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Key Agronomic Factors Influencing Rapeseed Yield and Quality and Optimization Strategies

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Abstract This study explores the key agronomic factors affecting the yield and quality of rapeseed (*Brassica napus* L.), aiming to enhance its economic value through optimized cultivation practices. The findings show that climatic conditions (such as temperature, precipitation, and sunlight) play a crucial role in rapeseed growth and oil synthesis; extended daylight at high altitudes can prolong seed development periods, thereby increasing yield. Additionally, soil fertility and nutrient management, particularly the balanced application of nitrogen, phosphorus, potassium, and trace elements, are essential for improving both yield and quality in rapeseed. Appropriate planting density, weed control, and pest management also significantly impact plant growth quality. The study indicates that integrating precision agriculture with modern breeding techniques, such as QTL mapping and GWAS, under different ecological conditions can effectively enhance rapeseed resilience and nutritional value, thereby promoting sustainable production. This study provides practical scientific insights for optimizing rapeseed cultivation, contributing positively to global edible oil and bioenergy demand.
Keywords Rapeseed (*Brassica napus* L.); Yield optimization; Quality improvement; Agronomic factors; Climate impact; Precision agriculture

1 Introduction

Rapeseed (*Brassica napus* L.), as a crucial oilseed crop, has a long history of cultivation and is widely grown globally. Rapeseed has a wide range of applications, including edible oil, animal feed, biodiesel, and environmental remediation, demonstrating significant potential in agriculture, industry, and ecological management (Raboanatahiry et al., 2021; Xiong et al., 2022; Zhou, 2024). With population growth and the increasing demand for sustainable energy, the economic value of rapeseed as a high-quality oilseed crop is becoming increasingly prominent. Especially in China, rapeseed is one of the major winter oil crops, with extensive cultivation areas accounting for approximately 20% of global production (Hu et al., 2017).

Yield and quality are key factors determining the market competitiveness and nutritional value of rapeseed. High yields form the foundation for meeting demands for vegetable oil and renewable energy, while the quality of rapeseed, especially in terms of oil content, fatty acid composition, and protein levels, directly influences its application value in food and industry (Raboanatahiry et al., 2021; Safdar et al., 2023). Achieving both high yield and quality under current arable land conditions has become one of the critical topics in agricultural research.

The yield and quality of rapeseed are significantly influenced by various agronomic factors, including climate conditions, soil fertility, nutrient management, pest and disease control, and planting density (Safdar et al., 2023). Studies have shown that the unique high-altitude ecological environment of the Qinghai-Tibet Plateau provides rapeseed with ample sunlight, extending the grain development period and significantly enhancing rapeseed yield (Xiong et al., 2022). Soil fertility forms the foundation of rapeseed growth, and proper soil management contributes to improved nutrient utilization efficiency, promoting the healthy growth of rapeseed. Safdar et al. (2023) found that the rational application of trace elements such as boron and zinc effectively increases the yield and quality of rapeseed grains and oil under semi-arid conditions. Additionally, pest and disease control is crucial for ensuring the healthy growth of rapeseed. A global survey highlighted that 16 diseases and 37 pests are present in rapeseed-producing regions, posing significant threats to yield (Zheng et al., 2020). Therefore, integrated agronomic measures that combine environmental conditions with optimized management techniques are essential pathways for improving rapeseed yield and quality (Yan et al., 2021; Ihien Katche and Mason, 2023).

This study systematically analyzes the key agricultural factors affecting rapeseed yield and quality, focusing on different environmental conditions and management practices, with the aim of providing effective ways to optimize rapeseed cultivation for yield enhancement and quality improvement. The study intends to formulate practical recommendations suitable for various planting conditions, thereby supporting the sustainable production of this important oilseed crop. This study will deepen the comprehensive understanding of rapeseed agriculture, aiding the further optimization and development of planting strategies.

2 Global Production and Characteristics of Rapeseed

2.1 Global production and distribution

Rapeseed (*Brassica napus* L.) is one of the most important oil crops globally, cultivated extensively for its vegetable oil, animal feed, and biodiesel production. The crop is grown in diverse ecological environments, from high-altitude areas like the Qinghai Plateau in China to the subtropical regions of Assam, India (Basumatary et al., 2021; Xiong et al., 2022). Major rapeseed-producing countries include Canada, China, India, and several European nations. In China, for instance, rapeseed is a crucial crop, with significant production zones in the Yangtze River Basin and other regions (Zhang et al., 2020; Liang et al., 2023). The cultivation of rapeseed on winter fallow fields in the Yangtze River Basin helps enhance bioenergy and edible oil security. Studies indicate that achieving 60% of the cultivation potential could significantly reduce China's reliance on imported rapeseed and soybeans by 2030 (Tian et al., 2021).

