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Effects of Planting Density on Yield of Oilseed Rape (*Brassica napus* L.)

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Abstract The rapeseed, as the second oilseed crop in China, is an important source of edible oil. Reasonable planting density can improve rapeseed production efficiency, and indirectly increase farmers' the production enthusiasm of planting rapeseed. To gain a more comprehensive understanding of the study on effect of rapeseed yield to planting density, this article reviews the effect on planting density to yield in rapeseed, including the influences of the interaction between cultivation factors (variety, sowing period, and fertilization), the impact of plant density to lodging resistance and growth and development (biological characteristics, agronomic characteristics, yield traits, and quality tracts), and planting density and the relationship between light and planting density, are reviewed. The lodging resistance of oilseed rape and population yield of different rape varieties can be improved by choosing the appropriate sowing date and fertilizer application, and give full play to the rational utilization of resources and the maximization of benefits. The oilseed rape can make rational use of light and nutrients, which is conducive to dry matter accumulation and yield improvement, with proper planting density. This review will provide a theoretical basis and practical support for rapeseed planting, management, and mechanized production.

Key words Rapeseed, Planting density, Yield, Effect

0 Introduction

The oilseed rape (*Brassica napus* L.) is a main oil crop in China and an important source of edible oil for residents. Its planting area is about 7.6 million ha, and mainly distributed in the middle and lower region of the Yangtze River. The production of its rapeseed oils accounts for about 47% of the plant edible oil production in China[1-2]. However, the degree of self-sufficiency in rapeseed oil of China is less than 30%, and the level of dependence on imports is increasing. In addition, rapeseed planting confronts the main problems of which are excessive use of chemical fertilizer, low level of mechanization and low yield per unit area[3-4]. At present, China's rapeseed cultivation is mainly planted by individual farmers. However, there is a significant decline in the efficiency of production due to the low degree of large-scale production, extreme weather, and increased pests and diseases. Under the condition of no increase the planting area in China, reasonable fertilization, improving the level of mechanization, and enhancing pest control are critical means to obtain high and stable yield of rapeseed. Besides, reasonable planting density is also a critical way to increase the yield of rapeseed. Reasonable density of rapeseed planting can increase the population structure of rapeseed, affect the structure of rapeseed canopy, improve the used efficiency of light energy obtained by rapeseed, give largest potential to the population advantage, and promote the rapeseed production.

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In production, although the individual rapeseed has a large living space and area, the plant growth is also very vigorous, and the production potential of a single plant is greatly developed, the lower planting density of rapeseed fails to have enough support for the rapeseed population, and, ultimately, is difficult to improve the rapeseed yield; the higher planting density of oilseed rape causes excessive competition of growth among individual plants, poor gas permeability of the population, inhibition of individual plants to use of sunlight, water, temperature, air and nutrition, limitation of plant growth and development, and aggravating lodging and disease and insect pests, resulting in the decrease of rapeseed yield[5-7]. The planting density also affects the rapeseed yield. Reasonable planting density can promote the lodging and angular cracking, the absorption potential of root population, the photosynthetic absorption area, and the used efficiency of light energy of the rapeseed, inhibit the weed growth and the occurrence of *Sclerotinia sclerotiorum* of rapeseed, and improve the rapeseed yield. In particular, it is more important to delay sowing and increase planting density[4,8-10]. The relationship between planting density and growth factors and traits affects rapeseed yield. Therefore, rapeseed planting density should be optimized and intensive rapeseed planting should be applied[11-12]. In the process of planting rapeseed, the planting is too dense, and prone to the stem lodging[13], which limits the substance synthesis and transportation, diminishes the effect of the permeability, increases the emergence of diseases and pests, and results in yield decrease[14]. Optimizing planting density, increasing planting area, and solving the contradiction between lodging resistance and high yield are the necessary choice to obtain efficient planting[15].

In this work, we reviewed the interaction between planting density and cultivation factors (variety, sowing date, fertiliza-

tion), the effects of planting density on lodging traits, growth and development characteristics (biological traits, agronomic traits, yield traits, quality traits), and the relationship between planting density and sunlight on the rapeseed yield, as shown in Fig. 1.

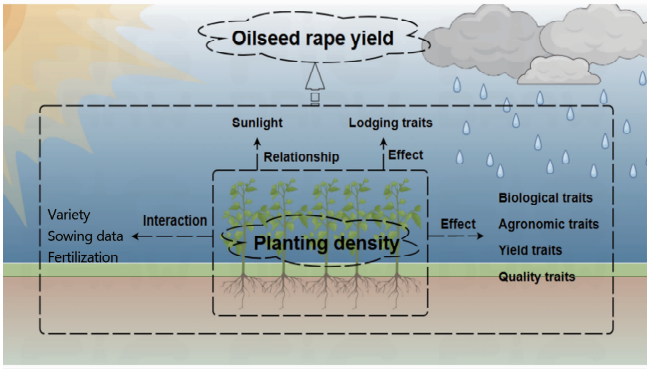

Fig. 1 Factors of the planting density influencing rapeseed yields

It is important instructive significance for the scientific and standardized production of rapeseed planting by elucidating the interaction between planting density and cultivation factors, the impact on lodging traits, characteristics of growth and development, and the relationship with light, and optimizing the most efficiency of rapeseed yield.

1 Effects of planting density and cultivation on yields

1.1 Effects of planting density and variety on yields To a certain degree, the traits of oilseed rape varieties determine the potential of rapeseed yield. The traits of different varieties (such as lodging resistance, plant type structure, and other biological traits) showed differences. For oilseed rape planting, its varieties with higher height, slenderer stems and shallower roots are usually not selected[16]. Although the aboveground biomass is large, the lodging risk is high. Varieties of well moderated gravity center and height of plant, with tight branches, are strong lodging resistance, and the yield and benefit of varieties with many branches and stable growth are significantly improved[17-18]. The lodging resistance of oilseed rape decides its stem quality[20], and plant height of the oilseed rape is not the only standard to evaluate its lodging resistance. The stem diameter and gravity center height of oilseed rape can show the genetic advantages and disadvantages of varieties[21]. The varieties with tight plant type, function period of long leaf, high mechanical strength of the stem and grain filling seed are strengthened the lodging resistance, and the adaptability of the stable and high yield. The interaction between planting density and varieties in Shaanxi, Jiangxi, Yunnan, Hunan, Hubei, Jiangsu, Anhui, Sichuan and Chongqing has an impact on yield, as shown in Table 1.

