data except for the 2013 pre-experiment soil nutrient status were from 2015 surveys. Microsoft Excel 2010 was used for data entry and calculations, and SPSS 20.0 was used for two-factor randomized block design analysis of variance and multiple comparisons ($LSD_{0\cdot05}$).

Results

2.1 Effects of Organic Fertilizer on Soil Nutrient Status Under Different Planting Densities

Variance analysis results (Table 2) showed that long-term organic fertilizer application significantly improved soil nutrient status. In the third experimental year, soil total nitrogen, available phosphorus, available potassium, and organic matter contents at the flowering stage under different planting densities all increased substantially compared with the no-organic-fertilizer treatment, while soil electrical conductivity and pH showed decreasing trends. For example, under medium density with high organic fertilizer treatment (D2O1), soil total nitrogen, available phosphorus, available potassium, and organic matter contents increased by 47.37%, 169.21%, 54.65%, and 13.77%, respectively, compared with the medium density no-fertilizer treatment (D2O3), reaching significant levels ($P < 0.05$). Under the same organic fertilizer treatment, soil total nitrogen, available phosphorus, and available potassium showed increasing trends with decreasing planting density. The high-density no-organic-fertilizer treatment (D1O3) had the lowest nutrient contents and relatively high electrical conductivity and pH values. These results indicate that organic fertilizer application facilitates neutralization of alkaline substances and reduction of water-soluble salt content in saline soils, alleviating soil salinization inhibition on crop growth while increasing soil nutrient content to varying degrees, thereby improving soil fertility and promoting crop growth and development.

Table 2 Effects of different planting densities and organic fertilization rates on soil chemical properties at flowering stage of castor in the third year of experiment

[Table content with D1O1, D1O2, D1O3, D2O1, D2O2, D2O3, D3O1, D3O2, D3O3 treatments and ANOVA results]

2.2 Effects of Organic Fertilizer Application on Leaf Area Index of Castor Population Under Different Planting Densities

Table 3 shows that at early growth stages (seedling to flowering), LAI increased with planting density under constant fertilization rates, though this trend decreased from the flowering stage compared with earlier stages, with all treatments reaching maximum LAI at the flowering-fruiting stage. At late growth stages (grain-filling maturity), LAI began to decline, with more gradual decreases under medium and low densities and more rapid declines under high density. At this stage, LAI under medium and low densities was significantly higher than under high density at the same organic fertilizer application rate ($P < 0.05$). Within the same density, organic fertilizer application showed no significant effect on LAI at the seedling and squaring stages, but its effects became evident from the flowering stage onward, significantly increasing LAI across all treatments. Under 12,000 $kg \cdot hm^{-2}$ organic fertilizer application, medium density treatment (D2O1) achieved LAI levels comparable to high density at both flowering and flowering-fruiting stages. At grain-filling maturity, LAI declined compared with the flowering-fruiting stage across all treatments, but organic fertilizer application significantly alleviated this decline. For example, under 6,000 $kg \cdot hm^{-2}$ organic fertilizer application, LAI increased by 17.65%, 9.69%, and 20.71% compared with no organic fertilizer treatment under high, medium, and low densities, respectively, reaching significant levels. Variance analysis showed that the interaction between planting density and organic fertilizer significantly affected LAI at the grain-filling maturity stage ($P < 0.05$), indicating that organic fertilizer application can maintain high photosynthetic productivity by delaying leaf senescence during late growth stages.

Table 3 Effects of different planting densities and organic fertilization rates on leaf area index at different growth stages of castor in the third year of the experiment

[Table content with seedling, squaring, flowering, flowering-fruiting, and grain-filling stages]

2.3 Effects of Organic Fertilizer Application on Chlorophyll Content of Functional Leaves at Different Growth Stages

Table 4 shows that SPAD values of the third functional leaf below the growth point showed no significant differences among treatments at the seedling and squaring stages. Under low density, the 6,000 $kg \cdot hm^{-2}$ organic fertilizer treatment (D3O2) maintained relatively high SPAD values across all growth stages, with increases of 20.07% and 11.44% at flowering and flowering-fruiting stages, respectively, compared with the no-fertilizer control, indicating that organic fertilizer application under low density conditions favors chlorophyll content improvement in functional leaves, laying a foundation for high yield. At grain-filling maturity, the high-density no-organic-fertilizer treatment (D1O3) showed rapid SPAD value decline, significantly lower than other treatments, demonstrating that high density is unfavorable for advantageous leaf growth during the grain-filling period. During this period, the 12,000 $kg \cdot hm^{-2}$ organic fertilizer treatment (D1O1) increased functional leaf SPAD values by 11.23% compared with the no-fertilizer treatment (D1O3) ($P < 0.05$), indicating that organic fertilizer application helps delay leaf senescence, positively affecting dry matter accumulation and grain filling during late growth stages and improving grain yield.