The global distribution of rapeseed cultivation is influenced by multiple factors, including climatic conditions, soil types, and agricultural practices (Jin et al., 2019; Raza, 2020). Research shows that in China's rapeseed-growing regions, temperature and cumulative sunlight have a significant impact on yield, with sunlight being a greater limiting factor, especially in the Yangtze River Basin. Furthermore, agronomic management has a more substantial effect on yield than climate change, suggesting the selection of high-yield varieties according to ecological zones to optimize agronomic management strategies (Li et al., 2022). In regions such as Poland, studies reveal that water availability and soil structure (e.g., sand content in soil) significantly influence rapeseed yield, with high variability in yield resulting from these factors (Zymaroieva et al., 2020).

2.2 Biological characteristics of rapeseed

Rapeseed is a member of the Brassicaceae family and exhibits several biological traits that contribute to its adaptability and productivity. It has a deep taproot system that allows it to access nutrients and water from deeper soil layers, making it relatively drought-tolerant. Research has shown that rapeseed exhibits deeper root systems and increased water-use efficiency under drought conditions, which contributes to stability in growth during dry seasons. By regulating root growth through hormone signaling, such as abscisic acid (ABA), rapeseed's adaptability to water stress can be further enhanced (Dai et al., 2020). Structural characteristics of rapeseed, such as branching patterns and silique (seed pod) formation, play crucial roles in determining yield. Shi et al. (2019) found a positive correlation between silique length and seed weight. Genes influencing silique length, such as *BnaA9.CYP78A9*, extend the growth period of the silique by regulating auxin levels, thus increasing both seed weight and silique length, which are essential for boosting rapeseed yield. During the maturation stage, siliques are prone to shattering, leading to seed loss, particularly during mechanical harvesting. Strengthening silique wall toughness and controlling cell separation can effectively reduce shattering rates and improve seed harvest rates (Mustafa et al., 2022). Genetic factors, such as specific alleles of the *BnaA3.IAA7* gene, also impact plant structure and yield advantage, enhancing overall productivity (Li et al., 2019).

Rapeseed exhibits complex adaptive mechanisms in response to abiotic stresses, such as drought, soil acidity, and nutrient deficiencies. These mechanisms involve intricate physiological and biochemical processes, including hormone regulation and antioxidant enzyme activity, helping the plant adapt to adverse conditions. Advances in breeding and biotechnology have further improved rapeseed's stress resistance. For instance, breeding programs selecting for specific traits have successfully enhanced stress tolerance, while modern biotechnological approaches, such as gene editing, offer promising avenues for increasing rapeseed's resilience to challenging environmental factors (Raza, 2020; Raboanatahiry et al., 2022).

2.3 Economic importance

Rapeseed holds substantial economic importance due to its versatile applications. It is the second most important oil crop globally, following soybean, and its oil is widely used for cooking, industrial purposes, and as a feedstock for biodiesel production (Raboanatahiry et al., 2022). The economic value of rapeseed is also linked to its by-products, such as meal, which is a high-protein animal feed. The economic value of rapeseed also relates to its by-products, such as high-protein rapeseed meal, which is an important animal feed. With the advancement of biorefining technology, rapeseed meal is now also regarded as a raw material for producing bio-based, high-value-added molecules, including antioxidants and protein isolates, opening up more applications and enhancing its economic worth (Di Lena et al., 2021). Studies further indicate that polyphenolic compounds in rapeseed meal exhibit strong antioxidant properties, making them suitable for applications in the food or pharmaceutical sectors (Laguna et al., 2018).

In regions like China, rapeseed cultivation is integral to food security and rural livelihoods, with socio-economic factors like rural electricity consumption and agricultural mechanization playing significant roles in yield enhancement (Liang et al., 2023). The development of high-yielding and disease-resistant rapeseed varieties through advanced breeding techniques, including QTL analysis and GWAS, further underscores its economic significance (Khan et al., 2021). The optimization of agronomic practices, such as weed control and drainage, can significantly narrow the yield gap, thereby boosting the economic returns from rapeseed cultivation (Zhang et al., 2020).

