Agricultural Water Management 298 (2024) 108863

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

# Integrated assessment of water-nitrogen management for winter oilseed rape production in Northwest China

Han Wang [a,b], Youzhen Xiang [b], Zhenqi Liao [b], Xin Wang [b], Xueyan Zhang [d], Xiangyang Huang [b], Fucang Zhang [b], Li Feng [c,*]

[a] *Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China*
[b] *Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling 712100, China*
[c] *School of Human Settlement Environment and Civil Engineering, Xi 'an Jiaotong University, Xi'an 712000, China*
[d] *Department of Hydrology and Atmospheric Sciences, The University of Arizona, Tucson, AZ, USA*

ARTICLE INFO

Handling Editor: Dr. B.E. Clothier

*Keywords:*
Winter oilseed rape
Supplementary irrigation
N fertilizer rate
Grain yield
Quality

ABSTRACT

With global warming, the winter oilseed rape planting area in Northwest China is gradually increasing. It is vital to address the problems faced by winter oilseed rape cultivation in this region, such as low winter temperature, water shortage and low resources utilization efficiency. To explore the coupling effects of supplementary irrigation level and nitrogen (N) application rate on winter oilseed rape growth, water and N use efficiency, and determine the multi-objective optimal water-N management strategies, a two-year field experiment was conducted (2020–2021 and 2021–2022). The experiments included three supplementary irrigation levels (I0: rainfed; I1: supplementary irrigation at overwintering stage; I2: supplementary irrigation at overwintering and budding stages) and five N application rates (N0: 0 kg/hm$^2$; N1: 120 kg/hm$^2$; N2: 200 kg/hm$^2$; N3: 280 kg/hm$^2$; N4: 360 kg/hm$^2$). The results showed that supplementary irrigation at overwintering and budding stages (I2) can improve the physiological growth indexes, N accumulation and utilization, main quality indexes, and yield of winter oilseed rape. Under I2, LAI, aboveground biomass, chlorophyll content, water use efficiency, N accumulation, N agronomy efficiency and yield of winter oilseed rape first increased and then decreased as N application rate increased, and all reached maximized at medium levels of N application rate (N2 or N3). Under the same irrigation level, the oil content of grain decreased as N application rate increased, while the protein and thioside acid content increased. Based on the TOPSIS with Nash equilibrium-combination weighting method, the multi-objective optimal strategies were determined to be the combination of supplementary irrigation at overwintering and budding stages (I2) and N application rate of 200 kg/hm$^2$ (N2). This method overcomes the limitations of subjective and objective weighting methods, and made the evaluation results more reasonable. The finding can provide a reference for the application of water and N application in winter oilseed rape production in semi-arid areas of Northwest China and other regions with similar environments.

## 1. Introduction

China is increasingly focusing on the issue of food security, and the country's overall grain production capacity has been steadily improving (Shen et al., 2018; Gao et al., 2021). However, current crop production still faces challenges such as diminishing arable land, agricultural water scarcity, and low returns, etc. (Wang et al., 2023). Winter oilseed rape, as one of the primary oil crops, constitutes 90% of the oilseed rape area in China, which was mainly planted in the Yangtze River basin (Gu et al., 2018a). With global warming, the planting area of winter oilseed rape in Northwest China has been gradually expanding. Shaanxi Province, one of the five provinces in Northwest China, is the primary planting area for winter oilseed rape. It produces approximately 45% of China's high-quality winter oilseed rape seeds (Wang et al., 2019). However, winter oilseed rape cultivation in this area still encounters several challenges, including the low overwintering rate due to winter's low temperature, and the waste of resources and environmental pollution caused by unreasonable application of water and fertilizer. Exploring the suitable combination of supplementary irrigation and nitrogen application rate is conductive to alleviating the problems faced by

* Corresponding author.
*E-mail address:* fengli726@xjtu.edu.cn (L. Feng).

https://doi.org/10.1016/j.agwat.2024.108863
Received 19 October 2023; Received in revised form 10 April 2024; Accepted 6 May 2024
Available online 14 May 2024

winter oilseed rape cultivation in Northwest China.

