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High-Density Planting with Narrow Row Spacing Enhances Yield and Oil Content of Winter Rapeseed in Southwest China's Ecologically Fragile Areas

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ABSTRACT

The impact of plant density (15×10^4, 30×10^4, 45×10^4, and 60×10^4 plants ha^{-1}) and row spacing (20, 30 and 40 cm) on the growth and yield of winter rapeseed (*Brassica napus* L.) cultivars was examined in field experiments conducted during the 2020-21 and 2021-22 growing seasons in Wawu county, Bijiang District, Tongren City, Guizhou province, Southwestern China. The findings revealed high-density planting and narrow row spacing resulted in a higher leaf area index. With the rise in plant density and the reduction in row spacing, the count of effective branches and pods per branch decreased. Moreover, oil content exhibited an increase with escalating plant density and narrowing row spacing for winter rapeseed. The highest seed yields of 3499 kg ha^{-1} and 3410 kg ha^{-1} were observed for plant densities of 60×10^4 plants ha^{-1} and 45×10^4 plants ha^{-1}, respectively, with the row spacing of 20 cm in Southwest China. This planting mode not only supports the mechanized planting and widespread adoption of winter rapeseed in the region but also contributes positively to the sustainable utilization of farmland in ecologically fragile areas within China and globally.

Keywords: plant density, row spacing, winter rapeseed, yield, oil content.

INTRODUCTION

The cultivation of winter rapeseed (*Brassica napus* L.) has witnessed a substantial expansion in various regions of China, attributed to its rising significance as a source of edible oil and residual meal for livestock (Zhang et al., 2012). While mechanized direct-sown is a prevalent cultivation method for winter rapeseed in Europe, the transplanting of seedlings remains a widely practiced crop establishment technique in numerous arable areas of Southwest China (Wang et al., 2015). The labor-intensive practice of transplanting crop seedlings into fields has become costlier with the sharp increase in labor wages in recent decades (Fu et al., 2016). Therefore, the traditional method of transplanting rapeseed seedlings is being gradually supplanted by the mechanized direct-sown approach in cropping regions of Southwest China (Wang et al., 2015). Nevertheless, a decline in yield and instability has been noted in the transition to mechanized direct-sown of rapeseed, primarily due to the incomplete integration of supporting cultivation techniques (Zhang et al., 2012). It is essential to optimize the intricately linked precise cultivation technology system for mechanized direct-seeded rapeseed. Seed yield is significantly influenced by factors such as planting density, seeding date, fertilizer level and other agronomic practices (Menendez et al., 2021). Therefore, adjusting plant density and row spacing are likely critical strategies to stabilize yields during the transition to mechanically direct-sown of rapeseed in Southwest China.

In China, a typical plant density ranged from 10 to 14 plants m^{-2} during the seedling transplanting process (Wang et al., 2015). Given that high seed yields can be attained at a relatively low plant density, it becomes evident that any elevation in plant density beyond this range only serves to escalate production costs, even in the transition to

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direct-seeded rapeseed (Fu et al., 2016). Moreover, an increase in plant density may trigger competitive shading within the leaf canopy structure of rapeseed plants, thereby hindering the interception of sunlight by the middle and lower stem leaves, particularly during the flowering stage (Kamal et al., 2022). This shading effect can result in reduced photosynthesis and net assimilation rates of individual plants (Liu et al., 2024). However, low plant densities may not facilitate reaching the yield plateau as there is less dry matter accumulation per unit area (Fu et al., 2016). Therefore, in mechanized direct-seeded rapeseed cropping systems, it is crucial to investigate and optimize planting density to achieve appropriate growth dynamics that align with sustaining and potentially enhancing yields (Zhang et al., 2012; Chen et al., 2023).

The adoption of wide row spacing for sowing rapeseed is increasingly favored due to the cost implications associated with labor and seed input, leading to a reduction in crop stands per unit area (Zhang et al., 2020). However, a diminishing trend in seed yield was observed with the widening of row spacing in winter rapeseed plantation. Leach et al. (1999) documented a gradual decline in growth and yield parameters, such as plant height, number of effective branches, seed number per pod, and total seed yield, with a row spacing of 40 cm. Adjusting row spacing can alter the crop canopy structure and light energy utilization, subsequently impacting the accumulation and distribution of carbohydrates among various plant organs and ultimately influencing seed yield in rapeseed (Leach et al., 1999). Compared with wide row spacing, rapeseed cultivated in narrow row spacing tends to yield more and experience relatively favorable growing conditions (Momoh and Zhou, 2001; Liu et al., 2023). Studies have shown that in China, the seed yield of rapeseed increases as row spacing decreases from 30 to 15 cm (Menendez et al., 2021). However, contrasting results were observed in Europe, where rapeseed grown at 12 cm yielded less than those at 24 cm (Leach et al., 1999). These discrepancies highlight the need for further investigation into the response of varied row spacing configurations for mechanized direct-seeded rapeseed in Southwest China.