2.4 Effects of Organic Fertilizer Application on Crop Growth Rate of Castor Population at Different Growth Stages

Variance analysis results (Table 5) showed that organic fertilizer application had no significant effect on crop growth rate (CGR) at the seedling and squaring stages across densities, with CGR primarily affected by density and showing an increasing trend with density. At the squaring stage under 6,000 $kg \cdot hm^{-2}$ organic fertilizer, CGR increased by 28.87% and 78.06% in D1 compared with D2 and D3, respectively, reaching significant differences ($P < 0.05$). CGR reached its maximum during the flowering stage, with organic fertilizer effects becoming evident as application significantly promoted CGR across density treatments. For example, under medium density D2, CGR increased by 33.17% and 31.97% with 12,000 $kg \cdot hm^{-2}$ (D2O1) and 6,000 $kg \cdot hm^{-2}$ (D2O2) organic fertilizer applications, respectively, compared with the no-fertilizer treatment (D2O3), reaching significant levels ($P < 0.05$). At flowering, medium density (D2O2) CGR was significantly higher than high density (D1O2) under 6,000 $kg \cdot hm^{-2}$ organic fertilizer ($P < 0.05$), indicating that organic fertilizer application better promotes CGR under medium density. CGR decreased significantly from flowering to flowering-fruiting stage, with organic fertilizer promoting CGR across density treatments. Under high-concentration 12,000 $kg \cdot hm^{-2}$ organic fertilizer, medium density (D2O1) CGR reached levels comparable to high density (D1O1). At grain-filling maturity, organic fertilizer significantly increased CGR under medium and low densities but had no significant effect under high density. Under the same organic fertilizer treatment, medium density (15,000 $plants \cdot hm^{-2}$) CGR exceeded high density (18,000 $plants \cdot hm^{-2}$) at grain-filling maturity, indicating that organic fertilizer application substantially promotes dry matter accumulation during late growth stages under medium and low densities.

Table 5 Effects of different planting densities and organic fertilization rates on crop growth rate at different growth stages of castor

[Table content with seedling, squaring, flowering, flowering-fruiting, and grain-filling stages]

2.5 Effects of Organic Fertilizer Application on Spike Traits and Yield Components Under Different Planting Densities

Table 6 shows that main spike and primary branch spike length and grain number per spike generally decreased with increasing planting density. Compared with medium and low density treatments (D2O3, D3O3), the high-density no-organic-fertilizer treatment (D1O3) decreased main spike and primary branch spike length and grain number by 14.28% and 19.48%, and 17.34% and 28.83%, respectively, reaching extremely significant levels. Planting density had no significant effect on secondary branch spike length and grain number. Organic fertilizer application under high density showed no significant effect on spike traits, while under low density, the 12,000 $kg \cdot hm^{-2}$ organic fertilizer treatment (D3O1) significantly increased main spike, primary branch, and secondary branch spike length and grain number compared with the no-fertilizer treatment, indicating that organic fertilizer application under certain planting densities favors advantageous spike development in individual plants, laying a foundation for improved population grain yield.

Comparing yield components among treatments (Table 7), effective spike number per plant, grain number per plant, 100-kernel weight, and yield per plant decreased with increasing planting density at the same organic fertilizer application rate. Organic fertilizer application significantly increased effective spike number and grain number per plant under medium and low densities but had no significant effect on these parameters under high density ($P < 0.05$). Organic fertilizer application significantly increased 100-kernel weight and yield per plant across all three density treatments, with the low-density high-organic-fertilizer treatment (D3O1) achieving the highest 100-kernel weight (33.71 g) and yield per plant ($312.06\ g \cdot plant^{-1}$), indicating that increased organic fertilizer application favors advantageous development of individual castor plants. Harvest index showed an increasing trend with organic fertilizer application under medium density, with the medium density 15,000 plants $\cdot\ hm^{-2}$ plus 12,000 $kg \cdot hm^{-2}$ organic fertilizer treatment (D2O1) increasing harvest index by 13.77% compared with the no-fertilizer control (D2O3), reaching significant difference ($P < 0.05$), indicating that organic fertilizer application within a certain density range facilitates transfer of photosynthate products to grains.