As one of the thirteen countries with poorest water resources in the world, water shortage has always been a short board limiting China's agricultural development (Wang et al., 2019). China's water resources account for only 6% of the earth total, with surface water resources amounting to only 2799.33 billion $m^3$ and a per capita availability of only 2077.7 $m^3$ (The China Statistical, 2020). With the population increasing and the significant improvement in people's quality of life, industrial and urban domestic water usage continues to rise, and squeezing water from agriculture, which further exacerbates the crisis of agricultural water resources in China (Huang and Shan, 1998). Total water resources in Northwest China amount to 262.32 billion $m^3$, while in Shaanxi Province, the total water resources are only 49.52 billion $m^3$. Furthermore, the main rainy season in Shaanxi Province does not synchronize with the water requirement time of spring/winter crops (Lu et al., 2021). Winter oilseed rape requires more water than other crops such as wheat, soybeans, and corn. Thus, supplementary irrigation at its main growth stage is essential for its growth, as well as for achieving high quality and yield (Rady et al., 2021; Rathke et al., 2006). Previous studies have shown that supplementary irrigation during the overwintering period can effectively increase the water content, heat capacity, and thermal conductivity of the soil, which will effectively reduce the diurnal temperature differences of the soil and thus improve the overwintering ability of the crop (Chun et al., 2022; Shi, 2002). Meanwhile, supplementary irrigation during the overwintering period can effectively alleviate the problem of "spring drought" and promote the growth and development of crops (Li et al., 2018). Therefore, appropriate supplementary irrigation can effectively alleviate the contradiction between high water consumption of winter oilseed rape and extreme winter conditions in Northwest China.

According to statistics, nitrogen is avital fertilizer that plays a crucial role in enhancing plant growth and improving crop yield. It contributes significantly, up to 30%-50%, to the increase in crop yield (Erisman et al., 2008; Galloway et al., 2008). However, blind over-application of nitrogen not only reduces its efficiency, but also causes a series of environmental problems (Gu et al., 2018b). These include high levels of residual nitrogen in the soil, increased risk of groundwater pollution from nitrogen fertilizer leakage after heavy rainfall, and serious damage to both the atmosphere and natural ecosystems due to nitrate nitrogen leaching and ammonia volatilization (Lu et al., 2021). Winter oilseed rape is a crop that requires a high amount of nitrogen, and previous studies have shown that around 60 kg of nitrogen is required to produce 1ton of winter oilseed rape (Rathke et al., 2006). Proper nitrogen application plays an important role in the accumulation of nitrogen and dry matter in winter oilseed rape organs. Additionally, it effectively promotes photosynthesis, which affects its final yield and quality (Zhang, 2018). In Northwest China, the adoption of rough water and fertilizer management (over-irrigation and over-fertilization) by local farmers has led to low N utilization efficiency and surplus of N fertilizer, resulting in serious waste of resources and environmental pollution (Su et al., 2014). Over-fertilization can also lead to plant futility and reduced stalk fullness, making the crop prone to massive collapse at a later stage, ultimately impacting the final yield and quality (Luo et al., 2020). Therefore, controlling the excessive application of N fertilizer while ensuring high quality and yield of crops has become an urgent problem in China.

TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) model, a comprehensive multi-indicator decision evaluation method proposed by Hwang and Yoon (1981), is now widely used in agriculture, and able to respond well to the combined impact of multiple indicators. There are no strict restrictions on data distribution, sample size, and the number of indicators (Wang et al., 2019b). Determining the weights of evaluate indicators is the key to using the TOPSIS model for multi-objective evaluation (Li et al., 2012). Sun et al. (2022) used the objective weighting method and TOPSIS model to analyze the parameter combination for high yield, high quality and high efficiency of water and fertilizer in Shaanxi sandy potato planting system. Yan et al., (2022) used subjective weighting method and TOPSIS method to optimize the multi-objective of sugar beet water and nitrogen application system in desert climate area. Previous studied usually used subjective or objective weighting methods to determine the weights of evaluation indicators, but both methods have certain limitations (Xiang, 2017; Wang et al., 2019c). The objective weighting method is solely based on the inherent information content of the indicators and does not emphasize the relative importance of certain indicators, while the subjective weighting method takes into account the knowledge and experience of experts but is susceptible to issues such as subjective bias (Zhang, 2018). We adopt the comprehensive weighting method in this study, which integrates the advantages of both subjective and objective weighting. The combined weights not only reflect the willingness of the evaluator, but also the contribution of each evaluation indicator to the overall results, effectively overcoming the limitations of the single approach (Zhang et al., 2023). And the Nash equilibrium in game theory was invoked in our study, which can achieve the dominant equilibrium of each decision unit through constant iteration of the constraint parameters (Lu and Zhang, 2022). In short, the Nash equilibrium-combination weighting method overcomes the limitations of subjective and objective weighting methods, and made the evaluation results more reasonable and practical.

We considered that the appropriate combination of supplementary irrigation and N application rate can better balanced the agronomic, economic and environmental benefits of winter oilseed rape cultivation. The main objectives of this study were to: (1) explore the responses of physiological growth parameters, overwinter ability, water/N use efficiency, yield, and quality of winter oilseed rape to the combination of supplementary irrigation and N application rate; (2) determine the multi-objective optimal strategies that suitable for winter oilseed rape cultivation in Northwest China and other regions with similar environments.

## 2. Material and methods

### 2.1. Experimental site

The experiments were conducted at the Key Laboratory of the Ministry of Education for Agricultural Water and Soil Engineering in Arid area, Northwest A&F University, China (108°04′E longitude, 34°20′N latitude and at an altitude of 524.7 m above mean sea level) (Fig. 1). The test site has a continental monsoonal semi-humid climate with an average annual temperature of 12.9°C. The average multi-year precipitation ranges from 550 to 600 mm, but the rainfall is mainly concentrated in July, August, and September. The average multi-year evaporation of the site is 1500 mm, the average multi-year sunshine hours is 2163.8 h, and the average multi-year frost-free period is 221d. Before sowing in 2020, the soil pH of 0–20 cm soil layer was 8.14, organic matter content was 10.02 g/kg, total nitrogen content was 0.89 g/kg, nitrate nitrogen content was 8.31 mg/kg, and ammonium nitrogen content was 6.27 mg/kg. Before sowing in 2021, the soil pH of 0–20 cm soil layer was 8.44, organic matter content was 10.3 g/kg, total nitrogen content was 1.21 g/kg, nitrate nitrogen content was 21.01 mg/kg, and ammonium nitrogen content was 6.05 mg/kg. The daily maximum temperature, daily average temperature, daily minimum temperature and daily rainfall amount during the two-year experiment were obtained through the weather station installed in the test site (Fig. 2).

### 2.2. Experimental design

The field experiment includes three supplement irrigation amounts (I0: rainfed; I1: supplementary irrigation at overwintering stage; I2: supplementary irrigation at overwintering and budding stages) and five nitrogen levels (N0: 0 kg/$hm^2$; N1: 120 kg/$hm^2$; N2: 200 kg/$hm^2$; N3:

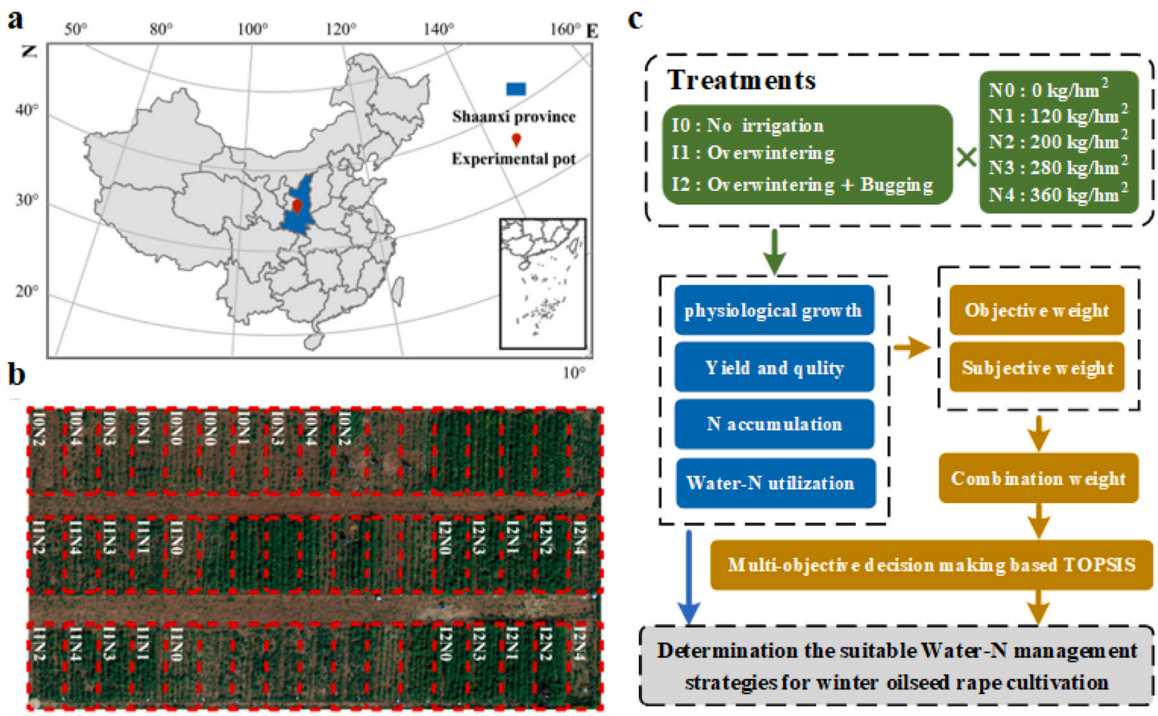


**Fig. 1.** Test site location and test scene diagram.

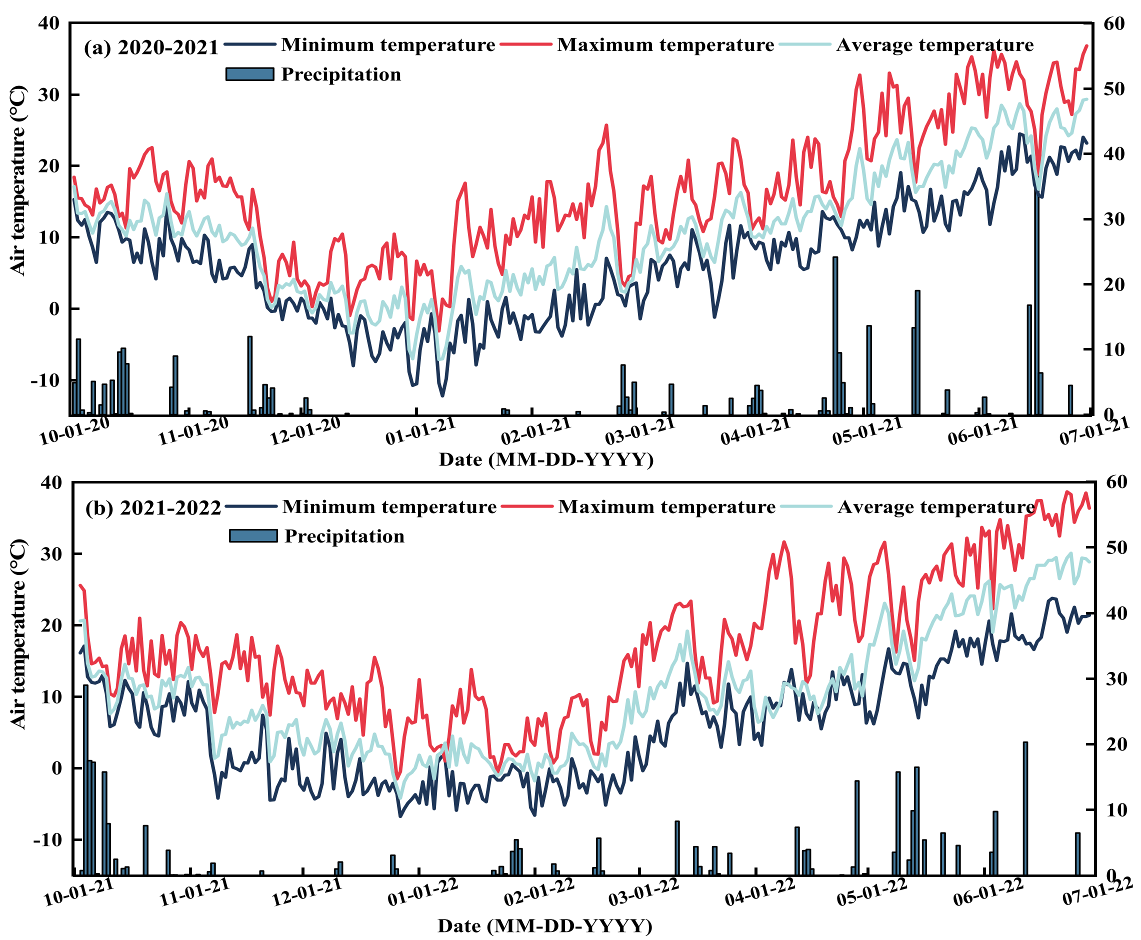


**Fig. 2.** Monthly maximum, mean, minimum temperatures and precipitation during the winter oilseed rape growing seasons in 2020–2021 and 2021–2022.

280 kg/hm$^2$; N4: 360 kg/hm$^2$) in a randomized complete block design with three replicates (Fig. 1). Before supplementary irrigation, we used the oven-dry method to measure the mass moisture content of 0–40 cm soil. And the soil mass moisture content was added to the field water holding capacity at overwintering and budding stages (Table 1). The nitrogen fertilizer used in the experiment was a pure nitrogen slow-release fertilizer with 45% urea content, and the slow-release period was two months. The nitrogen fertilizer, phosphorus fertilizer (90 kg/ hm$^2$) and potassium fertilizer (120 kg/ hm$^2$) were used as the base fertilizer for each treatment and mixed into the soil layer (0–15 cm) at once before planting. Common local winter oilseed rape variety "Shanyou-18" was seeded on 16 October and harvested on 8 June during 2020–2021, while it was seeded on 13 October and harvested on 12 June during 2021–2022. After the winter oilseed rape has grown 3 real leaves, the seedlings will be separated and fixed according to the density of 120,000 plants/hm$^2$, and the other agronomic management followed the local practices.

### 2.3. Measurements and calculations

#### 2.3.1. Physiological growth parameters and overwinter ability

The growth stages of winter oilseed rape were divided into seedling stage, overwintering stage, budding stage, flowering stage, and harvesting stage according to the method of Wu et al. (2007). At different growth stages, three winter oilseed rape plants that represent the growth of the entire plot were selected, and the different organs (leaves, stems and fruits) were separated after removing surface dirt. The length as well as the maximum width of each leaf of the whole plant was measured with a steel ruler and the leaf area index (LAI) was calculated as Eq.1. Meanwhile, the oven temperature was set at 105°C to kill-greening for 30 minutes, followed by drying the crop to constant weight at a constant temperature of 70°C. The dry matter weight of different organs of winter oilseed rape was measured with an electronic scale to calculate the above-ground biomass (AGB) of the crop.

$$\text{Leaf area index} = 0.75 * \rho * \frac{\sum_{i=1}^{m}\sum_{i=1}^{l}(L_{ij} \times B_{ij})}{m} \quad (1)$$

Where $l$ is the total number of leaves of $j$ th plant; $m$ is the number of measured plants; $\rho$ is the planting density; $L_{ij}$ and $B_{ij}$ are the length and width of the $i$ th leaf of j th plant, respectively.