The transition from a transplanting system to mechanically direct-seeded rapeseed necessitates a reassessment of the appropriate plant density and row spacing within this altered planting framework in Southwest China. Furthermore, limited information is available on the plant growth dynamics of rapeseed at individual and population levels, particularly concerning leaf growth traits. Therefore, the objective of this study was to investigate the responses of leaf growth and yield to different plant densities and row spacings in mechanized direct-seeded rapeseed in Southwest China.

MATERIAL AND METHODS

Experimental site and design

Field trials were carried out over two consecutive growing seasons in Wawu county, Bijiang District, Tongren City, Guizhou, Southwestern China (109°13E, 27°47N, and 470 m above sea level). The cultivation took place on red-loam soil with the following characteristics: 3.05% organic matter, 0.11% total nitrogen, 11.76 mg kg^{-1} soil available phosphorus and 94.61 mg kg^{-1} soil available potassium. A split-plot experiment was conducted with three replications in the two seasons. The research utilized Huayouza no. 9, a prominent rapeseed cultivar extensively cultivated in the local arable areas and other cropping regions of China. Seeds were sown on October 5, 2020, for the 2020-21 season and on October 1, 2021, for the 2021-22 season. Four plant densities were implemented: 15×10^4, 30×10^4, 45×10^4, and 60×10^4 plants ha^{-1}. Each plant density was combined with three row spacing: 20, 30 and 40 cm. The final thinning of rapeseed seedling was conducted at 5th leaf stage according the designed plant densities.

Morphological characteristics were assessed at different growth stages, including seedling, rosette, floral bud formation, flowering, pod formation and harvest, with plant samples collected from the central rows of each plot (Hu et al., 2017). Morphological and physiological measurements were conducted and recorded in both field and laboratory settings. The oil content of various samples was determined using near infrared reflectance spectroscopy (NIRS, Foss NIR System Inc., USA) following standard protocols (Zhang et al., 2012). Other field management practices adhered to the conventional methods employed by local farmers throughout the growing season.

Data analysis

An independent ANOVA was conducted to evaluate the primary effects of plant densities, row spacing, and their interactions on crop plant growth, yield, and yield components for each growing season. Subsequent multiple comparisons were conducted to assess significant effects utilizing the least significant difference test at a significance level of $P \leq 0.05$, employing SPSS Statistics version 25.0 (SPSS, Armonk, NY, USA). Graphical representations were constructed using SigmaPlot 10.0 (Systat Software Inc., USA).

RESULTS AND DISCUSSION

Growth and development

Across the three developmental stages (rosette, floral bud formation, and pod formation) of winter rapeseed, average increases of 3% and 16%, respectively, were noted in the largest-leaf length and width when row spacing was reduced by 10 cm from 40 to 30 cm. Further enhancements of 16% and 11%, respectively, were observed when the row spacing was narrowed from 30 to 20 cm (Figure 1). Planting densities were determined at 15×10^4, 30×10^4, 45×10^4, and 60×10^4 plants ha^{-1} at 5th leaf stage. In contrast, decreases of 7 and 5%, respectively, were observed in largest-leaf width and length when planting density was increased from 15×10^4 to 30×10^4 plants ha^{-1}. Similarly, decreases of 3 and 7%, respectively, were noted when transitioning from 30×10^4 to 45×10^4 plants ha^{-1}, and further decreases of 6 and 3%, respectively, were observed when progressing from 45×10^4 to 60×10^4 plants ha^{-1} averagely across the stages (Figure 1).

