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Impact of Irrigation and Fertilization Regimes on Rapeseed Yield

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Abstract Rapeseed (*Brassica napus* L.) shows a relatively obvious response to changes in water and nutrients. If the water is not applied appropriately or the fertilization is not reasonable, it can easily affect the yield. This study mainly collated and analyzed the performance of rapeseed in terms of yield formation, water use efficiency, and yield stability under different irrigation amounts, limited irrigation methods, and rainwater harvesting cultivation conditions. At the same time, the combined application effects of nitrogen, phosphorus, potassium fertilizers, and organic fertilizers under different water supply conditions were summarized, and the impacts on the growth of rapeseed, yield composition, nutrient absorption, and nitrogen utilization efficiency were analyzed in detail. Under moderate water shortage conditions, the use of multiple fertilizers in combination is more conducive to increasing yield and maintaining yield stability. From the perspective of coordinated regulation of water and nutrients, this research provides a reference basis for rapeseed to achieve high yield, high efficiency, and green production.

Keywords Rapeseed; Irrigation system; Fertilization management; Water use efficiency; Nitrogen use efficiency

1 Introduction

Rapeseed (*Brassica napus* L.) is highly affected by soil moisture. This influence is stronger at several key growth stages. These stages include branching, flowering, and pod filling. If nitrogen is applied at a suitable level, rapeseed growth improves. Plants accumulate more dry matter. The number of branches increases, and more pods are formed. As a result, seed yield becomes higher. In contrast, excessive nitrogen application often leads to negative outcomes. Nitrogen partial productivity declines. Nitrogen recovery efficiency also becomes lower. At the same time, overall nitrogen use efficiency is reduced. To reduce these problems, more appropriate fertilization practices can be used. Deep fertilization, layered fertilization, and fertilizer placement close to the root zone can improve soil conditions near the roots. These methods promote root development and increase soil macroporosity. This creates a better soil environment for rapeseed growth (Gao et al., 2024).

Increasing climate variability has resulted in alternating seasonal drought and waterlogging events, making traditional fixed irrigation quotas or rigid irrigation schedules difficult to balance water risk and economic efficiency across different years (Raza, 2020). Many high-yield cultivation systems still rely on relatively high nitrogen application rates, which, under conventional tillage and flat planting conditions, are often associated with substantial nitrate leaching and low nitrogen use efficiency. This poses increasing pressure on groundwater quality and the surrounding ecological environment.

This study quantitatively evaluates the responses of rapeseed yield and its components, water consumption, and water use efficiency under different irrigation levels or rainwater harvesting cultivation patterns. It further analyzes the interactive effects of irrigation and fertilization on root-zone water and nutrient conditions, nutrient uptake, and crop population structure. The results are expected to provide scientific evidence and technical references for achieving high yield, high efficiency, and environmentally friendly rapeseed production in arid and semi-arid regions as well as areas with seasonal fluctuations between dry and wet conditions.

2 Conceptual Framework of Irrigation and Fertilization in Rapeseed Production

2.1 Characteristics of rapeseed yield formation

Rapeseed seed yield is determined by the number of effective plants per unit area, the number of effective pods per plant, the number of seeds per pod, and the thousand-seed weight. The core of yield formation lies in the formation of branches and pods, as well as the seed filling capacity. The biological yield of winter rapeseed is the product of growth rate and the length of the growing season, while an increase in the harvest index can significantly increase seed yield. In yield composition, the number of pods per plant is usually considered a key trait determining yield, its essence depending on the survival rate of branches, flowers, and young pods, rather than the potential number of flowers or pods. Appropriate nitrogen fertilizer levels and management can significantly increase the number of pods per plant, the number of branches, and the number of seeds per pod. Rapeseed yield is highly sensitive to seasonal conditions, with differences in planting time, precipitation, and temperature patterns in different years leading to yield variations of approximately 80%. Under drought and water deficit conditions, rapeseed maintains leaf function and tries to maintain the supply of photosynthetic products by regulating osmotic adjustment substances (soluble sugars, proline) and antioxidant enzyme activity, but yield and pod number still decrease significantly.

2.2 Water requirements at different growth stages

The water requirements of rapeseed throughout its entire growth period are significantly stage-dependent. The seedling and overwintering stages require moderate water to ensure seedling emergence and safe overwintering, while the branching-flowering-pod filling stage is the peak period of water demand. Water availability is the dominant factor for winter rapeseed seed yield and oil content, especially precipitation and soil moisture conditions during the budding, flowering, and pod filling stages, which have a high explanatory power for yield and oil content variations. In supplementary irrigation experiments in semi-arid regions, supplementary irrigation at the initial flowering stage, when approximately 50% of the effective soil moisture in the root zone is consumed, can maximize yield and economic benefits without significantly reducing water use efficiency; while moderately reducing or stopping irrigation in the later stages of pod filling has limited impact on yield but is beneficial for saving irrigation water. In rain-fed areas with alternating seasonal droughts and floods, cultivation practices such as ridge-and-furrow rainwater harvesting and straw mulching can significantly improve soil water storage and buffer water fluctuations, thereby increasing dry matter accumulation and grain yield (Teymoori et al., 2020).