Measuring chlorophyll content of winter oilseed rape at different growth stages, the third new leaf was randomly selected 0.1 g from the heart leaf, wiped the tissue surface and then cut and stirred it into the test tube. Meanwhile, 10 mL of 96% alcohol solution was added to the test tube, and when the leaves in the test tube were free of green indicated that chlorophyll had been completely extracted. The solution was fixed to 25 mL, and the chlorophyll content of winter oilseed rape was measured by UV-Visible spectrophotometer model EV300PC after shaking well. The chlorophyll content (mg/g) was calculated as follows (Guo, 2022):

$$Chlorophylla = (13.95D\_665 - 6.88D\_649)V/1000M \quad (2)$$

$$Chlorophyllb = (24.96D\_649 - 7.32D\_665)V/1000M \quad (3)$$

$$\text{Total chlorophyll} = \text{Chlorophyll a} + \text{Chlorophyll b} \quad (4)$$

Where $D$ is the value of optical density at different wavelengths; $V$ is the volume of extraction solution (mL); $M$ is the fresh weight of the leaf (g).

The overwintering ability of winter oilseed rape was evaluated by the overwintering rate. The average values of pre-winter and post-winter seedlings were obtained from the area (2×2 m) delineated in advance in each plot and used to calculate the overwintering rate of winter oilseed rape under different treatments.

#### 2.3.2. Winter oilseed rape yield and its components

Yield measurement area (2 m×2 m) was delineated in each plot before sowing, and 10 plants were selected after crop maturity to measure the yield and its composition of winter oilseed rape.

#### 2.3.3. Winter oilseed rape quality

Near-infrared spectroscopy analyzer (NIRSTM DS 2500 F) was used to measure the quality (Grain oil content, protein content, erucic acid content, thioside and oleic acid content) of winter oilseed rape grain.

#### 2.3.4. Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Soil samples were collected at depths of 0–20, 20–40, 40–60, 60–80, 80–100 cm before and after the experiment. The soil mass water content ($C_i$, %) was measured by drying method and the soil water storage (S, mm) was calculated. Evapotranspiration (ET, mm) is the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere (Wang et al., 2006). Soil water storage (mm) and ET (mm) were calculated as follows:

$$S = \sum_{i=1}^{n} C_i H_i \gamma_i \times 10 \quad (5)$$

Where $C_i$is the soil mass moisture content (%) of i-th soil layers; $H_i$is the soil depth of i-th soil layers (mm);$\gamma_i$ is the soil bulk density (g/cm$^3$) of i-th soil layers; $n$ is the number of soil layers, $n = 5$.

$$\text{ET} = \text{P} + \text{I} + \Delta S - \text{R} - \text{D} \quad (6)$$

Where $P$ is precipitation (mm); $I$ is irrigation amount (mm); $\Delta S$ is the decrease of soil water storage from sowing to harvesting (mm); $R$ is runoff volume (mm); $D$ is deep leakage volume (mm). Since the ground

**Table 1**
Irrigation and nitrogen application program for winter oilseed rape.

| Treatments | Frequency | 2020–2021 Irrigation (mm) | 2021–2022 Irrigation (mm) | Nitrogen (kg ha$^{-1}$) | Stage |
|---|---|---|---|---|---|
| I0N0 | 0 | 0 | 0 | 0 | / |
| I0N1 | | | | 120 | |
| I0N2 | | | | 200 | |
| I0N3 | | | | 280 | |
| I0N4 | | | | 360 | |
| I1N0 | 1 | 72.5 | 70.8 | 0 | Overwintering |
| I1N1 | | | | 120 | |
| I1N2 | | | | 200 | |
| I1N3 | | | | 280 | |
| I1N4 | | | | 360 | |
| I2N0 | 2 | 72.5+85.2 | 70.8+87.6 | 0 | Overwintering and budding |
| I2N1 | | | | 120 | |
| I2N2 | | | | 200 | |
| I2N3 | | | | 280 | |
| I2N4 | | | | 360 | |

slope of this experiment is small and the buried depth of groundwater is greater than 50 m, *R* and *D* are not considered.