3 Influence of Climatic Conditions on Rapeseed Yield and Quality

3.1 The impact of temperature on the growth cycle and oil content

Temperature significantly affects the germination rate of rapeseed seeds and the vigor of seedlings. A study compared the effects of 21/18 °C (control temperature, CT), 28/18 °C (moderate temperature, MT), and 34/18 °C (high temperature, HT) on seed development in rapeseed (Mácová et al., 2022). The results showed that under higher temperature conditions, seed viability and germination rates in rapeseed significantly decreased, while abnormalities in embryo development intensified. Further analysis revealed that early-stage embryonic abnormalities persisted into the seedling stage, with high temperatures impacting embryo structure and subsequently diminishing the growth quality of both seeds and seedlings (Figure 1). Low-temperature conditions (e.g., 8 °C or lower) significantly inhibit germination rate, as well as root and shoot growth in rapeseed. Genetic studies indicate that under low-temperature stress, rapeseed seeds activate a gene expression regulatory network involving transcription factors such as WRKY, bZIP, and MYB to manage oxidative stress induced by cold, maintain cell wall relaxation, and support embryo expansion, which is critical for improving germination rates in low-temperature environments (Luo et al., 2019; Korniychuk and Yurchuk, 2023).

Temperature also significantly affects oil synthesis and composition in rapeseed. High temperatures during the seed development phase can lead to reduced oil content and altered fatty acid composition, negatively impacting oil quality (Mácová et al., 2022). Studies have shown that cooler temperatures during seed development are associated with higher oil content and better oil quality (Marjanović-Jeromela et al., 2019). The interaction between temperature and other climatic factors, such as precipitation and humidity, further influences oil synthesis, necessitating a comprehensive understanding of these dynamics for optimal oil production (Marjanović-Jeromela et al., 2019; Jannat et al., 2022).

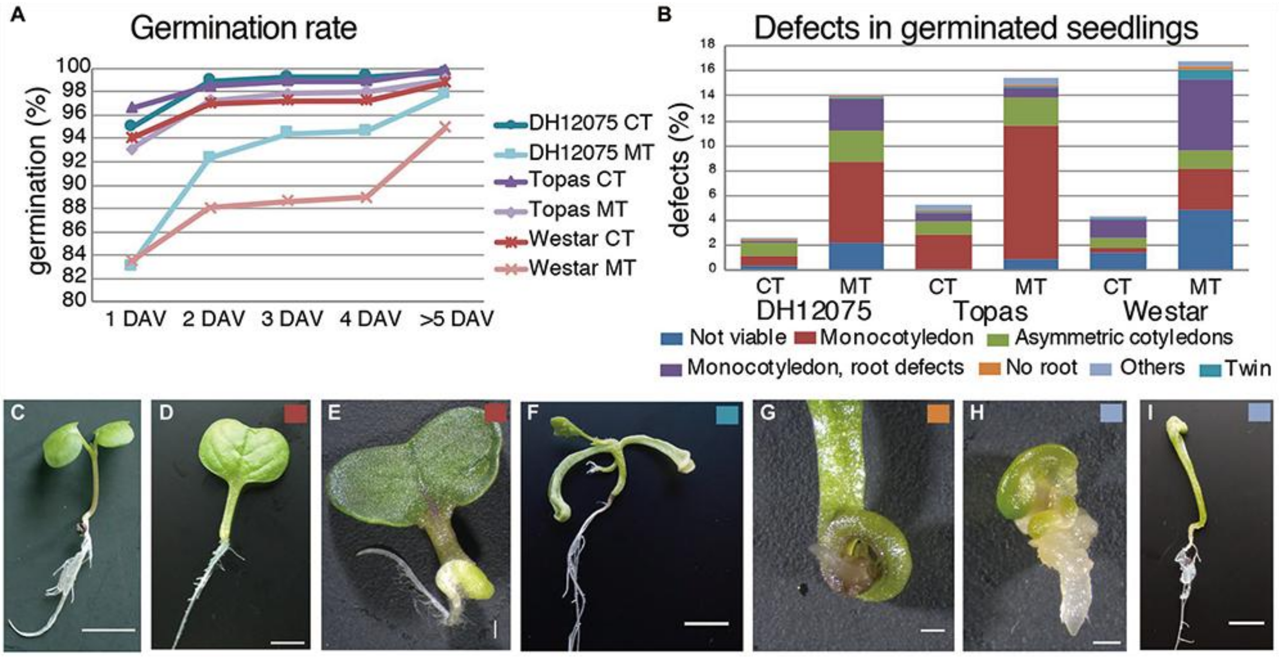

Figure 1 Seed development at high temperatures affects seedling viability (Adopted from Mácová et al., 2022)

Image caption: (A) Graph displaying the cumulative percentage of seed germination at 1, 2, 3, and 4 days after vernalization (DAV), and later for seeds produced by DH12075, Topas, Westar plants grown at CT and MT. (B) Percentage of defective seedlings per categories of defects: not viable (dark blue), with one cotyledon (red), asymmetrically positioned cotyledons (green), twin seedlings (turquoise), with one cotyledon, and defective root (purple), without any root (orange) and other categories (light blue). The analysis was performed on seedlings from seeds produced by DH12075, Topas, Westar plants grown at CT and MT. (C – I) Range of observed seedling phenotypes. A wild-type seedling is shown (C). Seedlings (D, E) are with one cotyledon (red). (F) The seedling is with two roots and two shoots (turquoise). (G) Zoom in of a seedling without root (orange). (H, I) are shown seedlings from the other categories (light blue). The small colored square in the upper right corner refers to the categories. Scale bars represent 10 mm (Adopted from Mácová et al., 2022)