2.3 Nutrient demand patterns and fertilization response characteristics

The optimal nitrogen fertilizer application rate is approximately 120~200 kg N ha^{-1}, which ensures high yield while balancing nitrogen use efficiency and economic benefits. Exceeding this range significantly reduces nitrogen use efficiency and nitrogen partial factor productivity (Zhu et al., 2023). Combined application of nitrogen and phosphorus can increase chlorophyll content, PSII quantum efficiency, and leaf area, extending the grain filling period, while increasing nitrogen alone at high levels does not significantly increase most traits. The yield response of rapeseed to N, P, S, and K follows the order N > P > S > K, and combined application of organic fertilizers (such as farmyard manure and vermicompost) with chemical fertilizers can significantly improve the agronomic efficiency and apparent nutrient recovery rate of major nutrients (Jehangir et al., 2024). In water-deficient or fluctuating water environments, integrated fertilization (chemical fertilizers + organic fertilizers + plant growth-promoting rhizobacteria (PGPR)) can significantly mitigate the adverse effects of drought on grain yield, oil content, and fatty acid composition by increasing antioxidant enzyme activity, maintaining leaf water content, and stomatal conductance. Synergistic application of N and K is crucial for achieving high yield and high nitrogen use efficiency; potassium deficiency will significantly reduce branching and pod number, and increase soil nitrogen surplus; while nitrogen application under sufficient potassium supply can increase nitrogen absorption, nitrogen use efficiency, and reduce nitrogen surplus.

3 Effects of Irrigation Regimes on Rapeseed Yield

3.1 Full irrigation and yield stability

In the Trakya region of Turkey, the "full irrigation" treatment, which avoided water stress during flowering, yield formation, and maturation stages, resulted in a seasonal irrigation amount of 251 mm and a total seasonal evapotranspiration of 715 mm, corresponding to a seed yield of 4.80 t/ha, the highest among all treatments (Istanbulluoğlu et al., 2010). Based on a 3-year supplemental irrigation experiment under semi-arid winter rapeseed conditions, all supplemental irrigation treatments significantly increased yield compared to the rain-fed treatment. The "full irrigation" treatment, which replenished soil moisture during three growth stages (vegetative growth, flowering, and early maturity), achieved the highest seasonal evapotranspiration and seed yield, while also resulting in the highest protein, oil, and fatty acid content. In two growing seasons in Egypt, the "full irrigation" treatment with a total of 4800 m^3/ha applied in five irrigations resulted in significantly higher seed and oil yields compared to treatments with reduced irrigation frequency and amount. 4 800 m^3/ha irrigation, compared to only 1 920 m^3/ha (two irrigations), increased plant height, number of branches, number of pods, single plant seed weight, and seed, oil, and protein yields by 40%~58% (Kandil et al., 2017). A population evaluation of 119 varieties under two water regimes (full irrigation vs. drought during the reproductive stage) over 3 years showed that average seed yield under full irrigation was significantly higher than under drought conditions, and the variation among varieties was more pronounced (Salami et al., 2024).

3.2 Irrigation strategies and yield trade-offs

In Iran, a two-year experiment applying water stress during the reproductive stage after tillering (with irrigation stopped during flowering, pod development, and grain filling stages, respectively) showed that, compared to full irrigation throughout the growing season, water restriction during flowering reduced grain and oil yield by 29.5% and 31.7%, respectively, while water restriction during pod development and grain filling resulted in smaller yield reductions (Ahmadi and Bahrani, 2009). Compared to full irrigation, the 0.75 FI and 0.50 FI treatments reduced grain yield by 15.0% and 25.9%, respectively, while in the second year, the 0.65 FI and 0.35 FI treatments reduced grain yield by 20.8% and 33.0%, respectively. This indicates that within a 10%~13% reduction in irrigation volume, grain, oil, and protein yields can remain relatively stable, while larger reductions in water lead to significant yield losses (Shabani et al., 2012). Based on simulations using the APSIM-Canola model at 10 locations, with 3 varieties and 4 irrigation scenarios (full irrigation, irrigation stopped during flowering, pod development, and grain filling), the average potential yield at temperate western locations was 2 852.6 kg/ha, while at hot southwestern locations it was only 1 885.1 kg/ha. In all scenarios, stopping irrigation after the start of grain filling resulted in the smallest yield reduction, only 13.6%, while stopping irrigation during flowering and pod development resulted in more significant yield losses (Rahimi-Moghaddam et al., 2021). In a 2015~2017 field experiment in Iran involving 17 varieties and two irrigation treatments, withholding irrigation from silique formation to maturity reduced average grain yield, but some genotypes (such as HL3721) maintained a grain yield of 3892 kg/ha and an oil content of 437 g/kg under limited irrigation conditions (Eyni-Nargeseh et al., 2019). In a multi-variety study in the Karaj region, among three gradients of withholding irrigation starting from stem elongation, flowering, or silique formation, the earliest treatment (no irrigation after stem elongation) resulted in an average yield reduction of 30%~50%, while withholding irrigation after silique formation resulted in a relatively lower yield reduction (Rad et al., 2014).

3.3 Water stress during critical growth stages and yield reduction effects

In a greenhouse pot experiment, drought stress was set at the flowering stage. Two soil water loss speeds were used, one slow and one fast. When water loss was slow, leaf relative water content only dropped by about 2% compared with the control. When water loss was fast, the drop reached about 6%. At the same time, stomatal conductance and CO_2 assimilation both fell clearly. Grain dry weight and silique number also decreased a lot (Xiang et al., 2024). When irrigation was stopped from flowering to silique formation, the impact became more serious. Grain yield dropped by 38%~49%. Oil content was reduced by about 4%~9%. Fatty acid composition also changed. Linolenic acid, erucic acid, and glucosinolate levels increased under drought stress (Amiri et al., 2024). Field experiments carried out in Karaj from 2015 to 2017 showed similar results. Under normal sowing time and full irrigation, the highest grain yield reached 4505.6 kg/ha. However, when sowing was delayed and irrigation was stopped after flowering, yield fell sharply to only 1814.6 kg/ha. This means the yield was reduced by nearly 60% (Shafighi et al., 2022). Under the same drought conditions during flowering, different genotypes responded differently. Drought-tolerant genotypes, such as Nap9, RGS003, and SLM046, showed smaller reductions in yield and oil content. These genotypes usually had longer roots and higher relative leaf water content than drought-sensitive ones.