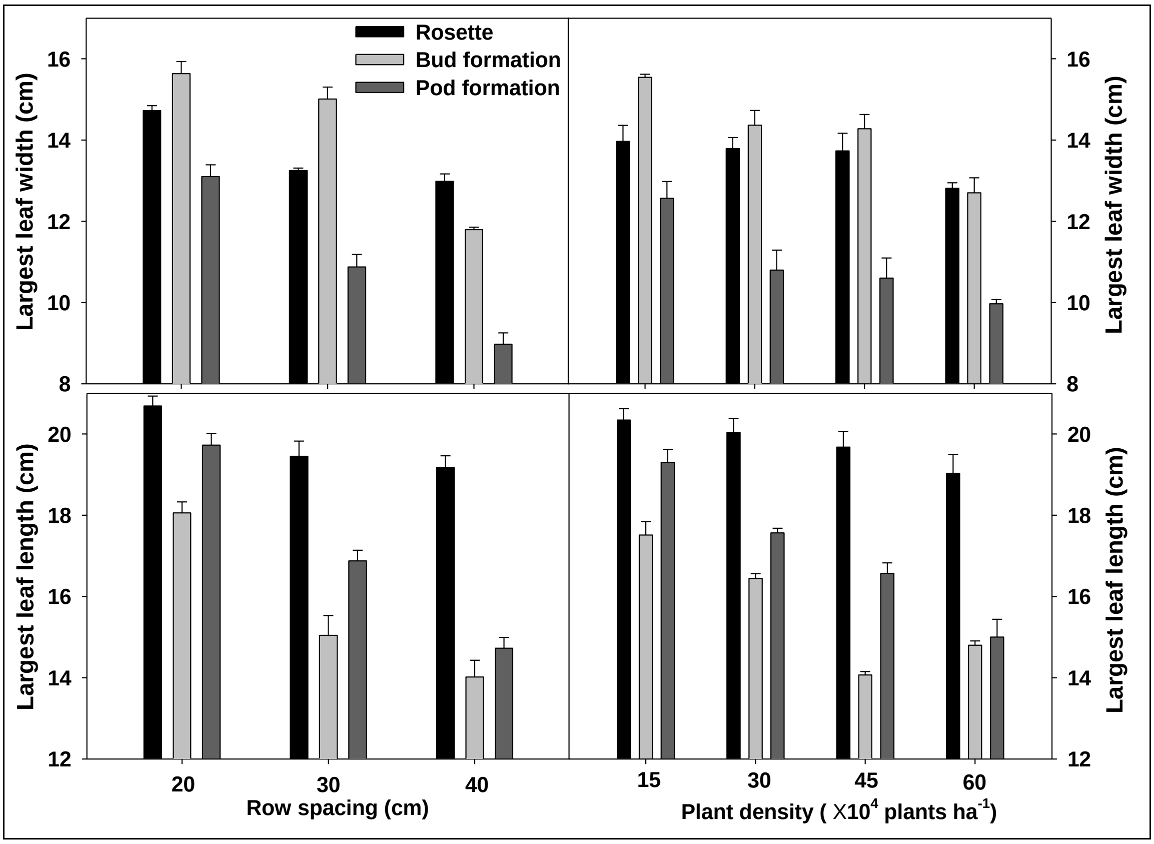

Figure 1. Effects of plant density and row spacing on the largest-leaf width and largest-leaf length of plant for winter rapeseed at different stages (Rosette, Floral bud formation, Pod formation)