3.2 The importance of precipitation and water management

Precipitation is a critical factor in determining rapeseed yield stability. Adequate rainfall during key growth stages, such as budding and flowering, is essential for maximizing yield potential (Marjanović-Jeromela et al., 2019). Insufficient rainfall can lead to water stress, reducing biomass production and seed yield (Raza, 2020). Conversely, excessive rainfall can cause waterlogging, negatively affecting root development and nutrient uptake. Studies have shown that rapeseed is prone to restricted growth and reduced yields under drought conditions. For example, in one study, insufficient water led to a decrease in chlorophyll content and photosynthesis rate in rapeseed, which subsequently reduced seed yield and oil quality (Teymoori et al., 2020). Conversely, excessive rainfall may cause waterlogging, negatively affecting root development and nutrient absorption. Nabloussi et al. (2019) found that waterlogging stress during different growth stages (e.g., germination and seedling stages) significantly reduced rapeseed yield, with the seedling stage being the most susceptible to waterlogging impacts on final yield.

Effective water management techniques are vital for optimizing rapeseed growth and yield. Practices such as controlled irrigation and drainage can mitigate the adverse effects of both drought and excessive rainfall (Zhang et al., 2020). Implementing these techniques helps maintain soil moisture at optimal levels, ensuring consistent water availability throughout the growing season. Additionally, adopting water-efficient practices, such as mulching and conservation tillage, can enhance water retention and reduce evaporation, further supporting plant growth and yield stability (Zhang et al., 2020; Jannat et al., 2022).

3.3 The relationship between sunlight duration and photosynthetic efficiency

Photoperiod directly affects biomass production in rapeseed. Longer daylight hours enhance photosynthetic activity, increase biomass accumulation, and improve yield potential. A study on rapeseed production in the Yangtze River Basin, China, indicated that factors like photoperiod during growth stages significantly impact biomass and leaf area index (Xu et al., 2021). In high-altitude regions, extended daylight hours have been shown to substantially boost rapeseed yield by increasing the number of siliques and seed weight (Xiong et al., 2022).

Additionally, research suggests that early sowing (e.g., mid-October) can extend the photosynthetic period, significantly enhancing biomass accumulation and yield. In contrast, delayed sowing shortens the growth duration, thus reducing yield (Kaur et al., 2018). Therefore, optimizing sowing dates to align with periods of maximum sunlight is a strategy to improve biomass production and overall yield. In areas with shorter daylight, supplemental lighting or selecting high photosynthetic efficiency varieties can mitigate limitations caused by insufficient light (Li et al., 2022).

4 Soil Fertility and Nutrient Management

4.1 Suitability of soil types for rapeseed growth

Soil texture significantly influences root development in rapeseed. In the Yangtze River Basin, subsoil tillage (Sub-T) has been shown to reduce soil bulk density and penetration resistance, which in turn promotes root and shoot growth of rapeseed. This method enhances the concentration of moisture, total nitrogen, organic matter, and available nutrients in the soil, thereby improving root bleeding sap and root hormone levels, which are crucial for robust root development (Wang et al., 2021). Additionally, poorly drained clay soils in this region negatively affect rapeseed growth, highlighting the importance of soil texture in crop productivity.

Soil pH is another critical factor affecting nutrient availability for rapeseed. Biochar application has been found to significantly increase soil pH, which in turn enhances the availability of phosphorus, organic carbon, and other essential nutrients (Jin et al., 2019; Liu et al., 2022). In upland red soils, biochar amendments improved soil pH and nutrient availability, leading to increased rapeseed yield, although these benefits diminished over time. Similarly, the combined application of biochar with organic and inorganic fertilizers improved soil pH and nutrient availability, promoting rapeseed growth in purple soils.

4.2 Roles of key nutrients

Nitrogen (N) is a vital nutrient for rapeseed, significantly impacting plant vigor and yield. Studies have shown that nitrogen application enhances leaf chlorophyll content, leaf area, and the quantum yield of photosystem II, which are essential for photosynthesis and plant growth (Zangani et al., 2021). Optimal nitrogen rates have been identified to maximize rapeseed yield, with higher nitrogen levels leading to increased seed and oil yield (Grzebisz et al., 2020; Zangani et al., 2021). However, excessive nitrogen can lead to nutrient imbalances and reduced efficiency in nutrient uptake (Khan et al., 2020).