3.4 Irrigation efficiency and water-saving potential

In the Trakya experiment, irrigation was applied only once after flowering. Under this condition, irrigation water use efficiency reached 71.6 kg/(ha·mm). The total water use efficiency was 7.7 kg/(ha·mm). This result shows that limited irrigation can still be effective at this stage (Istanbulluoğlu et al., 2010). In Southwest China, a two-year rainfed rotation with seasonal drought was tested. In drought years, using only one water management method, such as ridge–furrow rainwater collection or straw mulching, did not greatly increase yield.

However, when these methods were combined with reduced-rate slow-release fertilizer (RF+SR or SM+SR), the results improved. Yield increased by 7.7%~29.9%, and water use efficiency increased by 14.8%~28.7% in both dry and wet years. At the same time, total water use during the growing season was lower than that of local traditional farming practices (Feng et al., 2020). In a semi-arid area of Qazvin, a three-level irrigation experiment was carried out. When soil moisture was kept at 80% of field capacity (FC80), the yield of the Hydromel variety was only slightly lower than at full irrigation (FC100). However, this treatment saved about 20% of irrigation water. Based on these results, the authors suggested that FC80 combined with 30 t/ha of farmyard manure is suitable for water-saving rapeseed production in this region. In contrast, 60% field capacity (FC60) was considered too low, as it greatly reduced pod number and seed yield (Janmohammadi et al., 2024).

4 Effects of Fertilization Regimes on Rapeseed Yield

4.1 Nitrogen management and yield response

At three nitrogen fertilizer levels (0, 180, and 240 kg N ha^{-1}), nitrogen application significantly increased nitrogen accumulation in rapeseed plants during flowering, the number of pods per plant, the number of branches, and the number of seeds per pod, and showed a significant positive correlation with grain yield. The 180 kg N ha^{-1} treatment showed the best overall performance in terms of grain yield and nitrogen use efficiency. When the nitrogen application rate increased from 180 to 240 kg/ha, the yield only increased slightly or not significantly, while nitrogen partial productivity (PPN) and nitrogen use efficiency (NUE) showed a downward trend. Leaf nitrate reductase (NR) and glutamine synthetase (GS) activities peaked at 180 kg N ha^{-1}, and increasing nitrogen levels did not increase the activity of key nitrogen metabolic enzymes (Wang et al., 2025).

In continuous ridge-tillage and mulching cultivation in the arid region of Northwest China, with six nitrogen levels from 0 to 300 kg N ha^{-1}, dry matter, nitrogen uptake, grain yield, and oil content were significantly higher at N180, N240, and N300 compared to N0~N120. However, WUE and N recovery efficiency did not differ significantly between N180 and N240, and both were significantly higher than N300; however, N240 had an average grain yield 11.9% higher than N180 (+427 kg/ha), making it the optimal nitrogen application rate (Gu et al., 2017). In a side-row mulching cultivation experiment under different soil fertility conditions, with nitrogen application rates of 0~360 kg/ha, low-fertility plots (F1, F2) required ≥360 or approximately 300 kg N ha^{-1} to achieve the highest yield, while high-fertility plots (F3, F4) reached peak yields at 272–312 kg N ha^{-1}, with corresponding yields 15.8%~242.3% higher than those with lower nitrogen treatments (Tian et al., 2023).

4.2 Balanced N, P, and K fertilization and yield-increasing effects

In a long-term experiment conducted at three sites over two cropping years in the rice-oilseed rape rotation system in Central China, comparisons of four mineral fertilizer treatments (NPK, NP, NK, and PK) showed that the total oilseed rape yield (two-year total) under the NPK treatment was 827~4 287 kg/ha, significantly higher than that under NP, NK, and PK treatments. Compared to the PK treatment, oilseed rape yield increased by 61%~76%, and rice yield increased by 19%~41%. Nitrogen deficiency was the primary limiting factor, followed by phosphorus and potassium. N, P, and K uptake were highest in the NPK treatment and lowest in the PK treatment, and all NP, NK, and PK treatments significantly reduced the soil's inherent nutrient supply capacity (INuS) (Yousaf et al., 2017). In a split-plot experiment in Zanjan, Iran, with a full factorial combination of N (0, 100, 200 kg ha^{-1}) and P (0, 75, 150 kg/ha), the combined application of 200 kg N ha^{-1} and 75 kg P ha^{-1} significantly increased chlorophyll content and photosystem II quantum efficiency, increased stomatal conductance after flowering, and prolonged the grain filling period; however, single application of 200 kg N or its combination with higher P levels did not show significant gains for most traits, and oil content even decreased (Zangani et al., 2021).

In a combination of four nitrogen application levels (0~270 kg/ha) × four potassium application levels (0~180 kg K_2O ha^{-1}), the combined application of N and K was a prerequisite for high yield. Compared to no N and K application, the grain yield of the control varieties Huayouza 9 and Zhongshuang 11 increased by 153.2–397.5% and 150.4%~322.9%, respectively, under the optimal combination of N180K120, which was significantly higher than that under single application of N or K (Gu et al., 2024). Potassium deficiency significantly reduces branching and pod number, and decreases nitrogen uptake, leading to a significant increase in soil nitrogen surplus under high nitrogen application conditions; while sufficient potassium application under N 180~270 kg/ha conditions can improve nitrogen recovery efficiency and reduce nitrogen surplus (Li et al., 2023).