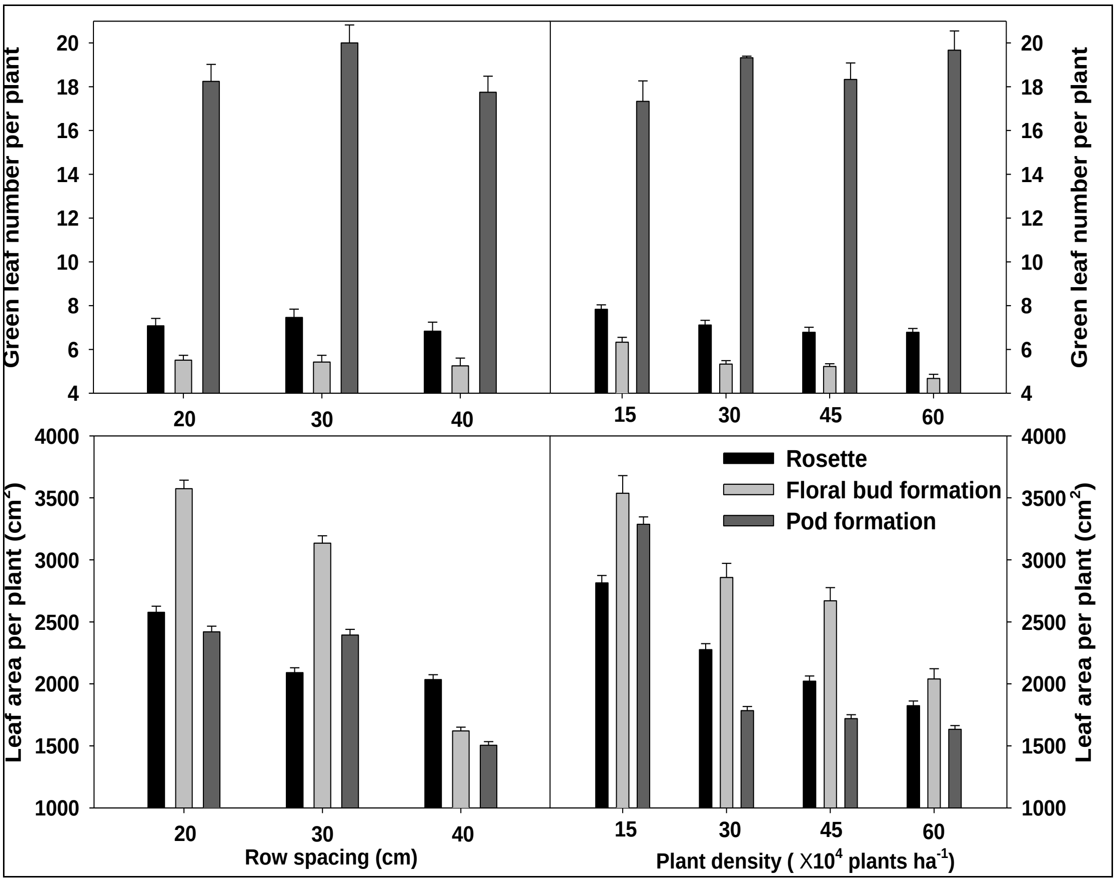

Figure 2. Effects of plant density and row spacing on the number of green leaves and leaf area per plant for winter rapeseed at different developmental stages (Rosette, Floral bud formation, Pod formation)

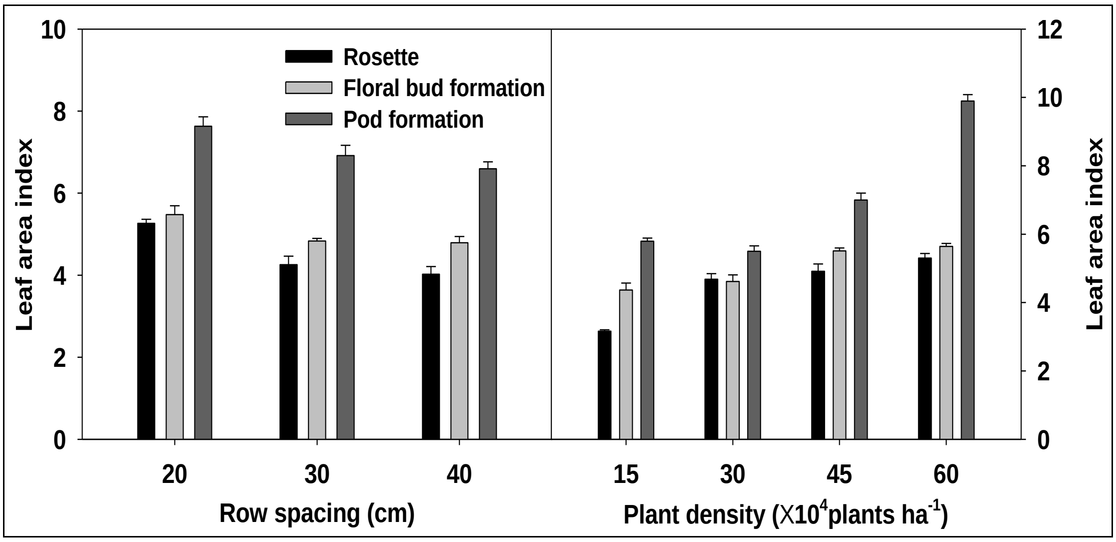

Figure 3. Effect of plant density (15, 30, 45 and 60×10^4 plants ha^{-1}, respectively) and row spacing (20, 30 and 40 cm between rows, respectively) on leaf area index at different developmental stages (Rosette, Floral bud formation, Pod formation) for winter rapeseed

The number of green leaves exhibited a gradual decline with rising planting density (Figure 2), although no significant differences were observed during the pod formation stages. Leaf area per plant decreased with higher plant density, while the leaf area index was observed to increase at various developmental stages with escalating crop density in direct-sown winter rapeseed (Figure 3). Likewise, leaf area per plant decreased with widening row spacing, and leaf area index decreased at all stages of development with the expansion of row spacing (Figure 3). The combined impact on the leaf area index was most pronounced during floral bud formation for a plant density of 60×10^4 plants ha^{-1} and a row spacing of 20 cm (Figure 4).