Phosphorus (P) and potassium (K) play crucial roles in the flowering and seed formation of rapeseed. Phosphorus application has been shown to increase leaf stomatal conductance and the quantum yield of photosystem II during the early flowering stage, thereby enhancing seed yield and quality (Zangani et al., 2021). Potassium, along with phosphorus, is essential for nutrient uptake and overall plant health. Studies have demonstrated that the combined application of phosphorus and potassium significantly improves rapeseed yield and nutrient status (Grzebisz et al., 2020; Zangani et al., 2021).

4.3 Effects of trace elements on quality and disease resistance

Micronutrients such as sulfur (S) and boron (B) are critical for improving the oil quality of rapeseed. Sulfur is essential for the biosynthesis of glucosinolates and sulfur-containing amino acids, which are important for oil quality (Basumatary et al., 2021; 2022). The combined application of sulfur and boron has been shown to enhance the oil content and protein quality of rapeseed seeds, thereby improving the overall quality of the crop.

Trace elements also play a significant role in enhancing disease resistance in rapeseed. Micronutrients such as magnesium (Mg) have been found to improve the nutritional status of plants, thereby enhancing their resistance to diseases (Geng et al., 2021). Improved magnesium nutrition not only increases seed yield and quality but also enhances the uptake of other essential nutrients like nitrogen and phosphorus, contributing to better plant health and disease resistance.

5 Planting Density and Field Management

5.1 Impact of planting density on yield

Optimal planting density is crucial for maximizing rapeseed yield. Studies have shown that the highest yields are often achieved at moderate planting densities. For instance, a planting density of 22.5×10^4 plant/ha combined with high fertilization rates resulted in the highest seed oil and protein yields (Tian et al., 2020). Similarly, the CROPGRO-Canola model simulations indicated that an optimal planting density of 45-75 plants/m^2, along with appropriate nitrogen rates, maximizes yield (Wang et al., 2022). Another study found that a density of 30.0×10^4 plants/ha with 144 kg N/ha was optimal for high yield and nitrogen utilization efficiency (Zhao, 2022).

Overcrowding can negatively impact plant health and yield. High planting densities can lead to reduced photosynthetic rates, lower pod numbers per plant, and increased competition for resources, ultimately reducing individual plant yield (Li et al., 2018). Additionally, excessive density can increase the lodging index, which negatively affects seed oil content and overall plant stability. Overcrowding also reduces biomass accumulation and root-to-shoot ratios, leading to lower survival rates after mechanized transplanting (Zuo et al., 2022).

5.2 Key measures for weed and pest management

Effective weed control is essential for optimizing rapeseed yield. Integrated weed management strategies, including timely planting and appropriate planting densities, can significantly reduce weed pressure. Higher planting densities have been shown to inhibit weed growth by reducing the space available for weeds to establish (Li et al., 2018). Additionally, the use of mulching can suppress weed growth by creating a physical barrier and altering soil conditions unfavorable for weed germination (Feng et al., 2020).

Combining biological and chemical pest control methods can effectively manage pest populations in rapeseed fields. Biological control involves using natural predators or parasites to reduce pest numbers, while chemical control uses pesticides. Studies have shown that integrated pest management (IPM) strategies, which combine these methods, can improve yield and reduce the reliance on chemical pesticides, thereby minimizing environmental impact (Zhang et al., 2020). Effective pest control is crucial for maintaining plant health and maximizing yield potential.

5.3 Mulching and soil moisture management

Mulching is a crucial practice for managing soil moisture and improving rapeseed yield, especially in regions with fluctuating climate conditions. Feng et al. (2020) conducted a field experiment during rainy and drought seasons in Southwest China to analyze the effects of different cultivation methods and fertilization strategies on rapeseed growth and resource use efficiency. The results showed that yields were lower in the rainy season than in the drought season. However, the combination of slow-release fertilizer with straw mulching or ridge-furrow rainfall harvesting systems effectively increased rapeseed yield and oil content by 7.71% to 29.93% (Figure 2). Additionally, these combinations significantly improved water and fertilizer use efficiency while reducing total water consumption.

Additionally, subsoil tillage (Sub-T) can improve soil properties such as bulk density and penetration resistance, further promoting root and shoot growth and increasing yield by up to 16.5% (Wang et al., 2021). These practices are particularly beneficial in poorly drained soils, such as those found in the Yangtze River Basin, where they can provide lasting improvements in soil conditions and crop yield.