Table 1 Effects of relationship between planting density and variety and the yield

Area (Province)	Variety	Planting density plants/ha	Yield level	Area (Province)	Variety	Planting density plants/ha	Yield level
Shanxi	Qinyou No. 28	45.0×10^4	Highest[19]	Hubei	Yangguang No. 131	52.5×10^4	Highest[28]
	Qinyou No. 7				Fengyou No. 520	45.0×10^4	Highest[29,32]
	Shanyou No. 28	67.5×10^4	Highest[19]		Huayouza No. 62		
	Qinyou No. 10	48.0×10^4	Highest[30]		Huayouza No. 9		
	Shanyou No. 1617	30.0×10^4	Highest[31]		Huazao No. 291	75.0×10^4	Highest[27]
	Fengyou No. 737	60.0×10^4	Highest[28]	Jiangsu	Zhongshuang No. 11	75.0×10^4	Highest[27]
Jiangxi	Ganyouza No. 1	27.0×10^4	Highest[25]		NingR101	52.5×10^4	Highest[28]
Yunnan	Yunyouza No. 28	15.0×10^4	Highest[23]		Ningyou No. 16	60.0×10^4	Highest[27]
	Yunyouza No. 15	45.0×10^4	Highest[23]		Ningza No. 1838	36.0×10^4	Highest[30]
Hunan	Zhongyou No. 36	60.0×10^4	Highest[27]	Anhui	Huiyou No. 50	52.5×10^4	Highest[28]
	Zhongyou No. 116			Sichuan	Chuanyou No. 36	30.0×10^4	Highest[22]
	Zhongyou No. 7819			Chongqing	Yuyou No. 28	30.0×10^4	Highest[24]
	C6823	36.0×10^4	Highest[26]				

The oilseed rape planting density and specific areas of different varieties affect its yield, as shown in Table 1. In Shaanxi Province, the planting densities of Qinyou No. 28, Shanyou No. 28 and Qinyou No. 7, Qinyou No. 10, Shanyou No. 1617 and Fengyou No. 737 are 45×10^4, 67.5×10^4, 45×10^4, 48×10^4, 30×10^4 and 60×10^4 plants/ha, respectively, with the highest population yield[19, 28-31], indicating that oilseed rape can be regulated according to the planting density of different varieties in the same region. In Jiangxi Province, the planting density of Ganyouza No. 1 is 27×10^4 plants/ha, with the highest population yield with[25]. The planting density of Ganyouza No. 1 in Jiangxi is lower than that in Shaanxi. This may be related to the climatic conditions in the north and south regions. In Yunnan, the planting densities of Yunyouza No. 28 and No. 15 are 15×10^4 and 45×10^4 plants/ha, with the highest yield, good adaptability and resistance[23]. The planting densities of the two varieties are significantly different may be related to the traits of quality. In Hunan Province, the planting densities of Zhongyou No. 36, No. 116 and No. 7819 are 60×10^4 plants/ha, and the population yield is the highest[27]; The planting density of variety C6823 is 36×10^4 plants/ha, and the population yield is the highest[26]. In Hubei Province, the planting densities of Yangguang No. 131, Fengyou No. 520, Huayouza No. 62, Huazao No. 291 and Huayouza No. 9 are 52.5×10^4, 45×10^4, 45×10^4, 75×10^4 and 45×10^4 plants/ha, with the highest population yield[28-29, 32]. In Jiangsu Province, the planting densities of Zhongshuang 11, NingR 101, Ningyou 16 and Ningza 1838 are 52.5×10^4, 60×10^4, 75×10^4 and 36×10^4 plants/ha, and the population yield is the highest[27-8, 30]. In Anhui Province, the

planting density of Huiyou No. 50 is 52.5×10^4 plants/ha, and the population yield is the highest[28]. In Sichuan Province, the planting density of Chuanyou No. 36 is 30×10^4 plants/ha, the population yield is the highest[22]. In Chongqing, the planting density of Yuyou No. 28 is 30×10^4 plants/ha, the population yield is the highest[24]. It shows that different varieties of oilseed rape are suitable for specific regions, and the application scope of oilseed rape varieties is also regional; reasonable decreasing the oilseed rape planting density can increase the mechanical strength or stem wall thickness of lodging resistant stem, and the content of stem fiber and lignin[34]. Dwarf lodging resistant varieties can increase the planting density of oilseed rape without affecting the contents of the oilseed rape lignin and fiber, while the accumulation of dry matter of oilseed rape in aboveground is the largest, with the highest population yield[35].

In short, from the microscopic analysis, the traits of different oilseed rape varieties are decided by their own genes, and which regulate the stem lignin, cellulose content and mechanical strength of lodging resistance of varieties in different regions, leading to oilseed rape yield are related to the close correlation between planting density and cultivated varieties[33].

1.2 Effect of the interaction of planting density and sowing time on oilseed rape yield Rice-oilseed rape crop is the main mode of oilseed rape planting in China. The different harvest periods of the rice often causes that the oilseed rape can be sown at the appropriate sowing date, and even shortens the growth process of oilseed rape[29]. Reasonable late sowing of oilseed rape can raise lodging resistance, and the plant height at late sowing is significantly decreased, but excessive planting density increases the lodging risk[10,36]. In this case, the oilseed rape planting density is adjusted according to the change of sowing date. The impact of the interaction between planting density and sowing date on yield is shown in Table 2.