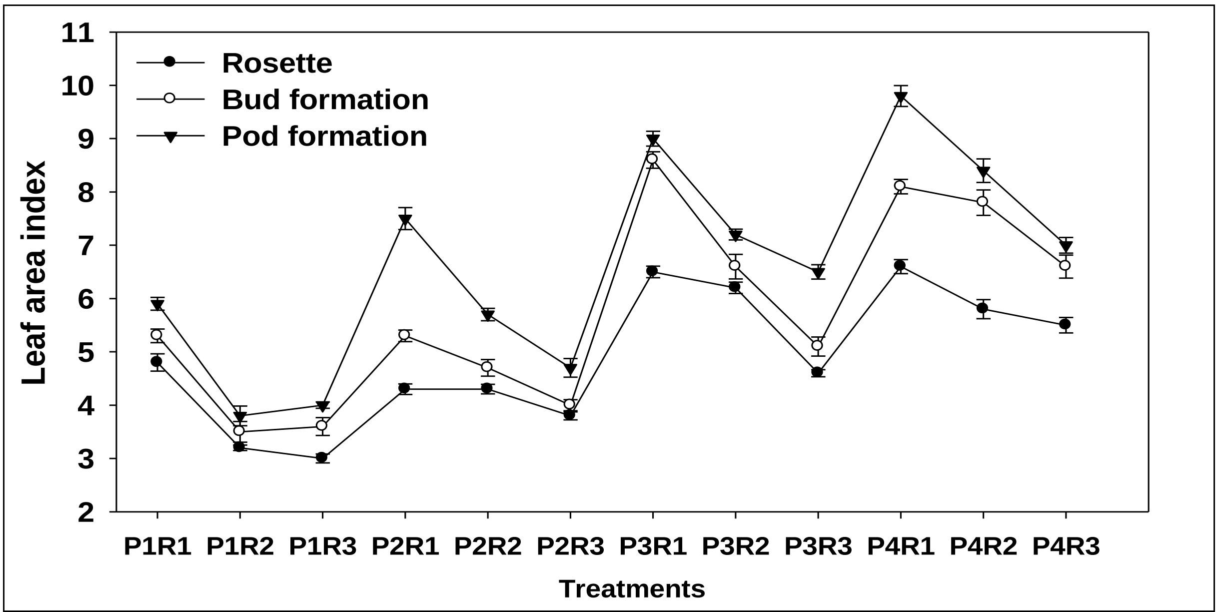

Figure 4. Combined effects of plant density (15, 30, 45 and 60×10^4 plants ha^{-1}, respectively) and row spacing (20, 30 and 40 cm between rows, respectively) at different developmental stages (Rosette, Floral bud formation, Pod formation) on leaf area index.
Bars represent standard errors. P1R1, P1R2, P1R3, P2R1, P2R2, P2R3, P3R1, P3R2, P3R3, P4R1, P4R2, and P4R3 represent the combinations of plant densities of 15×10^4 (P1), 30×10^4 (P2), 45×10^4 (P3) and 60×10^4 (P4) plants ha^{-1} with row spacing of 20 (R1), 30 (R2) and 40 (R3) cm, respectively.

Yield components and yield

As shown in Table 1, the average values from both the 2020-21 and 2021-22 growing seasons elucidate a gradual and statistically significant decrease in the number of effective branches as the plant density escalates from 15×10^4 to 60×10^4 plants ha^{-1}. In contrast, row spacing did not yield any significant differences. The pod number per branch, the pods on the terminal raceme, and consequently the pods per plant all exhibited a consistent downward trend with increasing plant density and row spacing.

Table 1. Effects of plant density and row spacing on the distribution of branches per plant and pods per branch

Treatments Plant density (plants ha^{-1})	Branches per plant	Pods of terminal raceme	Pods of branches per plant	Pods per plant
15×10^4	9.0 a	95.5 a	324.4 a	419.9 a
30×10^4	8.5 ab	91.1 ab	269.6 b	360.7 b
45×10^4	7.6 c	83.0 c	202.1 c	285.1 c
60×10^4	6.2 d	72.1 d	125.3 d	197.3 d
Row spacing (cm)				
20	7.4 a	81.9 a	200.0 b	281.8 a
30	7.7 a	84.6 a	213.9 ab	298.5 a
40	8.5 a	89.8 a	277.1 a	366.9 a
Interaction				
15×10^4				
20 cm	8.9 b	89.6 b	296.4 b	386.0 b
30 cm	8.0 b	96.4 ab	285.3 bc	381.6 b
40 cm	10.3 a	100.6 a	391.5 a	492.1 a
30×10^4				
20 cm	8.0 b	87.4 bc	235.3 c	322.6 bc
30 cm	8.6 b	90.9 b	263.1 c	354.0 b
40 cm	9.0 ab	95.1 b	310.4 ab	405.5 ab
45×10^4				
20 cm	7.0 bc	80.0 c	175.3 cd	255.3 c
30 cm	7.9 b	81.6 c	196.5 c	278.1 c
40 cm	8.0 b	87.3 c	234.6 c	321.9 bc
60×10^4				
20 cm	5.8 c	70.5 d	93.0 d	163.5 d
30 cm	6.1 c	69.5 d	110.9 d	180.4 d
40 cm	6.6 c	76.3 cd	171.9 d	248.1 cd