Table 6 Effects of different planting densities and organic fertilization rates on spike characters of castor in the third year of the experiment

[Table content with main spike, primary branch spike, and secondary branch spike measurements]

Table 7 Effects of different planting densities and organic fertilization rates on yield components of castor in the third year of the experiment

[Table content with effective spike number, grain number, 100-kernel weight, yield per plant, and harvest index]

2.6 Effects of Organic Fertilizer Application on Aboveground Dry Matter Accumulation and Distribution Under Different Planting Densities

Figure 1 [Figure 1: see original paper] shows that organic fertilizer application significantly increased aboveground dry matter accumulation across density treatments, with accumulation increasing as organic fertilizer application rate increased. The medium density 15,000 plants $\cdot\ hm^{-2}$ with 12,000 $kg \cdot hm^{-2}$ (D2O1) and 6,000 $kg \cdot hm^{-2}$ (D2O2) organic fertilizer treatments showed no significant difference in aboveground dry matter accumulation compared with high density 18,000 plants $\cdot\ hm^{-2}$ with the same organic fertilizer rates, indicating that organic fertilizer application better promotes individual plant development under medium and low densities, thereby compensating for field dry matter loss due to reduced density.

Variance analysis results (Table 8) showed that the interaction between organic fertilizer and density had no significant effect on dry matter distribution ratio among organs at flowering, indicating that dry matter distribution at this stage was not affected by density or organic matter. At maturity, stem dry matter distribution ratio tended to increase with planting density. For example, under 6,000 $kg \cdot hm^{-2}$ organic fertilizer, stem dry matter proportion in high density 18,000 plants · hm^{-2} (D1O2) increased by 9.3% and 11.46% compared with medium (D2O2) and low (D3O2) densities, respectively, reaching significant differences ($P < 0.05$). Organic fertilizer application under medium and low densities significantly increased leaf dry matter distribution ratio. For instance, the medium density 12,000 kg · hm^{-2} high-organic-fertilizer treatment (D2O1) increased leaf dry matter distribution index by 10.01% compared with the no-fertilizer treatment (D2O3), reaching significant difference ($P < 0.05$). Stem dry matter distribution ratio at maturity decreased compared with the flowering stage, with organic fertilizer application reducing stem dry matter distribution ratio across density treatments. Organic fertilizer application significantly increased dry matter distribution ratio in panicles under medium density at maturity, with the medium density 6,000 kg · hm^{-2} organic fertilizer treatment (D2O2) increasing dry matter distribution ratio by 23.73% compared with the no-fertilizer treatment (D2O3), reaching significant difference ($P < 0.05$). These results indicate that organic fertilizer application facilitates transfer and distribution of dry matter from vegetative organs to reproductive organs.

Figure 1 Effects of different planting densities and organic fertilization rates on aboveground dry matter of castor in the third year of the experiment

[Figure description: D1, D2 and D3 represent planting densities of 18,000, 15,000 and 12,000 plants · hm^{-2}; O1, O2 and O3 represent organic fertilizer rates of 12,000, 6,000 and 0 kg · hm^{-2}. Different lowercase letters indicate significant differences at 5% level.]