Table 2 Effects of the interaction of planting density and sowing time on oilseed rape yields

Variety (series)	Characteristics of planting density and sowing period
Shanyou No. 28, Qinyou No. 28 and Qinyou No. 7	Tolerant density and late sowing varieties are planted in Shaanxi on October 8th, with a planting density of 67.5×10^4 plants/ha, achieving higher population yields[19]
Huashuang No. 5	At the experimental site of Huazhong Agricultural University, direct-sow in no tillage on October 15th, with a planting density of 60×10^4 plants/ha. Compared with the no tillage downward planting and tillage transplanting seedlings with a density of 30×10^4 plants/ha, the rapeseed yield increased by 43.1%[37]
Fengyou No. 737	In Chizhou of Anhui Province, late sowing from from October 1 to 10, with a planting density of 60×10^4 plants/ha, achieving higher population yields[28]
Hui No. 50, NingR 101 and Yangguang No. 131	In Chizhou of Anhui Province, late sowing from October 1 to 10, with a planting density of 55.25×10^4 plants/ha, achieving higher population yields[28]
Mengyou No. 4	In the arid areas at the northern foot of Yinshan Mountain, early sowing and moderate planting density can significantly increase yield advantages, while late sowing and appropriate sparse planting density can achieve higher yields with the same amount of fertilizer[38]
Zhongshuang No. 11 and Ganyouza No. 1	In the near area of Wuhan in central China, delaying planting until mid October with a planting density of 36×10^4 to 48×10^4 plants/ha can achieve better rapeseed yield and oil content[39]
Huayouza 62 and Fengyou No. 520	In the experimental base in Huazhong Agricultural University, when sown on September 25th compared to October 25, with a planting density of 45×10^4 plants/ha, achieved higher rapeseed yield[29]
Mianyou No. 16 and De-5-you No. 66	In the Plateau of western Sichuan, spring rapeseed is planted in April, with a planting density of 30×10^4 to 45×10^4 plants/ha under conditions of direct-sowing at open field and film covered live streaming. is The planting density at between 9×10^4 and 18×10^4 plants/ha achieved higher rapeseed yield[40]
Chuannongyou No. 3	In the areas of Shehong and Qionglai in Ya'an of Sichuan, rapeseed is directly sowed from September 20 to October 20. Suitable planting densities are 30×10^4 to 60×10^4 plants/ha, and achieve higher rapeseed yield[41]

As shown Table 2, some rape varieties can adapt to different sowing dates according to different regional characteristics. And the higher oilseed rape yield can be obtained by controlling the planting density. The varieties of Shaanyou No. 28, Qinyou No. 28 and Qinyou No. 7 are late sowing and density tolerant varieties, and can obtain higher population yield with a planting density of 67.5×10^4 plants/ha[19], indicating that the interaction of sowing date and planting density has a significant impact on rape yield. Huashuang No. 5 was directly sowed under no tillage and late sowed with a planting density of 60×10^4 plants/ha. Compared with the planting density of 30×10^4 plants/ha under no tillage and tillage, the rapeseed yield increased by 43.1%[37], indicating that the planting density of direct sowed and late sowed was higher than that of transplanted and sowed. Fengyou No. 737, Hui No. 50, Ning R101 and Yangguang No. 131 were sown late, and the higher population yield could be obtained when the planting density was 60×10^4 plants/ha and 52.5×10^4 plants/ha[28]; However, late sowing and reasonable planting density can obtain higher yield, but effect of different sowing dates and densities on yield is not significant. The planting density of Zhongshuang No. 11 and Ganyou No. 1 at the late sowing are 36×10^4 to 48×10^4 plants/ha, which can obtain higher rapeseed yield[39], and it also implies that reasonable sowing date can prevent the impact of drought on winter oilseed rape. Oilseed rape varieties (series) (Huayouza No. 62 and Fengyou No. 520) with higher yield were sown early than late[29]. The planting density of spring oilseed rape Mianyou No. 16 and De-5-you No. 66 under direct sowing in the open field is higher than that under direct sowing with film

mulching[40], indicating that different direct sowing modes affect the planting density. But the variety of chuannongyou No. 3 had no significant impact on planting density during direct sowing[41]. Some oilseed rape varieties, early sowing and reasonable planting density, can significantly increase the yield. Therefore, late sowing and increasing planting density can inhibit the growth of weeds and promote the nutrient absorption and utilization by oilseed rape[37]. The varieties with high density and late sowing tolerance can be selected using reasonable late sowing. Reasonably increasing the planting density can offset for the low unit yield, the content of cellulose and lignin, and the lodging resistance of rape, and reconcile the contradiction between improving yield improvement and lodging resistance[19].

The sowing date delay will affect the normal growth and development of oilseed rape, limit its growth process, shorten its growth cycle, result in reducing the rapeseed yield of rapeseed per plant. And reasonably increasing the planting density can offset the impact of the sowing date delay on the yield per plant, and achieve a higher population yield of oilseed rape.

1.3 Effect of the interaction between planting and fertilization on yield The application of nitrogen fertilizer greatly affects the internode plumpness and length of oilseed rape. The lodging resistance is enhanced with high c/n ratio. However, with the increase of nitrogen fertilizer and planting density, the rapeseed yield is decreased. Therefore, reasonable adjustment of the relationship between planting density and fertilization, and the optimal ratio C/N can improve rapeseed yield[40]. The effect of the interaction between nitrogen fertilizer and planting density on rapeseed yield is shown in Table 3.