A phosphorus fertilizer gradient experiment (0~180 kg P ha^{-1}) showed that the seed yield of direct-seeded winter rapeseed increased significantly with P application from 0 to 90 kg/ha, but the yield increase was not significant at 135 and 180 kg P ha^{-1}; P efficiency initially increased and then decreased between 0–90 kg ha^{-1}, and decreased significantly after approximately 120 kg P ha^{-1}, with extra P being allocated more to stems and pods, contributing little to seed yield. Based on this, the optimal P application rate for direct seeding is recommended to be 90~120 kg/ha (Wang et al., 2023).

4.3 Fertilization timing and nutrient absorption and utilization efficiency

Under three sowing dates and five spring nitrogen management strategies, without nitrogen application, the ratio of total crop nitrogen uptake at harvest to the sum of soil mineral nitrogen and plant nitrogen after overwintering (SNUpE) was 1.13~1.14 (early sowing) and 1.68 (late sowing), reflecting that soil mineralization during the growing season provided an additional 11~38.6 kg N ha^{-1} of available N; the economically optimal nitrogen application rate (Nopt) under different sowing dates was 148~175 kg N ha^{-1}, corresponding to an apparent fertilizer nitrogen absorption efficiency (FNUpE) of 0.486~0.574, indicating that adjusting spring nitrogen application based on overwintering plant nitrogen content, sowing date, and expected mineralization can reduce total nitrogen application while maintaining a seed yield of 4.34~4.93 t/ha (Rahimitanha et al., 2022).

In the rice-rapeseed-rice rotation system in Southwest China, a pot experiment was conducted to adjust the nitrogen application rate during the rapeseed season and the split application pattern during the rice season (40% basal fertilizer + 40% tillering fertilizer + 20% panicle fertilizer). Compared with conventional nitrogen application in the rapeseed season (Nc) + M3 split application pattern in the rice season (PrNcM3), reducing nitrogen in the rapeseed season (Nr) and using the M3 pattern in the rice season (PrNrM3) increased the agronomic nitrogen efficiency and nitrogen partial productivity of rice by 23.9% and 1.6%, respectively, while the total annual system yield only decreased by 3.95% (Ma et al., 2021). For direct-seeded rapeseed, introducing a mixture of controlled-release nitrogen and quick-release nitrogen also showed a significant temporal effect: reducing nitrogen by 25% from the conventional application rate of 180 kg N ha^{-1} to 135 kg N ha^{-1}, and combining it with 30%~50% controlled-release nitrogen (N135R1–R3), resulted in no significant difference in pod number, seeds per pod, and grain yield compared to the full quick-release nitrogen control. The N135R2 treatment even increased yield by 1.3%, while apparent N recovery rate, agronomic utilization efficiency, and nitrogen partial productivity all showed an initial increase followed by a decrease, reaching their highest values at a 50% controlled-release nitrogen ratio (Hu et al., 2023) (Figure 1).

4.4 Environmental risks of excessive fertilization

In conventional high-input systems, rapeseed NUE (crop nitrogen uptake/nitrogen input) often does not exceed 60%, and a large amount of unabsorbed nitrogen is lost through nitrate leaching or in the form of N_2O and NH_3, putting pressure on water bodies and the atmospheric environment (Bouchet et al., 2016). When the nitrogen application level exceeds the "economically optimal N rate" for the variety and environment, the increase in grain yield tends to flatten or even stagnate, but the oil content decreases, and the grain protein content increases, accompanied by an increased risk of plant lodging and aggravated disease occurrence, thereby indirectly increasing pesticide input and energy consumption (Yahbi et al., 2022). In nitrogen-sulfur fertilization trials in Poland, when N $\geq$ 180 kg/ha, the energy consumption per unit area increased from 14.5~19.3 GJ/ha to 22.4~27.0 GJ/ha, while the yield increase was limited (Groth et al., 2020).

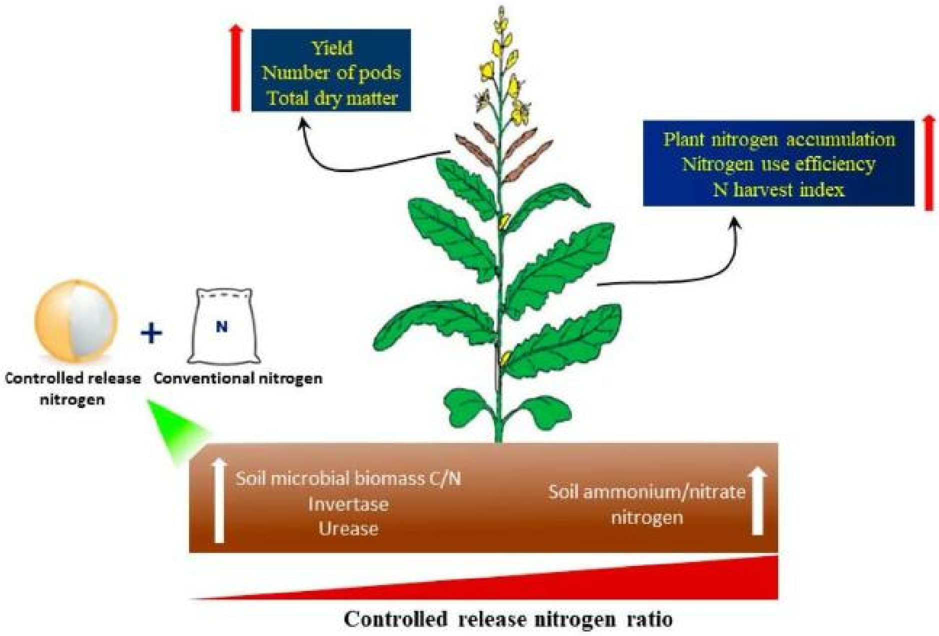

Figure 1 Effects of controlled-release nitrogen on yield and nitrogen use efficiency (Adapted from Hu et al., 2023)