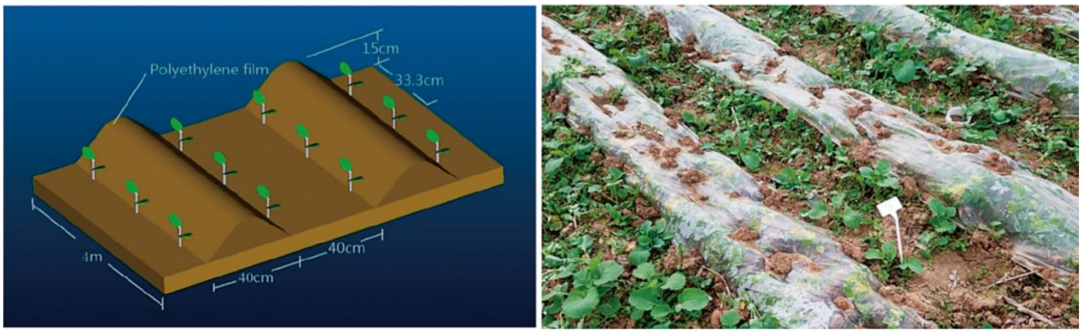

Figure 2 The schematic diagram of ridge-furrow rainfall harvesting system (Adopted from Feng et al., 2020)
Image caption: The ridge-furrow rainfall harvesting system uses transparent polyethylene film to cover the ridges, reducing soil water evaporation and promoting crop growth by retaining soil moisture and regulating temperature. In the experiment, this technique significantly improved soil moisture retention, positively impacting water use efficiency and yield of rapeseed, providing stable water support for rapeseed cultivation during both drought and rainy seasons (Adapted from Feng et al., 2020)

6 Growth Regulators and Hormone Management

6.1 Application of growth regulators in rapeseed production

The application of growth regulators in rapeseed production has shown significant potential in enhancing yield and quality. For instance, wood vinegar, a byproduct of biochar production, has been found to act similarly to plant growth regulators. Zhu et al. (2021) found that applying 400-fold diluted wood vinegar during the seedling and overwintering stages significantly enhanced rapeseed seed yield, leaf area index, and silique number per plant by 9.58%, 23.45%, and 23.80%, respectively. When wood vinegar was combined with gibberellins, sodium gluconate, and melatonin, yields increased further, while the incidence of diseases such as *Sclerotinia sclerotiorum* and *Peronospora parasitica* was reduced, thereby improving rapeseed quality.

Another study showed that foliar spraying with salicylic acid and putrescine alleviated the effects of water stress on rapeseed production. This treatment enhanced antioxidant enzyme activity, increased leaf water content, membrane stability, and chlorophyll content, leading to significant increases in seed and oil yield, demonstrating the effectiveness of plant growth regulators in improving plant stress tolerance (Ghassemi-Golezani et al., 2019). Additionally, exogenous strigolactones (SLs) promoted lateral root growth by reducing endogenous auxin levels, thus enhancing overall plant growth and seed yield (Ma et al., 2020).

6.2 Influence of hormone balance on rapeseed flowering and pod formation

Hormone balance plays a crucial role in the flowering and pod formation of rapeseed. Auxin, a key plant hormone, has been shown to regulate the timing of the transition from vegetative to reproductive growth. A study on the effects of different nitrogen levels on floral primordium differentiation in rapeseed found that high nitrogen treatment advanced the timing of floral primordium differentiation by 4 to 7 days and increased yield by approximately 11.1% to 22.6% (Hao et al., 2022). During this process, auxin synthesis primarily occurred through the significant accumulation of indole-3-acetonitrile. The study also demonstrated that the expression of genes related to auxin synthesis and signaling pathways varied across five differentiation stages under different nitrogen levels, further indicating that high nitrogen levels accelerated floral primordium differentiation by modulating the auxin pathway.

The balance of other hormones such as gibberellins and strigolactones also influences flowering time and pod formation. For example, gibberellins have been implicated in promoting floral initiation under low-temperature conditions, particularly in semi-winter rapeseed varieties (Luo et al., 2022). Moreover, the interaction between 14-3-3 proteins and vernalization-related flowering regulators further underscores the importance of hormone balance in flowering regulation (Fan et al., 2022).

6.3 Hormone requirements at different stages of the growth cycle

The hormone requirements of rapeseed vary significantly at different stages of the growth cycle. During the early stages, auxin and gibberellins are critical for promoting vegetative growth and the transition to reproductive stages. High nitrogen application rates have been shown to enhance auxin biosynthesis, thereby accelerating floral meristem differentiation and increasing seed yield (Hao et al., 2022). Cytokinins play a crucial role in the reproductive development stage of rapeseed, particularly during floral bud differentiation under low-temperature conditions, where their levels rise significantly and then gradually decrease. This hormonal fluctuation is essential for the timing regulation of floral bud development (Tarkowská et al., 2019).