Table 3 Effects of the interaction between fertilization and planting density to oilseedrape yields

Area	Oilseed rape variety	Planting sites	Rational fertilization and planting density
Chongqing	Yuyou No. 28	Xiema	Nitrogen fertilizer: 40 kg N/ha, planting density: 30×10^4 plants/ha, highest yield of plant population[24]
		Beibei	Nitrogen fertilizer: 360 kg N/ha, phosphate fertilizer: 45 kg P_2O_5/ha, planting density: 45×10^4 plants/ha, highest yield of plant population[42]
Guizhou	Qianyou No. 28	Suiyang	Nitrogen fertilizer: 224 kg N/ha, planting density: 22.5×10^4 plants/ha, highest yield of plant population[44]
Hunan	Fengyou No. 737	Shaoyang	Nitrogen fertilizer: 60.0 kg N/ha, planting density: 22.5×10^4 plants/ha, highest yield of plant population[43]
Yunnan	Yunyou No. 28	Luoping	Nitrogen fertilizer: 75 kg N/ha, planting density: 15.0×10^4 plants/ha, highest yield of plant population[23]
Shanxi	Jinyou No. 12	Jinbei	Nitrogen fertilizer: 150 – 225 kg N/ha, planting density: 55.5×10^4 plants/ha, highest yield of plant population[46]
Shaanxi	Shanyou No. 21 and 52	Yangling	Nitrogen fertilizer: 180 kg N/ha, planting density: 15×10^4 plants/ha, highest yield of plant population[31]
	Shanyou No. 1617		Nitrogen fertilizer: 108 kg N/ha, planting density: 30×10^4 plants/ha, highest yield of plant population[31]
Sichuan	Chuanyou No. 36	Chengdu	Nitrogen fertilizer: 180 kg N/ha, planting density: 22.5×10^4 plants/ha, highest yield of plant population[45]
	Mianyou No. 32	Mianyang	Nitrogen fertilizer: 180 kg N/ha, planting density: 45×10^4 plants/ha, highest yield of plant population[49]
	Huayouza No. 9	Jianyang	Nitrogen fertilizer: 120 kg/ha, planting density: 45×10^4 plants/ha, highest yield of plant population[36]
Jiangxi	Zhongyou No. 607	Ji'an	Slow release fertilizer: 600 kg/ha, planting density: 60×10^4 plants/ha, highest yield of plant population[48]

As shown Table 3, for the same variety, reasonable adjustment of planting density can achieve the higher benefit of the population yield under different fertilization conditions in the same region. For example, Yuyou No. 28 can obtain relatively high population yield with using 40 kg N/ha nitrogen fertilizer and planting density of 30×10^4 plants/ha, and using 45 kg P_2O_5/ha phosphorus fertilizer and 360 kg N/ha nitrogen fertilizer and planting density of 45×10^4 plants/ha[24, 42]. For Hunan and Guizhou regions, when nitrogen fertilizer application was 60.0 and 224 kg N/ha, respectively, a relatively high population yield was obtained at the same planting density of 22.5×10^4 plants/ha[43-44], indicating that higher rapeseed yield can be obtain in different regions using adjusting planting density and fertilization. In some regions, increasing the use of nitrogen fertilizer and decreasing the planting density can raise the rapeseed yield[23]. For example, when the use of nitrogen fertilizer is 75 kg N/ha in Yunnan region and 180 kg N/ha in Shaanxi region, the population yield with a planting density of 15×10^4 plants/ha is higher; In general, in the north, reasonably increasing nitrogen fertilizer and planting density can increase the population yield. For example, in Shaanxi, when the nitrogen content is 150 – 225 kg N/ha, the planting density is 55.5×10^4 plants/ha, while in Shaanyou No. 1617, when the use of nitrogen fertilizer is 108 kg N/ha, with a planting density of 30×10^4 plants/ha, and the population yield is higher[31, 46]; In some regions, some oilseed rape varieties can obtain higher population yield with increasing nitrogen fertilizer and reducing planting density. For example, in Chengdu Plain, Chuanyou No. 36, when the use of nitrogen fertilizer is 180 kg N/ha, with a planting density of 22.5×10^4 plants/ha, and the population yield is the highest[45]. While some oilseed rape varieties can also obtain higher population yield with reasonably increasing planting density and nitrogen fertilizer, such as Mianyou No. 32 and Huayouza No. 9, when the nitrogen fertilizer is 180 kg N/ha and 120 kg/ha, respectively, with a planting density of 45×10^4 plants/ha, and the population yield is higher[36, 49]. In some regions, varieties of oilseed rape can obtain higher population yield with reasonably increasing planting density and fertilization. For example, in Ji'an, Jiangxi, Zhongyou No. 607, using slow release fertilizer of 600 kg/ha, a planting density of 60×10^4 plants/ha, and rapeseed yield is higher[48]. Due to the increase of nitrogen fertilizer application rate and the higher planting density, the effective branches, plant height, and effective pods are narrowed. In addition, under the high planting density, even if the use of nitrogen fertilizer is increased, the individual development is also

limited, which ultimately decreases the effect of promoting nitrogen fertilizer on oilseed rape[47]. Therefore, according to the climate characteristics of different regions, it is worth paying attention to increasing the total production benefit by rational fertilization and planting density for different oilseed rape varieties.

The number of grains per pod and 1 000-grain weight is affected by the genetic factors. Therefore, the planting density and fertilization have little effect on rapeseed yield, but rapeseed yield is related to oilseed rape root neck diameter, dry matter accumulation of the whole plant and organs, number of green leaves in the population, chlorophyll of functional leaves, number of effective pods, pods distribution ratio, and number of effective branches. The rapeseed yield is mainly decided by the number of effective pods and branches. Interaction of reasonable of planting density and fertilization can improve the number of effective branches and pods, and then rapeseed yield.