5 Interactive Effects of Irrigation and Fertilization

5.1 Synergistic effects of water and nutrient supply

Different irrigation intervals (70, 100, 130, and 160 mm evaporation) together with different fertilizer treatments had a strong influence on leaf N and P content and grain yield. When irrigation was delayed from 70 mm to 160 mm, both nutrient content in leaves and grain yield gradually went down. Even so, applying fertilizer still increased leaf N and P content under all irrigation conditions. Under serious water shortage (160 mm), the mixed fertilizer treatment, which included chemical fertilizer, vermicompost, and PGPR, performed the best and gave the highest leaf N and P content. When water supply was normal, chemical fertilizer alone (around 300 kg N + 150 kg P ha^{-1}) produced the highest yield. However, its yield was very close to that of the mixed fertilization treatment, and the difference was not significant. As water stress increased to moderate and severe levels (130 and 160 mm), the mixed fertilization treatment clearly produced more grain than chemical fertilizer, PGPR, or vermicompost used alone (Mamnabi et al., 2020).

In another study, three irrigation levels (60%, 80%, and 100% CPE) were combined with three fertilizer rates (60%, 80%, and 100% of the recommended amount). The results showed that drip irrigation at 80% CPE, together with 80%~100% of the recommended fertilizer rate, could achieve nearly the same grain yield as full irrigation and full fertilization. At the same time, this treatment showed the best irrigation use efficiency and water use efficiency. Compared with the traditional practice of flood irrigation with soil-applied fertilizer, this method saved about 35.4% of water and increased grain yield by 18% (Kumar et al., 2021).

5.2 Constraining effects of water-nutrient imbalance

Under conventional tillage, nitrate leaching was very high when normal irrigation was used together with urea. The average value was 83.1 kg/ha. When water supply was reduced and no fertilizer was applied, nitrate leaching dropped sharply. In this case, the value was only 10.4 kg/ha. Compared with urea alone, vermicompost clearly helped reduce nitrate loss. The reduction ranged from 49% to 67%. When urea and vermicompost were used together (VU), nitrate leaching was also lower, with a reduction of about 34%~50%. Across all irrigation levels and tillage methods, the VU treatment performed best overall. Grain yield was the highest under this treatment. Oil content and nitrogen use efficiency (NUE) also reached their highest levels (Khodabin et al., 2022).

Another study was carried out in the semi-arid Qazvin region. This experiment combined three irrigation levels (FC60, FC80, and FC100) with different rates of farmyard manure (0, 15, and 30 t FYM ha^{-1}). Under severe water stress (FC60), plant performance clearly declined. Chlorophyll content, branch number, and pod number all decreased, and adding farmyard manure did not change this trend. Under moderate deficit irrigation (FC80), the situation was different. Applying 30 t FYM ha^{-1} significantly increased pod number and yield in the Hydromel variety. The yield under this treatment was close to that of full irrigation with manure (FC100 + FYM30). At the same time, about 20% of irrigation water was saved (Janmohammadi et al., 2024).

6 Implications for Rapeseed Production Practice

6.1 Irrigation quota and scheduling recommendations

Using only rainfall was not the best option. When extra irrigation was added at different stages, including the vegetative stage, flowering stage, and early grain filling stage, crop yield increased clearly. Among all treatments, irrigating when about 50% of the available soil water in the root zone was used up at the start of flowering gave the best result. This method balanced water use efficiency and economic benefit well. In an experiment using ridge–furrow full-film mulching in the arid areas of Northwest China, clear differences were observed. Without any irrigation, the RFFM0 treatment still greatly increased root and shoot biomass, as well as nutrient uptake. Compared with flat planting without irrigation (FP0) and flat planting with only 30 mm of winter irrigation (FP1), yield increased by 23.7–39.0%. Water use efficiency also rose by 71.3%~86.5%. In normal and wet years, the yield under RFFM0 was close to that of FP3, which included three irrigations totaling 150 mm (Gu et al., 2019).

6.2 Fertilization Strategies under Different Water Scenarios

Under normal or nearly full irrigation conditions, a high rate of chemical nitrogen fertilizer (around 300 kg N ha^{-1}) produced the highest grain yield of spring rapeseed in the Tabriz experiment. This result was observed under conventional irrigation management. However, the yield was very close to that of the integrated fertilization treatment, which included 1/3 chemical fertilizer, 1/3 vermicompost, and PGPR. The difference between these two treatments was not significant (Mamnabi et al., 2020). Under water-limited conditions, including moderate and severe water deficit levels (130 and 160 mm supplemental irrigation), the integrated fertilization treatment showed better performance than using only chemical fertilizer or only organic fertilizer. Even with about a 67% reduction in chemical fertilizer input, this combined approach still increased leaf nitrogen and phosphorus contents. At the same time, grain yield was also significantly improved under drought conditions (Nasrollahzadeh et al., 2023).

6.3 Relevance to sustainable and climate-resilient agriculture

In the Karaj experiment, nitrate leaching changed a lot under different fertilizer and water treatments. When conventional tillage was used, irrigation was normal, and urea was applied only once, nitrate loss was relatively high. The average leaching amount was 83.1 kg/ha. This showed that nitrogen was easily lost under this management practice. When irrigation conditions stayed the same, part of the urea was replaced with vermicompost. After this adjustment, nitrate leaching was clearly reduced. The loss amount was only about half of that under full urea application. At the same time, crop performance did not decline. Grain yield and oil yield remained stable. Nitrogen use efficiency also improved to some extent (Khodabin et al., 2022).