Means within a column followed by the same by the same letter are not significantly different by LSD (P>0.05).

The collective effects were evident in the total biomass accumulation, as presented in Table 2. A reduction of 21-54% in the biomass accumulation per plant was noted with increasing planting density, contrasting with a 15-20% increase observed with narrower row spacing. Nonetheless, the total biomass accumulation per unit area demonstrated an increase with higher plant density and narrower row spacing.

Table 2. Effects of plant density and row spacing on total above-ground biomass at harvest in winter rapeseed

Treatments Plant density (plant ha^{-1})	Above-ground biomass (g plant^{-1})	Above-ground biomass (kg hm^{-2})
15×10^4	71.7 a	11570 c
30×10^4	57.0 ab	12730 b
45×10^4	47.1 bc	13036 ab
60×10^4	33.0 c	13591 a
Row spacing (cm)		
20	43.7 c	12879 a
30	50.2 b	12875 a
40	62.6 a	12425 b
Interaction		
15×10^4 plants ha^{-1}		
20 cm	61.0 b	11880 cd
30 cm	64.1 b	11580 d
40 cm	69.9 a	11250 d
30×10^4 plants ha^{-1}		
20 cm	47.8 c	13450 b
30 cm	57.1 b	13114 bc
40 cm	66.0 ab	12579 c
45×10^4 plants ha^{-1}		
20 cm	39.9 cd	12995 bc
30 cm	46.0 c	12871 c
40 cm	55.5 bc	12345 c
60×10^4 plants ha^{-1}		
20 cm	26.2 d	13994 a
30 cm	33.8 d	13558 ab
40 cm	38.8 cd	13221 b

Means within a column followed by the same by the same letter are not significantly different by LSD ($P > 0.05$).

The average seed number per pod was observed to decrease with escalating plant density and widening row spacing, with statistical differences noted in the interaction between plant density and row spacing at a significance level of 0.05 (Table 3). Conversely, the 1000-seed weight remained unaffected by different treatments of plant density and row spacing.

Table 3. Effects of plant density and row spacing on the yield of winter rapeseed

Treatments	Number of seeds per pod	1000-seed weight (g)	Seed yield (kg ha^{-1})	Oil content (%)
Plant density (plants ha^{-1})				
15×10^4	25.7 a	2.45 a	3008 c	39.30 b
30×10^4	23.9 ab	2.57 a	3183 b	39.39 b
45×10^4	25.0 b	2.44 a	3390 a	40.16 a
60×10^4	22.6 c	2.56 a	3398 a	39.98 ab
Row spacing				
20 cm	23.4 c	2.47 a	3292 a	40.02 a
30 cm	25.0 ab	2.49 a	3271 a	39.66 b
40 cm	24.4 a	2.55 a	3171 b	39.45 c
Interaction				
15×10^4 plants ha^{-1}				
20 cm	26.0 a	2.43 c	3011 fg	39.80 de
30 cm	24.7 b	2.45 c	3089 f	39.14 h
40 cm	26.3 a	2.47 bc	2925 g	38.95 i
30×10^4 plants ha^{-1}				
20 cm	23.0 bc	2.51 b	3249 d	39.86 d
30 cm	25.3 ab	2.46 bc	3210 d	39.32 f
40 cm	26.7 a	2.74 a	3089 f	39.00 i
45×10^4 plants ha^{-1}				
20 cm	24.3 b	2.41 c	3410 ab	40.23 a
30 cm	25.3 ab	2.44 c	3396 b	40.14 a
40 cm	22.0 cd	2.46 bc	3363 bc	40.11 ab
6×10^4 plants ha^{-1}				
20 cm	20.3 d	2.53 b	3499 a	40.18 a
30 cm	24.7 b	2.62 ab	3390 b	40.02 bc
40 cm	22.7 c	2.53 b	3305 cd	39.74 e

Means within a column followed by the same by the same letter are not significantly different by LSD (P >0.05).