2 Effects of planting density on lodging resistance

Planting density affects the canopy structure and light intensity of oilseed rape, resulting in the metabolic accumulation of carbohydrate in the stem, thus affecting the oilseed rape lodging resistance. The results showed that planting density significantly affected oilseed rape lodging, and the dry matter accumulation law of super cold resistant winter oilseed rape population showed a logistic curve. With the planting density increase, growth stages and the leaf area index firstly increased and then decreased, while the chlorophyll content increased, and the highest at full flowering stage; Under low planting density, the oilseed rape stem-base is relatively thick, with strong bending and lodging resistance, but the fresh weight of the upper part and height of plant are increased, resulting in increasing lodging index of the stem-upper, decreasing the lodging resistance, and easily generating stem lodging[50]. Decreasing the planting density of oilseed rape can reduce the plant height, while the stem is short and hard, which can enhance the lodging resistance of the stem[51]. And reducing the planting density of oilseed rape can make oilseed rape nutrient riches, lush plants and sufficient light, but inhibit the potential of oilseed rape yield. Therefore, reasonable planting density can increase the oilseed rape yield, but excessive dwarfing is a negative effect, and even leads to reducing oilseed rape yield[52-53]. The middle and upper parts of the oilseed rape stem are easy lodging. Reasonably increasing oilseed rape planting density, the lodging index in the middle and upper parts of the stem is decreased, and the lodging resistance is enhanced, and synergistic of oilseed rape lodging resistance and yield are increased[35]. The reasonably increasing oilseed rape planting density can improve the stem biomass and lignin content. For example, under different planting densities (15×10^4, 30×10^4, 45×10^4 and 60×10^4 plants/ha), the lodging index of Fengyou No. 520 and Huayou No. 62 decreased, the lodging resistance increased, and the synergistic of the yield and lodging resistance are increased[29]; From macroscopic analysis, with increasing oilseed rape planting density within a certain range, the plant height of direct sowing oilseed rape will decrease. Inaddition, the lodging angle, lodging index, and the occurrence of oilseed rape lodging risk will reduce; Planting density increase can induce the genes related to lignin synthesis in the upper stem to show a positive regulatory effect, and up regulate the gene expression, result in the lignin content increase in the oilseed rape stem, and it is not easy to make the stem lodging. However, when the oilseed rape planting density is too large, the diameter and bending resistance of the oilseed rape stem will be decreased, the lodging index and lodging risk will be increased[50,54], and the lodging resistance will be enhanced, the rapeseed yield will maintain a high level. The reasonable planting density increase is conducive to the concentration of pod maturity, decreasing the harvest loss caused by the difference in pod maturity, and ultimately reducing the oilseed yield[22]. The canopy structure of oilseed rape is changed due to excessive planting density, which makes the stem easy to topple or even break, resulting in plant crossing and even overlapping[40]. In the experimental base of northwest agriculture and Forestry University, the lodging index of Shaanyou No. 28, Qinyou No. 28 and Qinyou No. 7 are firstly decreases and then increases with the increase of planting density, while the population yield increases, the lodging index decreases, and the lodging resistance and yield increase synergistically[19]. In extreme weather, the stem lodging risk will be increased and the yield will be reduced.

The oilseed rape planting density increase leads to the increasing content of lignin in the upper stem, which enhances the plant lodging resistance. For the over planting density, stem diameter and bending resistance can be reduced. Therefore, the reasonable increase of the plant density will enhance the overall lodging resistance of oilseed rape individuals. The relationship with oilseed rape individuals, populations, high yield and lodging resistance are adjusted, which realize the control of grass with density, supplement of delay sowing with density, fertilizer saving with density, yield increase with density and the appropriate opportunity with density[54].

3 Effects of planting density on growth development traits

3.1 Effects of planting density on biological traits Reasonable planting density can enhance the growth and development traits of oilseed rape. The oilseed rape's growth and development were affected by soil nutrients, light distribution and its space occupied, and indirectly by planting density. The planting density is too small, lead to the smaller population per unit area, reducing competition of intraspecies, increasing the plant height, stem diameter, number of branches, leaves, and fresh weight of oilseed rape per plant, but the land use efficiency is not high, resulting in the lower population yield[55]; with increasing planting density of oilseed rape, the number of branches and plant height decreased. For example, in Ya'an, Shehong and Qionglai experimental areas, the planting experiment of chuannongyou No. 3 showed that the planting density affected the branch position of oilseed rape. With increasing planting density, the number of branches per time and plant height decreased[40]. The population density per unit area is too large, and lead to the poorly spatial permeability of a single plant due to land resources and insufficient space, which affects the leaf photosynthesis and the growth of a single plant, resulting in reduction of yield. For example, after the planting density of Huaza No. 62 and strain No. 1301 was increased, the mature indi-

viduals of oilseed rape were significantly inhibited, the root neck became thinner and the plant height decreased, the number of branches of oilseed rape decreased, and the yield per plant decreased by 57.14% and 55.73%[50]. Under reasonable planting density, the utilization rate of plant space is increased, the resource distribution tends to be reasonable, the light energy efficiency is enhanced, and good growth and development of single plant, will be improve the oilseed yield. Therefore, one of the key measures to improve the growth and development traits of oilseed rape is the reasonable planting density[56,22]. Reasonable planting density can increase the light utilization rate of population growth, make the oilseed rape leaves grow best, increase the leaf area index, improve the chlorophyll content, contribute to the accumulation of dry matter in oilseed rape, decrease the competition of weed nutrients and clumping, and make oilseed rape obtain greater resource utilization. Reasonable planting density can coordinate the spatial relationship between individuals and groups, and maximize the utilization of water and light resources[19]. The rhizome diameter, total leaf number, green leaf number and leaf area decreased with the increase of planting density at bolting stage and flowering stage[23]. At late sowing, with the increase of planting density, the lignin and cellulose content in stems, fresh weight of shoots, yield per plant, vascular bundle and stem cross-sectional area of Shanyou No. 28, Qinyou No. 28 and Qinyou No. 7 decreased, while the population yield increased[19].

Planting density affects biological traits. The competition between oilseed rape individuals in soil nutrients and light absorption will affect the nutrient absorption and photosynthesis of oilseed rape individuals due to the increase of planting density. All carbon sources of oilseed rape, including lignin, cellulose and oil in rapeseed, come from photosynthesis. Therefore, the planting density should be regulated reasonably to the best biological traits to maximize the rapeseed yield.