Table 8 Effects of different planting densities and organic fertilization rates on dry weight ratio of different organs at flowering and maturity stages of castor

[Table content with leaf, stem, and spike dry matter ratios]

Discussion and Conclusion

Planting density and fertilization amount are the most important basic cultivation factors in crop growth, development, and yield formation. Previous studies have extensively investigated the effects of planting density or fertilization amount on castor growth and yield [1-5], but most focused on the effects of quick-release fertilizers [8-11,22], with few reports on the effects of organic fertilizer application under different planting densities on castor growth and development. This study found that without organic fertilizer application, castor population grain yield tended to increase with planting density, but excessively high density was unfavorable for individual plant development, with effective spike number, grain number, 100-kernel weight, and yield per plant decreasing as density increased, adversely affecting population grain yield improvement. Organic fertilizer application significantly increased 100-kernel weight and yield per plant across density treatments, thereby improving castor grain yield. Organic fertilizer application showed good promotion effects on effective spike number and grain number per plant under medium and low densities but no significant effect under high density, enabling the medium density 15,000 plants · hm^{-2} with 12,000 kg · hm^{-2} organic fertilizer treatment to achieve grain yield comparable to high density 18,000 plants · hm^{-2}. This indicates that organic fertilizer application has a certain "density effect" on castor population grain yield improvement, with optimal organic fertilizer effects achieved only under suitable planting densities. Ma et al. [3] suggested that the main reason for castor yield inhibition under high planting density is excessive nutrient accumulation in the main spike and primary branches, preventing other branch panicles from maturing and increasing empty grain rate. This study found that 12,000 kg · hm^{-2} organic fertilizer application significantly increased effective grain number in main spike, primary, and secondary branches, indicating that appropriate organic fertilizer application can improve castor seed setting rate and reduce empty grain rate, thereby increasing individual plant grain yield.

Applying bio-organic fertilizer can promote plant growth and improve crop yield by increasing soil nutrients [14-16,23]. Lü et al. [18] found that organic fertilizer application effectively regulated castor seedling physiology and ecology under certain salt stress levels, facilitating robust seedling cultivation in saline-alkali soils. This study found that three consecutive years of decomposed chicken manure application improved physicochemical properties of coastal shoal soil, with soil total nitrogen, available phosphorus, available potassium, and organic matter contents increasing to varying degrees with fertilizer application, while soil pH and electrical conductivity decreased. This indicates that long-term decomposed chicken manure application facilitates neutralization of alkaline substances and reduction of water-soluble salt content in saline soils, alleviating salinization inhibition on castor growth while increasing soil nutrient content and improving soil fertility, laying a nutrient foundation for castor grain yield improvement. Variance analysis results showed that the soil improvement effect of organic fertilizer on coastal saline soil correlated with castor planting density, with overall better soil nutrient status under medium and low densities than under high density. From the perspective of soil improvement and fertility enhancement, castor planting density in coastal areas should not be excessive.

Crop leaf area index (LAI) and relative chlorophyll content (SPAD) are important indicators for measuring population size and leaf photosynthetic capacity, with their magnitude evaluating population photosynthetic productivity. The prerequisite for high castor yield is ensuring adequate photosynthetic source leaf area and leaf photosynthetic productivity [2]. This study showed that excessive density was unfavorable for improving LAI and leaf photosynthetic productivity during the flowering-fruiting stage, while organic fertilizer application significantly increased LAI across density treatments. Specifically, medium density with 12,000 kg · hm^{-2} organic fertilizer (D2O1) achieved LAI levels comparable to high density (D1O1), indicating that increased organic fertilizer application under lower density conditions promoted rapid LAI growth during late growth stages. At grain-filling maturity, LAI and functional leaf SPAD values began to decline to varying degrees across treatments, with slower declines under medium and low densities compared with high density. This demonstrates that organic fertilizer application can delay leaf senescence in medium and low density castor populations, maintaining relatively high photosynthetic and material production efficiency during grain-filling maturity, facilitating population dry matter accumulation and grain filling during late growth stages and laying a foundation for grain yield improvement.

Population dry matter accumulation and rational distribution are the foundation for castor yield formation [3]. Increasing planting density can improve castor population dry matter accumulation to a certain extent, but excessive density is unfavorable for individual plant dry matter accumulation, with the contradiction between these factors restricting population dry matter accumulation increase. This study found that increasing population density improved aboveground castor CGR and dry matter accumulation during early growth stages, but high density treatment was unfavorable for population dry matter accumulation after flowering, easily causing CGR decline. This may be because excessive density caused vigorous vegetative growth in early stages, creating conflicts between population and individual growth and reducing photosynthetic and material production capacity during grain-filling maturity. Organic fertilizer application effectively promoted CGR and dry matter accumulation during grain-filling maturity under medium and low densities, with no significant difference in mature-stage dry matter accumulation between high and medium density treatments under 12,000 $kg \cdot hm^{-2}$ organic fertilizer, indicating that organic fertilizer application under medium density enabled castor populations to maintain relatively high photosynthetic and material production capacity during late growth stages, delaying population senescence and maintaining CGR at levels comparable to high density. This achieved maintenance of population dry matter accumulation despite reduced planting density, creating material conditions for improved castor grain filling and high stable yield. This is consistent with Ren et al. [24] in maize, indicating that increased organic fertilizer application can also avoid early-stage excessive growth and late-stage premature senescence through "early suppression and late promotion" of medium and low density population material growth, thereby achieving yield increase.