The total seed yield exhibited a relative increase with higher plant density and narrower row spacing. On average, reductions of 1% and 3% were noted in seed yield when row spacing was expanded by 10 cm from 20 to 30 cm and from 30 to 40 cm (Table 3). Conversely, increases of 6%, 12%, and 12% were observed in seed yield when planting density was increased from 15×10^4 to 30×10^4, 45×10^4 plants ha^{-1} and 60×10^4 plants ha^{-1}, respectively, across the stages. However, there was no significant difference in the yield between plant densities of 45×10^4 and 60×10^4 plants ha^{-1}. The combination of 20 cm with both 60×10^4 plants ha^{-1} and 45×10^4 plants ha^{-1} produced the highest seed yields of 3499 kg ha^{-1} and 3410 kg ha^{-1}, respectively. As the plant density increased from 15×10^4 to 60×10^4 plants ha^{-1}, a notable increase of approximately 5% in seed oil content was observed. Furthermore, varying row spacing led to significant differences in seed oil content, demonstrating an upward trend in seed oil content with narrowing row spacing for winter rapeseed (Table 3).

Growth and development

During the experimental seasons of 2020-21 and 2021-22, the weather conditions and soil hydrothermal characteristics were notably conducive to the normal growth and development of direct-sown winter rapeseed. Notably, the swiftest crop establishment was observed when the row spacing was set at 20 cm, indicating that this spacing configuration is optimal for direct-sown winter rapeseed, potentially maximizing the benefits of a mechanized direct-sown cropping system (Wang et al., 2015; Ren et al., 2017).

During the transition from floral bud formation to the pod developmental stage, individual plants exhibited the highest leaf area index in high-density plantings, indicating that closer spacing is linked to accelerated growth and larger crop leaf canopies (Van Dijk et al., 2017). The leaf area of plants with a density of 15×10^4 plants ha^{-1} exceeded that of other plant densities, with the leaf area per plant decreasing as plant density increased. This decline may be attributed to increased senescence and reduced leaf production at higher plant densities, aligning with the findings of Ren et al. (2017). They noted that while individual leaves were larger, closer plant spacing resulted in larger and faster development of leaf canopies, however, this effect was transient as subsequent leaves were smaller, leading to accelerated leaf canopy senescence. It was observed that plants at lower population densities could sustain a larger leaf area throughout an extended developmental timeframe (Wang et al., 2015). Wang et al. (2015) observed that greater leaf areas were evident in plant densities as low as 8 plants m^{-2}, where reduced shading facilitated larger leaf expansion and prolonged higher activity levels, especially during the critical flowering period. Nonetheless, a positive impact of increasing population density on leaf area index was observed, with the peak leaf area index attained prior to the initiation of reproductive growth across all treatments (Liu et al., 2024). Narrow row spacing, which likely led to enhanced competition among plants within the row due to increased senescence and reduced leaf production, produced a consequent decrease in leaf area (Xu et al., 2015).

Components of yield and seed yield

Wang et al. (2015) found that plant density exerts the most significant influence on seed yield and yield components of individual plants. He noted that varying plant populations define limits for intraspecific competition within the canopy (Wang et al., 2015; Fu et al., 2016). The escalation of plant density from 15×10^4 to 60×10^4 plants ha^{-1} resulted in a significant reduction in the number of effective branches per plant, underscoring that a reduction in plant density significantly increases the number of branches and pods per plant (Farooq et al., 2011). Likewise, narrowed row spacing had similar impacts on the number of branches and pods per plant.

As shown in Table 2, results of biomass accumulation in the experiment align with the research conducted by Zhu et al. (2018), who reported that a reduction in plant density led to increased biomass accumulation per plant. In direct-sown rapeseed at lower plant densities, a pattern emerged where plants exhibited a tendency to accumulate more biomass gradually, accompanied by prolonged leaf duration (Tian et al., 2021). The decrease in plant biomass under high densities is attributed to the intense competition among plants, which probably kept these smaller individual plants (Su et al., 2015). Both biomass accumulation of individual plant and that of unit area were lower for narrower row spacing, since individual plants were smaller due to strengthen competition within the row (Wang et al., 2014). The effect of narrower row-spacing could be attributed to physiological limitations in the formation of reproductive organs, leading to suboptimal growth and restricted leaf expansion, particularly during the flowering phase (Wang et al., 2014; Zou et al., 2011).