3.2 Effects of planting density on agronomic traits Planting density affects the plant height of oilseed rape. The decreasing planting density leads to the decrease of plant height, and at the same time, prolonging the growth period of oilseed rape. The reasonable increase of planting density can increase the thickness of roots, chlorophyll content, and number of green leaves in a single oilseed rape plant. However, a certain extent, the thickness of roots, chlorophyll content, and number of green leaves remain at a certain level[57]. Increasing the planting density further will lead to the decrease in the proportion of roots and leaves, shifting final flowering period, and the complete shedding of leaves with the arrival of the harvest period. Continuing to increase planting density can increase population and soil moisture, leading to increased damage from clubroot disease and ultimately affecting rapeseed yield[36]. The yield factors of rapeseed refer to the number of individual pods, thousand pod weight, and effective pods per unit area[58]. The planting density is correlated with the number of single and effective siliques[25]. Excessive increasing planting density can lead to the decrease of lodging resistance, and a large population can easily cause oilseed rape lodging[36]. The high planting density of oilseed rape leads to the increasing disease index and decreasing disease percentage, disease resistance, the number of effective pods per plant, and the number of branches per plant[59-60]. As the planting density of oilseed rape increases, the height of the canopy decreases. The reasonable planting density can decrease the thickness of oilseed rape rhizomes, concentrate the canopy, consistent growth and development, and facilitate mechanical harvesting[61]. Excessive increasing planting density can decrease the effective number of siliques in the main inflorescence, the number of siliques per plant, the number of primary branches, and the number of siliques in the population[62]. The report showed that the root neck thickness of oilseed rape Zhongyou No. 607 induced with the decrease of fertilizer application, and also showed a decreasing trend with the planting density increase; The plant height, number of branches, and leaf SPAD value (soil and plant analyzer development, which measures the relative content of chlorophyll) of oilseed rape decrease with decreasing fertilizer application and show a decreasing trend with increasing planting density[48]. It has been reported that the height and effective branch number of oilseed rape plants treated with low planting density were higher than those treated with high planting density. Low planting density resulted in less competition for nutrients and water in oilseed rape plants, increased growth space, ventilation, and light transmission, which was beneficial for the growth of plant height and effective branch number of oilseed rape[46]. It has also been reported that under late sowing, the number of grains per horn, number of siliques, yield, population yield, and aboveground fresh weight of Shaanyou No. 28, Qinyou No. 28, and Qinyou No. 7 significantly decreased with increasing planting density[19].

The planting density, which is limited by nutrition and light absorption, affects the branch number, stem diameter, yield and 1 000 grain weight of rapeseed, and adjusts the gene expression of these agronomic traits. Therefore, reasonable planting density can adjust the gene expression of these agronomic traits, make the agronomic traits optimal, and maximize the rapeseed yield.

3.3 Effects of planting density on yield traits The planting density will affect the rapeseed yield, and the optimization of planting density is conducive to the reasonable establishment of plant population structure[63-64]. The increasing planting density leads to the decrease of plant space and land resource utilization, even insufficient, hindering the growth and development of individual plants, decreasing stem thinning, plant height, and rapeseed yield[65]. Reasonably increasing the planting density can improve the starting point of pod bearing and the height of effective branches, and decrease the canopy height. When the planting density is 45×10^4 plants/ha, the proportion of low effective branches will be decreased[61]. In actual agricultural production, planting density affects growth and development of individual plant. The competition among high-density populations is intense, and the environment is abominable[66], and the dry matter weight of leaves, stems, roots, pods and branches is decreased[67-68], leads to small main stem, easy lodging, the number of reduced pods, the high height of branches, the small number of branches, and the yield per unit area of serious decrease. Therefore, planting density affects rapeseed yield and its components[69-70]. The planting density, which was significantly correlated with the plant shape of oilseed rape, could increase or decrease the yield of oilseed rape population by affecting the plant shape, and finally af-

fect the harvest. Tapping the potential of a single plant is the key factor for rapeseed to achieve stable and high yield. It has been reported that tested the oilseed rape variety C6823 with different planting densities: when the planting density was 36×10^4 plants/ha, the rapeseed yield was 2 256 kg/ha. Increasing the planting density leads to the increase of the plant height, the decrease of the stem diameter , the number of effective pods, branches and 1 000 grain weight, and the yield per plant[26]. The test of different densities of Ganyouza No. 1 revealed that when the density was 27×10^4 plants/ha, the yield was the highest (2 216. 1 kg/ha), the plant shape structure was the best, and the resistance was enhanced[25]. Reasonable planting density can increase the leaf area index of oilseed rape, effectively increase light energy interception, which is conducive to canopy light absorption, carbon dioxide utilization and dry matter accumulation, resulting in improving the yield[71]. It has been reported that the effect of no tillage direct sowing and planting density on rapeseed yield, and the results showed that increasing planting density can shorten the length of oilseed rape main inflorescence per plant, and decrease the number of main flower pods and effective pods. For example, when the planting density in range from 15×10^4 to 39×10^4 plants/ha, the length of main inflorescence per plant, the number of pods and effective pods and the yield of rapeseed per plant gradually decreased[62]. It has been reported that the rapeseed yield of 94 oilseed rape varieties with planting density between 15×10^4 and 75×10^4 plants/ha, with the increasing planting density, the agronomic traits of stem diameter, plant height and main inflorescence length showed a decrease trend. When the planting density was 60×10^4 plants/ha, the highest rapeseed yield was 3 381. 1 kg/ha[27]. It has been reported that the yield of Jinyou No. 12 in northern Shanxi reached 79 052. 8 kg/ha on average when the fertilization was 225 kg/ha and the planting density was 60×10^4 plants/ha[46]. It has also been reported that in the Zhenjiang experimental area, Jiangsu Province, Qinyou No. 10 showed high firstly and then low with the increasing planting density, the planting density was 48×10^4 plants/ha, and the highest yield was 4 988. 5 kg/ha. Ningza No. 1838 was $3\ 660 \times 10^4$ plants/ha, and the highest yield was 5 154. 4 kg/ha[30].

Yield traits are related to variety traits and planting density. For oilseed rape varieties adapted to different regions, planting density affects yield traits, such as effective number and branch number regulating gene expression, results in affecting the yield of rapeseed. Therefore, reasonable planting density can optimize rape yield traits and maximize rape yield.

3.4 Effects of planting density on quality traits The planting density is related to its quality traits. Different oilseed rape planting densities are different effects on their quality, as shown in Table 4.