Post-anthesis dry matter accumulation and redistribution are important factors affecting crop grain yield. Grain filling materials can be divided into two parts based on timing: (1) photosynthates temporarily stored in vegetative organs produced before flowering and transferred to reproductive organs during grain filling; and (2) photosynthates accumulated during grain filling after flowering [25]. This study showed that organic fertilizer application increased dry matter accumulation proportion in leaves during flowering under high density, possibly because organic fertilizer improved leaf LAI, giving leaves strong photosynthetic production capacity while reproductive organs were just beginning to form with low dry matter transfer efficiency, so leaf photosynthates were temporarily stored in leaves. At maturity, organic fertilizer application increased dry matter distribution proportions in leaves and panicles under medium density, while significantly decreasing stem dry matter accumulation proportion. This may be because increased organic fertilizer improved leaf LAI and SPAD content under medium density, enabling leaves to maintain strong photosynthetic production capacity during late growth stages. The decreased stem dry matter proportion indicates that organic fertilizer application promoted dry matter transfer from vegetative organs to reproductive organs, laying a material foundation for castor grain yield improvement.

Overall, long-term organic fertilizer application promoted both soil fertility improvement and castor grain yield increase in coastal shoal areas. Under medium density planting conditions, organic fertilizer effects were maximized by increasing soil nutrients and delaying leaf senescence in medium density castor populations during late growth stages, enabling populations to maintain relatively high photosynthetic and material production capacity during late growth stages and facilitating transfer and accumulation of population dry matter production to reproductive organs during late stages. This ultimately improved mature-stage biomass, grain number per plant, and 100-kernel weight under medium density, achieving grain yield comparable to high density while avoiding risks of population deterioration and lodging associated with high density. Considering all factors, under this study' s conditions, the treatment with 12,000 $kg \cdot hm^{-2}$ organic fertilizer application and medium density of 15,000 $plants \cdot hm^{-2}$ showed ideal population indicators and achieved the highest yield of 3,943.77 $kg \cdot hm^{-2}$ across all treatments.

References

[1] Jiang X J. Effect of different planting density on growth and yield of castor[J]. Journal of Modern Agricultural Science and Technology, 2007, (11): 8-13
[2] Tian F D, Li J Q, Zhang C H, et al. Influence of density and fertilizer on the photosynthesis characters and output of castor bean[J]. Journal of Jilin Agricultural Science, 2000, 25(1): 29-31
[3] Ma D F, Zhang C H, Bao H X, et al. Influence of different planting density on growth development of canopy dynamics in castor[J]. Chinese Journal of Oil Crop Sciences, 1998, 20(1): 57-59
[4] Zhang Y P, Chen M, Chen X G, et al. Effects of different planting density on growth and development and yield of castor beans (Ricinus communis L.)[J]. Journal of Anhui Agricultural Science, 2012, 40(19): 10043-10045
[5] Zhou G S, Dong W W, Xia Y R, et al. Effects of density and nitrogen application amount on yield and nutrient absorption of castor plant grown in saline soil along coastal mudflat[J]. Chinese Journal of Oil Crop Sciences, 2011, 33(3): 270-274
[6] Zhou G S, Ma B L, Li J, et al. Determining salinity threshold level for castor bean emergence and stand establishment[J]. Crop Science, 2010, 50(5): 2030-2036
[7] Zhou G S, Li J, Tong C, et al. Growth characteristics and above-ground dry matter accumulation of castor plant grown on medium saline soil[J]. Journal of Yangzhou University: Agricultural and Life Science Edition, 2011, 32(1): 30-34
[8] Wu B B. The effects of phosphorus and ear numbers on agronomic and yields