During the flowering and pod development stages, the balance of nitrogen and other hormones such as gibberellins and strigolactones becomes crucial. For instance, shading during these stages can disrupt nitrogen dynamics and hormone balance, leading to reduced yield. However, appropriate nitrogen application can mitigate these effects by improving pod wall morphology and carbon metabolism (Javed et al., 2022; Kuai et al., 2023). Additionally, wood vinegar and its compounds, when applied during the seedling and overwintering stages, have been shown to enhance growth, yield, and quality by modulating hormone levels and improving stress resistance (Zhu et al., 2021).

7 Case Studies on Rapeseed Yield and Quality Improvement

7.1 Study on the mechanism of high rapeseed yield in special plateau ecological environments

In the Xiangride area of the Qinghai Plateau, with its unique high-altitude and extended daylight ecological environment, an ideal setting is provided for studying the high-yield mechanisms of rapeseed (*Brassica napus* L.). A study comparing the Qinghai Plateau's Xiangride area (XRD) and the lower-yielding Xining area (XN) found that extended daylight in Xiangride is a key factor for high yield, directly promoting significant increases in thousand-seed weight and silique number by approximately 52.1% and 59.6%, respectively (Xiong et al., 2022). The study showed that seed development in Xiangride begins earlier and lasts longer (Figure 3). Transcriptomic data revealed key yield-related gene expression changes, encompassing processes such as photosynthesis, lipid metabolism, and seed storage protein synthesis. For example, the *XTH24* gene, involved in cell wall degradation, was significantly downregulated in Xiangride, whereas genes related to lipid metabolism and oxidation processes showed an upregulation trend. These findings confirm the positive impact of extended daylight on rapeseed yield and provide crucial theoretical support for rapeseed cultivation in high-altitude regions.

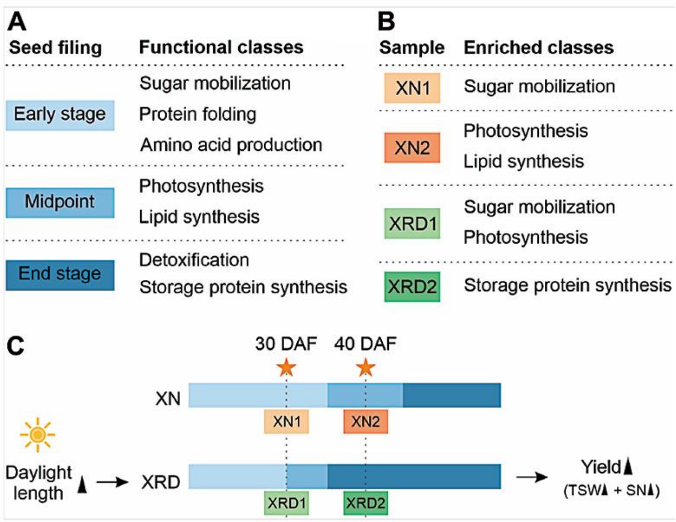

Figure 3 A proposed working model for rapeseed high yield in the unique plateau habitat (Adopted from Xiong et al., 2022)

Image caption: The figure shows that, compared to the Xining region (XN), rapeseed seed development in the Xiangride region (XRD) advances into the late stage earlier, with an enrichment of genes related to storage protein synthesis. The results indicate that longer daylight accelerates the transition to late-stage development, thus extending the seed-filling period and increasing yield, revealing the molecular mechanisms behind the high yield of rapeseed in the unique ecological environment of XRD (Adapted from Xiong et al., 2022)

7.2 Study on optimizing fertilizer and density to enhance rapeseed efficiency

As an important source of edible oil and biofuel, the demand for rapeseed has been increasing year by year. To meet market demand while ensuring planting efficiency, scientific and rational cultivation management is particularly critical. Tian et al. (2020) studied the effects of fertilization levels and planting density on rapeseed yield, quality, and economic benefits. The experimental results showed that increasing fertilizer input significantly improved the dry matter accumulation, seed oil yield, and protein content of rapeseed, but the oil content slightly decreased. Although planting density had no significant effect on oil and protein content, an appropriate combination of fertilizer and planting density helps maximize economic benefits. The results indicated that the optimal combination was high fertilizer input (240 kg of nitrogen, 52.4 kg of phosphorus, etc.) and medium planting density (225,000 plants per hectare), achieving the highest yields of rapeseed oil and protein under this combination.