Model simulations over a long time period indicate that similar issues may occur in central China, where rainfall is relatively high. In these regions, nitrogen fertilizer input should be properly controlled. The recommended long-term application rate ranges from 120 to 160 kg N ha^{-1}. Applying nitrogen within this range can help avoid excessive input and reduce nitrogen loss. In addition, field management practices also play an important role. Planting density and sowing time can be adjusted based on local soil properties and weather conditions. These adjustments help stabilize crop yield and economic benefits. They also lower environmental risks and contribute to long-term food security (Wang et al., 2022)..

7 Challenges, Limitations, and Future Perspectives

7.1 Regional differences and production constraints

In the semi-arid regions of Iran, FC80 combined with 30 t/ha of farmyard manure can maintain high Hydromel yields while saving 20% of water, while FC60 was proven to be "stress-induced deficit irrigation" and is not recommended in the area (Janmohammadi et al., 2024). Annual fluctuations in rapeseed yield in China have been confirmed to be highly dependent on socioeconomic factors such as effective irrigated area, total fertilizer application, and agricultural machinery power, with up to 89% of the variation in winter rapeseed yield being explained by economic variables.

7.2 Knowledge gaps in irrigation-fertilization synergy research

Most studies only set 2~4 irrigation levels (e.g., 70~160 mm evapotranspiration replenishment, FC60-FC100, CPE60-100%) and 3–5 fertilizer treatments. While this can reveal response curves under moderate deficit and normal irrigation, it is difficult to characterize thresholds and failure points under extreme environmental stress conditions (e.g., extreme high temperature and drought, extreme waterlogging). Most water and fertilizer experiments focus on N and P supply and a small amount of organic fertilizer substitution, while the hydraulic effects of K, S, trace elements, layered fertilization (e.g., shallow-deep double-layer application), and root-pore structure coupling have only been preliminarily quantified under a few mechanical direct seeding conditions using CT imaging. Most water and fertilizer studies use yield, oil content, WUE, and NUE as end-point indicators, and quantitative analysis of ecological consequences such as greenhouse gas emissions, soil carbon pool evolution, and long-term background nutrient supply (INuS) changes remains insufficient (Yousaf et al., 2017).

7.3 Future applications and observational research directions

Utilize CROPGRO-Canola to derive optimal regional nitrogen fertilizer ranges under long-term time series and different price scenarios (e.g., the long-term optimal range for Central China is 120~160 kg N ha^{-1}), and combine this with random forest analysis to decompose the relative importance of natural and socioeconomic factors (e.g., spring rapeseed yield is affected by natural and economic factors by approximately 47% and 53%, respectively) (Liang et al., 2023), to construct regionalized recommendations for water and fertilizer management systems in different ecological zones. Long-term field experiments and a crop rotation system perspective are needed, for example, systematically tracking the 10-year scale effects of different NPK ratios on yield, soil inorganic nitrogen (INuS), and environmental risks in rice-rapeseed rotation.

Existing 2-year experiments have shown that unbalanced fertilization significantly reduces soil nutrient supply capacity and amplifies dependence on nitrogen. Layered fertilization, drip/micro-irrigation, conservation tillage, and high-throughput root phenotyping and electrical characterization (e.g., root capacitance and impedance) should be combined to simultaneously diagnose root water and nitrogen uptake capacity and lodging risk. Future research should combine field water and fertilizer optimization with simple measures accessible to farmers (e.g., drainage, flood control, straw mulching, small-scale rainwater harvesting facilities) through cross-site observation networks and "yield gap" analysis. Long-term observation and modeling of irrigation quotas, limited irrigation in the late season, and drought-tolerant genotype combinations are necessary in arid and semi-arid regions.

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Conflict of Interest Disclosure

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

References

Ahmadi M., and Bahrani M., 2009, Yield and yield components of rapeseed as influenced by water stress at different growth stages and nitrogen levels, American-Eurasian Journal of Agricultural and Environmental Science, 5: 755-761.

Amiri S., Yarnia M., Mirshekari B., Farahvash F., and Rashidi V., 2024, Restricted Irrigation Regimes and Rapeseed High-Yielding Genotypes Can Be Applied to Cope With the Water Shortage Crisis and More Stable Oil Production. Journal of Crop Health, 76: 917-927.
https://doi.org/10.1007/s10343-024-00995-9

Bouchet A., Laperche A., Bissuel-Belaygue C., Snowdon R., Nesi N., and Stahl A., 2016, Nitrogen use efficiency in rapeseed. A review, Agronomy for Sustainable Development, 36: 1-20.
https://doi.org/10.1007/s13593-016-0371-0

Eyni‐Nargeseh H., AghaAlikhani M., Rad S., Mokhtassi‐Bidgoli A., and Sanavy S., 2019, Late season deficit irrigation for water-saving: selection of rapeseed (*Brassica napus*) genotypes based on quantitative and qualitative features, Archives of Agronomy and Soil Science, 66: 126-137.
https://doi.org/10.1080/03650340.2019.1602866

Feng J., Hussain H., Hussain S., Shi C., Cholidah L., Men S., Ke J., and Wang L., 2020, Optimum Water and Fertilizer Management for Better Growth and Resource Use Efficiency of Rapeseed in Rainy and Drought Seasons. Sustainability.
https://doi.org/10.3390/su12020703