traits of castor[D]. Changchun: Jilin Agricultural University, 2015
[9] Zhou G S, Wan S W, Dong W W, et al. Impact of nitrogen application amount on dry matter accumulation, yield and yield components in castor-oil plant[J]. Chinese Journal of Oil Crop Sciences, 2009, 31(1): 39-43
[10] Liu C, Hong L Z, Wang M W, et al. Effect of fertilizing N and P on the growth and yield of castor in the coastal area of north Jiangsu Province[J]. Hubei Agricultural Sciences, 2011, 50(8): 1534-1537
[11] Ahmed S R, Khadke K M, Reddy K C, et al. Soil test based optimal fertilizer requirements for attaining different yield targets of castor (Ricinus communis) in dryland alfisols[J]. Indian Journal of Agricultural Sciences, 2001, 71(1): 27-30
[12] Reddy K R, Matcha S K. Quantifying nitrogen effects on castor bean (Ricinus communis L.) development, growth, and photosynthesis[J]. Industrial Crops and Products, 2010, 31(1): 185-191
[13] Wang Q Q, Tian C Y, Zhao Z Y, et al. Effects of nitrogen levels on yield and biological and nutritional characters of castor[J]. Agricultural Research in the Arid Areas, 2014, 32(3): 150-154
[14] Wang L G, Li W J, Qiu J J, et al. Effect of biological organic fertilizer on crop growth, soil fertility and yield[J]. Soil and Fertilizer, 2004, (5): 12-16
[15] Tian C, Peng J W, Song H X, et al. Effects of organic manure application combined with chemical fertilizers on absorption of nutrient, yield and quality of rapeseed[J]. Soil and Fertilizer Science in China, 2012, (4): 70-74
[16] Wang Y B. Effect of application of organic-inorganic mixed fertilizers on growth of crops and soil nitrogen supply[D]. Nanjing: Nanjing Agricultural University, 2007: 1-54
[17] Geng Z M. Use bio-organic fertilizer on saline soil improvement effect and corn yield[D]. Harbin: Northeast Agricultural University, 2013: 55-60
[18] Lü L Y, Wu Y P, Sun Z J, et al. Effect of organic fertilizer on growth of castor bean seedling under saline sodic soil[J]. Journal of China Agricultural University, 2013, 18(3): 73-80
[19] Zhang X S, Yang J G, Xu N S. Effect of plant density, fertilizer and the number of effective spikes per plant on yield of castor (Ricinum comununis L.)[J]. Chinese Journal of Oil Crop Sciences, 2006, 28(4): 487-491
[20] Lin D X, Fan X H, Hu F, et al. Ammonia volatilization and nitrogen utilization efficiency in response to urea application in rice fields of the Taihu lake region, China[J]. Pedosphere, 2007, 17(5): 639-645
[21] Wang C L, Han G Q, Xu W H, et al. Characteristics of soil ammonia volatilization and the absorption and utilization of nitrogen, phosphorus and potassium of pepper under slow-release fertilizer application[J]. Chinese Journal of Eco-Agriculture, 2014, 22(2): 143-150
[22] Zhou G S, Zhang Z D, Lu S Y, et al. Effect of nitrogen and phosphorus on growth characteristics and yield of castor in medium saline soil[J]. Agricultural Research in the Arid Areas, 2014, 32(6): 100-105
[23] Sun R L, Zhu L S, Zhao B Q, et al. Effects of long-term fertilization on soil microorganism and its role in adjusting and controlling soil fertility[J]. Chinese Journal of Applied Ecology, 2004, 15(10): 1907-1910

[24] Ren W, Zhao X, Huang S B, et al. Effects of application of organic fertilizer under different planting densities on dry matter production and yield formation of summer maize[J]. Chinese Journal of Eco-Agriculture, 2014, 22(10): 1146-1155

[25] Jiang L N, Liu P, Qi B Y, et al. Effects of different nitrogen application amounts and seedling densities on nitrogen accumulation and transport in winter wheat at anthesis stage[J]. Chinese Journal of Eco-Agricultural, 2016, 24(2): 131-141

Note: Figure translations are in progress. See original paper for figures.