While the seed yield per plant was higher at lower densities, the seed yield per unit area exhibited an increase with rising plant density in mechanized direct-sown winter rapeseed (Ma et al., 2009). A row spacing of 20 cm resulted in the highest seed yield, whereas widening the row spacing to 30 cm and 40 cm led to a reduction in seed yield. These outcomes, as indicated by Wang et al. (2015), were linked to heightened competition conditions among plants within the row when row spacing was expanded (Wu et al., 2024). Seed oil content was affected by both plant density and row spacing, with oil content increasing as plant density increased. Furthermore, there was a significant rise in oil content associated with narrower row spacing.

Implications of appropriately narrowed row spacing and increased density for winter rapeseed

Optimal row spacing can optimize sunlight utilization and enhance yield potential (Wang et al., 2015). Adequately reduced row spacing can enhance population light interception. Elevated planting density and narrowed row spacing have the potential to enhance plant uniformity, increase yield, and facilitate mechanical harvesting (Wu et al., 2024). Compared with traditional rapeseed seedling transplanting methods, mechanized direct-sowing of seeds has been extensively adopted in numerous rapeseed cultivation regions, particularly in southwestern China (Wang, 2010). The integration of agricultural unmanned aerial vehicles (UAVs) has further facilitated the implementation of mechanized direct-sowing technology, which forms a component of the comprehensive mechanization approach for winter rapeseed production (Wu et al., 2024). Currently, the comprehensive mechanization technology encompasses mechanized land preparation and fertilization pre-sowing, mechanized direct-sown, utilization of UAVs for pest management and topdressing during the rapeseed growth phase, and mechanized harvesting upon maturity (Xu, 2012). This integrated approach significantly diminishes manual labor requirements prior to sowing and at harvest, eliminating the need for manual intervention into the field during winter rapeseed growth period (Wang, 2010).

In traditional transplanting practices, growers typically employ wider row spacing (often exceeding 30 cm) to minimize the number of transplanted plants per unit area, thereby reducing manual labor input (Wang, 2010; Fu et al., 2016). This approach also considers the convenience requirements for growers to move efficiently within the field for tasks such as pesticide application, pest and weed control, and fertilization (Huang et al., 2020). However, within the context of the comprehensive mechanization system for winter rapeseed production, increasing row spacing and planting density not only does not result in elevated manual labor input but can also effectively suppress or reduce damage caused by weeds during the seedling stage of winter rapeseed (Ma et al., 2009; Wu et al., 2024). Following the utilization of UAVs for pesticide application and fertilization throughout the rapeseed growth phase, implementing a narrower row spacing of 20 cm in this investigation does not impact the field management requirements during the subsequent growth stages (Wang et al., 2015). Furthermore, it helps diminish grass damage between rows during the rapeseed seedling stage. The narrower row spacing enhances the efficient utilization of unit area by rapeseed seedlings, thereby reducing the germination and growth of weeds in the field (Zhu et al., 2018). Simultaneously, appropriately reducing row spacing proves advantageous in enhancing planting density and achieving a more uniform distribution of plants per unit area, thereby fostering an increase in yield per unit area (Menendez et al., 2021). Additionally, narrowing row spacing and increasing planting density not only fail to diminish oil content but also exhibit a stimulating effect on enhancing seed oil yield for winter rapeseed.

On the other hand, smaller row spacing can enhance the capture and utilization of winter temperature and light resources more efficiently (Wang et al., 2015). Importantly, the judicious reduction in row spacing and increase in density can partially mitigate the exposed area of surface soil in winter farmland, thereby reducing evaporation and nutrient loss in delicate farmland soils (Xu, 2012), particularly in the mountainous regions of Southwestern China where this experiment was conducted (Wang et al., 2023). This approach is advantageous for optimizing the utilization of winter arable land resources and leveraging row spacing advantages to safeguard arable land utilization to the fullest extent possible (Xu, 2012). While this study represents a minor optimization adjustment in traditional rapeseed cultivation regarding row spacing and planting density, it holds substantial implications for improving rapeseed seed yield in the region and protecting agricultural farmland in ecologically fragile areas.

CONCLUSIONS

To enhance the yields of mechanized direct-sown winter rapeseed, it is recommended to increase plant density to $45\text{-}60\times10^4$ plants ha^{-1} and align it with a suitable row spacing arrangement of 20 cm in Southwest China and comparable rapeseed planting regions. This planting strategy not only supports the comprehensive mechanization and advancement of winter rapeseed cultivation in the area but also contributes positively to the sustainable utilization of farmland in ecologically delicate regions within China and globally.

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