Table 4 Effects of high planting density to oilseed rape quality[76]

Variety (series)	1 000-grain weight	Colour	Chlorophyll	Acid value	Peroxide value	Oleic acid and linoleic acid	Arachidonic acid	Carotense	Tocopherol	Sterol	Oil contents
Dwarf N91	−	+	+	+	+	+	−	+	−	−	+
Tall − culm Chuanyou No. 20-CY20	+	+	+	+	+	+	−	+	+	−	+
Tigh branch ERAKE	+	+	+	−	+	+	−	+	−	Un	+
Loose branching 11 − 9 − 704	−	+	+	+	−	+	−	+	−	Un	+
Tongling-TLHY incision flowers and leaves	+	+	+	+	+	+	−	+	−	−	+
Huayouza No. 62-HZ62 conventional plant type	−	+	+	+	+	+	−	+	+	Un	+

NOTE " −", " +" and "Un" are represented reduced, increased and unchanged.

As shown table 4, increasing planting density leads to the decrease of the number of branches of oilseed rape plant and rapeseed yield, but increasing the number of rapeseed in main inflorescence and oil content of rapeseed. For examples, with increasing plant density of oilseed rape Shuangyou No. 11and Ganyou No. 1, their number of rapeseed of individual plant and branching inflorescence are significantly induced, but proportion of main inflorescence rapeseed and individual plant yield increase with increasing planting density. And the oil content of rapeseed and the yield are firstly increase, then decrease with increasing planting density, but which are not less than that of low planting density[39]. The reasonable planting density leads to the number of pod per plant, thousand grain weight, number of grains per pod, grain yield per plant and dry weight ratio of the whole plant are the best. Therefore, their oil yields of rapeseed are the highest. For example, the oil yield of oilseed rape variety Huayouza No. 62 and Fengyou No. 520 are firstly increase, then decrease with increasing planting density[29]. And superoxide dismutase and peroxidase activities in leaves of oilseed rape variety Mengyou No. 4 decrease with increasing planting density. Implying stress resistance enhance, mustard acid and malondialdehyde and oil content increase, and glucosinolate and protein contents of rapeseed decrease, but effect of planting density on the contents and components of fatty acids (palmitic acid, stearic acid, oleic acid, linoleic acid, and erucic acid) is not significant[38]. It has been reported that the content of erucic acid, linoleic acid, glucosinolates, and oil in *Brassica napus* L. varieties (series) is positively correlated with planting density, while the protein content is negatively correlated with planting density. The plant shape and structure is affected by planting density, and the difference in the external resources utilization on individual plants leads to different grain quality of oilseed rape. It has been reported that protein content of rapeseed decrease with increasing planting density, and late sowing leads to improving protein content with increasing planting density of oilseed rape variety Qingza No. 10. The oil content of rapeseed was positively correlated with planting density, on the contrary, and negatively correlated with sowing time. For example, the study about effect of planting density on oilseed rape

quality at physiological and biochemical aspects shows that phosphatase activity and oil yield of rapeseed increase with increasing plant density. On the contrary, glutamine synthetase activity in leaves, grains and pericarps of oilseed rape lead to the decrease of oilseed rape protein content[74]. In different regions, the oil content of the same winter rapeseed variety varies significantly. The rapeseed oil content in the Yangtze River lower reaches is the highest, followed by that in the middle reaches, and the rapeseed oil content in the upper reaches is the lowest[75]. The study also showed that, some oilseed rape varieties, the planting density don't affect significantly the quality. It has been reported that Chuanyou No. 6 variety as the material, and the planting density of 15×10^4, 30×10^4, and 60×10^4 plants/ha, the planting density don't affect significantly on the grain quality[22]. It has been reported similar research results with 10 rape varieties as the experimental materials. From breeding, according to variety characteristics, corresponding cultivation and management techniques can improve oilseed rape quality[59]. It has been reported that the direct sowing of high planting density of oilseed rape affected the rapeseed quality, and analyzed the quality characteristics of six oilseed rape varieties (series) (N91 short stem, ERAKE branch compact, Tongling flower leaf-TLHY cut flower leaf, 11-9-704 loose branch, Chuanyou 20-CY20 high stem, Huayouza 62-HZ62 conventional plant type): except that the thousand grain weight of N91 short stem, 11-9-704 loose branch, Huayouza 62-HZ62 conventional plant type decreased significantly, the thousand grain weight of other varieties (series) increased significantly; the color, chlorophyll content, peroxide value, acid value, oleic acid and linoleic acid content of fatty acids, carotene and oil content of six varieties (series) increased significantly, while the arachidonic acid content decreased; The tocopherol content of other varieties decreased significantly, except that the tocopherol content of Chuanyou 20-CY20 high stem and Huayouza 62-HZ62 conventional plant type increased. The sterol content of ERAKE branch compact, 11-9-704 loose branch, and Huayouza 62-HZ62 conventional plant type Huayouza 62-hz62 conventional plant type remains unchanged, while other varieties (series) sterol contents are significantly reduced[76].

The increasing planting density leads to light absorption competition, which restricts photosynthesis and impairs plant carbon accumulation, and limits growth. Simultaneously, higher planting density leads to individual nutritional competition among oilseed rape plants, affecting various physiological processes for growth and development and quality traits (including acid value, peroxide value, fatty acids, carotene content, tocopherol levels, sterols, and oil yield). Therefore, reasonable planting density can enhance the quality traits as increased oil content indirectly boosting production of rapeseed.