Another study in Assam, India, showed that the application of sulfur (S) and boron (B) fertilizers improved the yield and quality of rapeseed. The combination of applying 20 kg S/ha and 1.5 kg B/ha achieved the highest grain and straw yields, while increasing the oil content of rapeseed by 35.6% and protein content by 22.9% (Marjanović-Jeromela et al., 2019).

8 Future Perspectives in Rapeseed Agronomy

8.1 Innovations in cultivation techniques

Precision agriculture offers significant potential for optimizing resource use in rapeseed cultivation. By employing technologies such as GPS-guided equipment, remote sensing, and data analytics, farmers can apply inputs like fertilizers and pesticides more efficiently, reducing waste and environmental impact. Studies have shown that precision agriculture can help close the yield gap in rapeseed by addressing specific agronomic constraints and improving overall management practices (Zhang et al., 2020; Li et al., 2022; Liang et al., 2023).

Automation and mechanization are transforming rapeseed farming by reducing labor costs and increasing operational efficiency. The use of advanced machinery for planting, irrigation, and harvesting can lead to more consistent crop management and higher yields. For instance, the integration of automated systems for precise sowing and irrigation has been shown to enhance yield and quality by ensuring optimal growing conditions (Liang et al., 2023).

8.2 Sustainable agronomic practices

Sustainable soil management practices are crucial for maintaining soil health and ensuring long-term productivity in rapeseed cultivation. Techniques such as crop rotation, cover cropping, and reduced tillage can improve soil structure, enhance nutrient cycling, and reduce erosion. Research indicates that these practices not only support higher yields but also contribute to the resilience of rapeseed crops against environmental stresses (Basumatary et al., 2021; Wolko et al., 2022; Yadav et al., 2022).

Water management is a critical factor in rapeseed production, especially in regions facing water scarcity. Implementing water-saving irrigation techniques, such as drip irrigation and scheduling based on soil moisture monitoring, can significantly reduce water use while maintaining or even improving yields. Studies have demonstrated that efficient irrigation practices can enhance water use efficiency and support sustainable rapeseed production (Marjanović-Jeromela et al., 2019; Basumatary et al., 2021).

8.3 Breeding for resilience and improved quality

Breeding programs focusing on developing drought and disease-resistant rapeseed varieties are also an important direction for future research. Advances in genetic research, including the identification of quantitative trait loci (QTLs) and the use of genome-wide association studies (GWAS), have facilitated the development of resilient varieties. These efforts are crucial for ensuring stable yields and reducing the reliance on chemical inputs (Raza, 2020; Khan et al., 2021).

Improving the nutritional quality of rapeseed through genetic approaches is another key area of focus. By leveraging modern biotechnological tools, researchers are working to enhance the oil and protein content of rapeseed. This includes the use of marker-assisted selection and genetic modification to introduce desirable traits. Enhanced oil and protein content not only increases the economic value of the crop but also meets the growing demand for high-quality edible oils and animal feed (Khan et al., 2021; Wolko et al., 2022).

9 Concluding Remarks

This study emphasizes the key agronomic factors affecting rapeseed yield and quality, highlighting the interactions between management practices, environmental conditions, and genetic factors. Climate variables such as precipitation and relative humidity during specific growth periods are critical in determining yield and oil content. Socioeconomic factors, including rural electricity consumption and effective irrigation area, play a significant role in yield variation, particularly impacting winter rapeseed yields. Additionally, the application of sulfur and boron fertilizers significantly improves seed and straw yield, as well as oil and protein content. In high-altitude regions, extended daylight hours prolong the grain development period, thereby supporting higher yields.

Based on research findings, several measures are recommended to optimize rapeseed yield and quality. Effective weed and drainage management should be prioritized as they help reduce yield gaps. During critical growth stages, water supply and temperature control should be aligned with specific climate conditions to enhance yield. Socioeconomic factors also play a significant role; improving rural infrastructure and expanding irrigation coverage can contribute to yield stability. In terms of fertilizer management, applying sulfur and boron based on soil conditions can improve nutrient use efficiency and enhance rapeseed quality. Breeding programs should focus on developing high-yield varieties adapted to specific ecological environments, especially in high-altitude regions with extended daylight hours. To address climate change, crop management strategies should optimize the utilization of cumulative daylight exposure. Integrating advanced genetic techniques is equally essential, with further application of QTL mapping and GWAS recommended to identify and harness genetic markers associated with high yield and quality traits.

The optimization of rapeseed yield and quality is a multifaceted challenge that requires a comprehensive approach, integrating agronomic practices, climatic considerations, socio-economic factors, and genetic advancements. By addressing these key factors, it is possible to significantly enhance rapeseed production, thereby contributing to global food and energy security. Future research should continue to explore the complex interactions between these factors and develop innovative solutions to meet the growing demand for rapeseed and its derived products.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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