Gao L., Wang C., Wu A., Chen H., Liao Q., and Liao Y., 2024, Effect of layered fertilizer strategies on rapeseed (*Brassica napus* L.) productivity and soil macropore characteristics under mechanical direct-sowing, Scientific Reports, 14(1): 25457.
https://doi.org/10.1038/s41598-024-76077-7

Groth D., Sokólski M., and Jankowski K., 2020, A Multi-Criteria Evaluation of the Effectiveness of Nitrogen and Sulfur Fertilization in Different Cultivars of Winter Rapeseed-Productivity, Economic and Energy Balance, Energies, 13: 4654.
https://doi.org/10.3390/en13184654

Gu H., Li J., Lu Z., Li X., Cong R., Ren T., and Lu J., 2024, Effects of combined application of nitrogen and potassium on oil concentration and fatty acid component of oilseed rape (*Brassica napus* L.), Field Crops Research, 306: 109229.
https://doi.org/10.1016/j.fcr.2023.109229

Gu X., Cai H., Zhang Z., Fang H., Chen P., Huang P., Li Y., Li Y., Zhang L., Zhou J., and Du Y., 2019, Ridge-furrow full film mulching: An adaptive management strategy to reduce irrigation of dryland winter rapeseed (*Brassica napus* L.) in northwest China, Agricultural and Forest Meteorology, 266: 119-128.
https://doi.org/10.1016/j.agrformet.2018.12.009

Gu X., Li Y., and Du Y., 2017, Optimized nitrogen fertilizer application improves yield, water and nitrogen use efficiencies of winter rapeseed cultivated under continuous ridges with film mulching, Industrial Crops and Products, 109: 233-240.
https://doi.org/10.1016/j.indcrop.2017.08.036

Hu Y., Zhang F., Javed H., Peng X., Chen H., Tang W., Lai Y., and Wu Y., 2023, Controlled-Release Nitrogen Mixed with Common Nitrogen Fertilizer Can Maintain High Yield of Rapeseed and Improve Nitrogen Utilization Efficiency, Plants, 12(24): 4105.
https://doi.org/10.3390/plants12244105

Istanbulluoğlu A., Arslan B., Gocmen E., Gezer E., and Paşa C., 2010, Effects of deficit irrigation regimes on the yield and growth of oilseed rape (*Brassica napus* L.), Biosystems Engineering, 105: 388-394.
https://doi.org/10.1016/j.biosystemseng.2009.12.010

Janmohammadi M., Kouchakkhani H., and Sabaghnia N., 2024, Effect of irrigation regimes and organic fertilizer on rapeseed performance in the semi-arid area, Field & Vegetable Crops Research/Ratarstvo i povrtarstvo, 61(2): 33.
https://doi.org/10.5937/ratpov61-48747

Jehangir I., Jan B., Al-Tawaha A., Hussain A., Nazir A., Bhat T., Bhat M., and Ali I., 2024, Assessing the impact of nutrient omissions on growth, yield, and nutrient use efficiency in winter rape (*Brassica napus* L.) under rainfed ecology, Journal of Plant Nutrition, 47: 2122-2133.
https://doi.org/10.1080/01904167.2024.2330527

Kandil A., Sharief A., El-Mohandes S., and Keshta M., 2017, Performance of canola (*Brassica napus* l.) genotypes under drought stress, International Journal of Environment, Agriculture and Biotechnology, 2: 653-661.
https://doi.org/10.22161/ijeab/2.2.12

Khodabin G., Lightburn K., Hashemi S., Moghada M., and Jalilian A., 2022, Evaluation of nitrate leaching, fatty acids, physiological traits and yield of rapeseed (*Brassica napus*) in response to tillage, irrigation and fertilizer management, Plant and Soil, 473: 423-440.
https://doi.org/10.1007/s11104-021-05294-0

Kumar D., Sharma R., and Brar A., 2021, Optimising drip irrigation and fertigation schedules for higher crop and water productivity of oilseed rape (*Brassica napus* L.), Irrigation Science, 39: 535-548.
https://doi.org/10.1007/s00271-020-00714-y

Li J., Zhou Y., Gu H., Lu Z., Cong R., Li X., Ren T., and Lu J., 2023, Synergistic effect of nitrogen and potassium on seed yield and nitrogen use efficiency in winter oilseed rape (*Brassica napus* L.), European Journal of Agronomy, 148: 126875.
https://doi.org/10.1016/j.eja.2023.126875

Liang J., Li H., Li N., Yang Q., and Li L., 2023, Analysis and Prediction of the Impact of Socio-Economic and Meteorological Factors on Rapeseed Yield Based on Machine Learning, Agronomy, 13(7): 1867.
https://doi.org/10.3390/agronomy13071867

Ma P., Lan Y., Lyu T., Li F., Yang Z., Sun Y., and Ma J., 2021, Nitrogen Fate and Efficiency of Fertilizer Application under a Rapeseed–Wheat–Rice Rotation System in Southwest China, Agronomy, 11(2): 258.
https://doi.org/10.3390/agronomy11020258

Mamnabi S., Nasrollahzadeh S., Ghassemi-Golezani K., and Raei Y., 2020, Improving yield-related physiological characteristics of spring rapeseed by integrated fertilizer management under water deficit conditions, Saudi Journal of Biological Sciences, 27: 797-804.
https://doi.org/10.1016/j.sjbs.2020.01.008

Nasrollahzadeh S., Mamnabi S., Ghassemi-Golezani K., Raei Y., and Weisany W., 2023, PGPR and vermicompost with reduced chemical fertilizer enhances biodiesel production, nutrient uptake and improve oil composition of rapeseed grown under water deficit stress, South African Journal of Botany, 159: 17-25.
https://doi.org/10.1016/j.sajb.2023.06.001

Rad A., Abbasian A., and Aminpanah H., 2014, Seed and oil yields of rapeseed (*Brassica napus* L.) cultivars under irrigated and non-irrigated conditions, Journal of Animal and Plant Sciences, 24: 204-210.