4 Effects of the relationship between plant density and sunlight on the yield

The relationship between planting density and sunlight affects the yield of oilseed rape. With stronger sunlight, planting density will reasonably decrease to be propitious to the yield rapeseed in the fields, which increased appropriately with weak sunlight to increase rapeseed yield. It has been reported that compared with controls, the leaf length and width increased by 15.9% and 18.9%, respectively, under low sunlight conditions during the bud stage, while chlorophyll content decreased by 49.2%. The plant height oilseed rape decreased significantly the stem thickness. The light intensity is closely related to the growth of oilseed rape stems and leaves during the bud stage. The entire growth cycle, high light intensity leads to higher rapeseed yields in oilseed rape, whereas low light conditions result in lower yields. In the later stage of oilseed rape growth, light intensity greatly affects oilseed rape yield[77]. For a single plant, the increasing planting density will lead to the stimulating competition of light energy, which will affect the growth of oilseed rape plants at some extent. On the contrary, the reasonably increasing planting density will improve the traits of oilseed rape as a whole. The photosynthetic physiology under different planting densities using B. napus as the model plant was reported. With increased planting density of 10×10^4 to 50×10^4 plants/ha resulted in reduced chlorophyll content and individual biomass. The net photosynthetic rate initially increased, peaking at approximately 20×10^4 plants/ha (medium planting density). Further increasing planting density resulted in a significant decrease of the net photosynthetic rate and leaf soluble sugar content, and a initially increase then decrease of total protein content. For population level, increasing planting density firstly led to an increase in green leaf area (peaking at 30×10^4 plants/ha) followed by reduction. The tight interception efficiency and leaf area index increase, reaching peaking values at 50×10^4 plants/ha (high planting density). The leaf area index at high densities was three times greater than at low density (10×10^4 plants/ha), but light interception efficiency increasing by 40%[71]. It has been reported that the oil content and oil yield per plant of two oilseed rape varieties (Huayouza No. 62 and Fengyou No. 520) decreased by 2.1% – 11.8% and 27.0% – 35.3%, respectively, under low sunlight conditions. By properly increasing planting density to increase population yield, the losses in oil content and yield under low light stress can be mitigated[34]. Therefore, reasonable planting density maintains optimal leaf area index, improves pod skin area index and sunlight interception efficiency, which is beneficial for yield formation[78].

For individual plants, higher planting density leads to decreased light exposure per plant, which weakens photosynthesis, restricts growth development, and ultimately decreasing yield. Although increasing planting density may provisionally reduce individual plant yield, the population yield shows a trend of initial increase followed by decrease. Therefore, reasonable planting density can adjust the net photosynthetic rate of individual plants of oilseed rape. While individual yield may be decreased, population yield may be maximized. The relationship between planting density and yield varies across different varieties, regions, and natural conditions. Thus, selecting optimal planting density should account for regional and variety-specific differences.

5 Conclusions and prospects

The influencing factors of rapeseed yield are complex, and the planting density is one of the most critical factor. Other environmental factors such as rapeseed variety, geographical location, and fertilization practices also influence the relationship between

rapeseed yield and planting density, which may necessitate adjustments in planting density. Optimizing planting density based on these factors can maximize the population yield of rapeseed.

(i) The rapeseed variety traits decide the rapeseed yield potential. Different varieties are different planting densities at sowing, while the same varieties can maximize the rapeseed yield by adjusting the planting density due to fertilization, sowing time and region.

(ii) The oilseed rape planting density affects the utilization of light per plant. Excessive planting density decrease the net photosynthetic rate of individual plants, hindering their growth, thereby improving the net photosynthetic efficiency should decrease planting density. Therefore, reasonable planting density can adjust the relationship between decreased net photosynthetic rate, leading to decreased yield per plant and maximizing the population yield.

(iii) The oilseed rape planting density significantly impacts nutrient absorption of individual plants. Excessive planting density leads to competition among individual plants for nutrients, hindering growth and decreasing yield. Optimal planting density enables adjusted rapeseed yield between individual plant and population yield, promoting dry matter accumulation and population yield enhancement. Reasonable fertilizer application further enhances lodging resistance, population yield and efficient resource utilization, and maximizing oilseed rape's economic benefits.

Currently, gradually decreasing oilseed rape cultivation area in China made oilseed yield increase become the primary goal for breeding researchers. By analyzing the influence factors of optimizing planting density like fertilization, sunlight exposure, and sowing timing according to different regional climates and oilseed rape varieties, we can maximize both individual plant yields and population yield. This will serve as an effective strategy to increase oilseed rape yield in the future. Establishing standards of region-specific planting density can instruct standardized cultivation and drive efficient development of the oilseed rape industry. While the oilseed rape yield are significantly affected by planting density, its relationship with oilseed rape varieties, geographical factors, sowing timing, fertilization methods, and sunlight exposure remains complex. These intricate relationships are optimized and maximize the rapeseed yields, intelligent regulation systems will be implemented in the future, paving the way for smart agriculture development.

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(From page 15)

hancement, and operational efficiency, it not only diversifies tourism offerings and elevates service quality but also reshapes the industry's value chain. Empirical analysis reveals that key scenic spots in Zhejiang implementing low-altitude tourism projects have achieved over 30% growth in per-visitor spending, while stimulating more than 20% revenue increases in adjacent sectors such as catering and accommodation. More importantly, low-altitude transportation networks address the persistent challenge of fragmented tourism resources, enabling coordinated regional development and catalyzing high-quality advancement across Zhejiang's tourism ecosystem.

To advance the deep integration of the low-altitude economy and tourism, we propose enhancing the policy framework through four key dimensions: First, it is necessary to formulate the *Special Plan for Low-Altitude Tourism Development in Zhejiang Province* and establish a 20 billion yuan industrial guidance fund; second, it is recommended to develop five low-altitude tourism demonstration zones in areas such as the Hangzhou Asian Games venues and Zhoushan Archipelago; third, it is recommended to create a provincial low-altitude economy innovation center with an annual investment of 100 million yuan to support critical technology R&D; and fourth, it is recommended to implement a structured "Low-Altitude Tourism Talent Program" to train 500 professional flight service personnel within three years. In addition, it is required to strengthen ecological compensation mechanisms to ensure low-altitude economic development proceeds in tandem with environmental conservation.

Looking forward to the future, Zhejiang's low-altitude economy holds immense growth potential. The advancement of smart tourism infrastructure will drive innovative applications, such as UAV logistics and VR aerial tours, to transform tourism service models. In rural revitalization, low-altitude tourism can serve as a catalyst for development in 26 mountainous counties of Zhejiang Province; through aviation-themed products like flight training camps and educational tours, rural annual revenues are projected to exceed 5 billion yuan. With maturing technologies like eVTOL, feasibility studies suggest Zhejiang Province could establish China's first Urban Air Mobility (UAM) network by 2025, unlocking new potential for tourism innovation.

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