Rahimi-Moghaddam S., Eyni‐Nargeseh H., Ahmadi S., and Azizi K., 2021, Towards withholding irrigation regimes and drought-resistant genotypes as strategies to increase canola production in drought-prone environments: A modeling approach, Agricultural Water Management, 243: 106487.
https://doi.org/10.1016/j.agwat.2020.106487

Rahimitanha S., Woodcock T., Spink J., Forristal P., and Berry P., 2022, The Impact of Sowing Date on Soil Mineral Nitrogen Uptake Efficiency and Fertilizer N Uptake Efficiency for Winter Oilseed Rape (*Brassica napus* L.) in Ireland, Agronomy, 12(7): 1551.
https://doi.org/10.3390/agronomy12071551

Raza A., 2020, Eco-physiological and Biochemical Responses of Rapeseed (*Brassica napus* L.) to Abiotic Stresses: Consequences and Mitigation Strategies, Journal of Plant Growth Regulation, 40: 1368-1388.
https://doi.org/10.1007/s00344-020-10231-z

Salami M., Heidari B., Alizadeh B., Batley J., Wang J., Tan X., Dadkhodaie A., and Richards C., 2024, Dissection of quantitative trait nucleotides and candidate genes associated with agronomic and yield-related traits under drought stress in rapeseed varieties: integration of genome-wide association study and transcriptomic analysis, Frontiers in Plant Science, 15: 1342359.
https://doi.org/10.3389/fpls.2024.1342359

Shabani A., Sepaskhah A., and Haghighi A., 2012, Responses of agronomic components of rapeseed (*Brassica napus* L.) as influenced by deficit irrigation, water salinity and planting method, International Journal of Plant Production, 7: 313-340.
https://doi.org/10.22069/ijpp.2012.989

Shafighi A., Teymoori M., Ardakani M., Rad A., Alavifazel M., and Rafiei F., 2022, Evaluation of the oil quality properties of Rapeseed genotypes contributed to drought stress at the flowering stage in semi-arid conditions, Journal of Biological Research - Bollettino della Società Italiana di Biologia Sperimentale, 95(1): 10297.
https://doi.org/10.4081/jbr.2022.10297

Teymoori M., Ardakani M., Rad A., Alavifazel M., and Manavi P., 2020. Seed yield and physiological responses to deal with drought stress and late sowing date for promising lines of rapeseed (*Brassica napus* L.). International Agrophysics, 34: 321-331.
https://doi.org/10.31545/intagr/124388

Tian X., Zhao Y., Chen Z., Li Z., and Liu Y., 2023, Effects of Nitrogen Fertilization on Yield and Nitrogen Utilization of Film Side Planting Rapeseed (*Brassica napus* L.) Under Different Soil Fertility Conditions, Journal of Soil Science and Plant Nutrition, 23: 368-379.
https://doi.org/10.1007/s42729-022-01030-4

Wang C., Wang X., Yang J., Zhang Z., and Chen M., 2025, Effects and Mechanism of Nitrogen Regulation on Seed Yield and Quality of Rapeseed (*Brassica napus* L.), Agronomy, 15(5): 1232.
https://doi.org/10.3390/agronomy15051232

Wang C., Xu M., Wang Y., Batchelor W., Zhang J., Kuai J., and Ling L., 2022, Long-Term Optimal Management of Rapeseed Cultivation Simulated with the CROPGRO-Canola Model, Agronomy, 12(5): 1191.
https://doi.org/10.3390/agronomy12051191

Wang R., Zheng W., Wu Y., Liu D., and Peng W., 2023, Effects of a range of phosphorus levels on yield, phosphorus efficiency and canopy sunlight interception in direct-seeded winter rapeseed, Agronomy Journal, 115(4): 2058-2070.
https://doi.org/10.1002/agj2.21394

Xiang J., Hare M., Vickers L., and Kettlewell P., 2024, A Comparative Study on Rapeseed Sprayed with Film Antitranspirant Under Two Contrasting Rates of Soil Water Depletion, Agronomy, 14(12): 2944.
https://doi.org/10.3390/agronomy14122944

Yahbi M., Nabloussi A., Maataoui A., Alami E., Boutagayout A., and Daoui K., 2022, Effects of nitrogen rates on yield, yield components, and other related attributes of different rapeseed (*Brassica napus* L.) varieties, OCL, 29: 8.
https://doi.org/10.1051/ocl/2022001

Yousaf M., Li J., Lu J., Ren T., Cong R., Fahad S., and Li X., 2017, Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system, Scientific Reports, 7(1): 1270.
https://doi.org/10.1038/s41598-017-01412-0

Zangani E., Afsahi K., Shekari F., Mac Sweeney E., and Mastinu A., 2021, Nitrogen and Phosphorus Addition to Soil Improves Seed Yield, Foliar Stomatal Conductance, and the Photosynthetic Response of Rapeseed (*Brassica napus* L.), Agriculture, 11: 483.
https://doi.org/10.3390/agriculture11060483

Zhu J., Dai W., Chen B., Cai G., Wu X., and Yan G., 2023, Research Progress on the Effect of Nitrogen on Rapeseed between Seed Yield and Oil Content and Its Regulation Mechanism, International Journal of Molecular Sciences, 24(19): 14504.
https://doi.org/10.3390/ijms241914504