The water use efficiency *(WUE, kg ha$^{-1}$·mm)* and rainfall use efficiency *(RUE, kg ha$^{-1}$·mm)* were calculated as follows (Wu et al., 2014; Ali et al., 2019):

$$\mathrm{WUE} = \mathrm{Y/ET} \tag{7}$$

$$\mathrm{RUE} = \mathrm{Y/(P+I)} \tag{8}$$

Where *Y* is the grain yield of winter oilseed rape (kg/hm$^2$); *ET* is the soil water consumption during the growth stage of winter oilseed rape (mm); *P* and *I* are the rainfall and supplementary irrigation amount during the growth season of winter oilseed rape, respectively (mm).

### 2.3.5. Nitrogen agronomic efficiency (NAE), and partial factor productivity of nitrogen (PFPN)

The above-ground tissues of winter oilseed rape were crushed with a small crusher, passed through 1 mm sieve, and then boiled by $H_2SO_4$-$H_2O_2$. Determination of total nitrogen content (g/kg) of plant tissues by Automatic Kjeldahl Nitrogen Tester (FOSS 2300). Nitrogen accumulation (NA, kg/hm$^2$), Nitrogen agronomic efficiency (NAE, kg/hm$^2$) and Nitrogen partial factor productivity (PFPN, kg/kg) were calculated as follows:

$$NA = (DM \times C_N)/1000 \tag{9}$$

Where *DM* is the cumulative amount of above-ground biomass (kg/hm$^2$); $C_N$ is the nitrogen content of the plant (g/kg); 1000 is the unit conversion factor.

$$NAE = (Y_N - Y_0)/F_N \tag{10}$$

$$PFPN = Y_N/F_N \tag{11}$$

Where $Y_N$ and $Y_0$ are winter oilseed rape grain yield (kg/hm$^2$) in N-applied and non-N-applied areas; $F_N$ is the amount of nitrogen applied (kg/hm$^2$).

### 2.3.6. Multi -objective decision -making and evaluation

Nash equilibrium-combination weighting method and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) model were used for the comprehensive evaluation of winter oilseed rape LAI ($x_1$), AGB ($x_2$), chlorophyll content ($x_3$), WUE ($x_4$), PFPN ($x_5$), oil content ($x_6$), protein ($x_7$), oleic acid content ($x_8$), 1000-seed weight ($x_9$) and yield ($x_{10}$). Since these ten indicators are not consistent in magnitudes and dimensions, the original data are processed consistency and dimensionless, and the matrix is constructed with the processed data. The analytic hierarchy progress (AHP) was used to calculate the subjective weights, while the entropy weight method (EWM) was used to calculate the objective weights, and the game theory is invoked to calculate the comprehensive weights by using the Nash equilibrium coefficient as an optimization objective to coordinate the subjective and objective weights.

In this study, YAAHP10 was used to establish the evaluation index system and analyze it. YAAHP is an auxiliary software for the analytic hierarchy progress, which uses the "proportional scaling method" proposed by Saaty and Kearns, (1985) to construct a judgment matrix by comparing two factors, and the software uses the "sum method" to analyze and calculate its subjective weights. Details of calculating its objective weights by the entropy weighting method can be found in Wang et al. (2019). The NASH equilibrium in game theory was introduced as an optimization objective for coordinating the subjective and objective weights to determine the final weights, and the steps are as follows:

(1) Determine the set of basic weight vectors and linear combination coefficient:

$$u_k = \{u_{k1}, u_{k2}, \ldots, u_{kn}\} \qquad (\mathrm{k} = 1, \quad 2, \quad \ldots, \mathrm{L}) \tag{12}$$

$$\alpha_k = \{\alpha_1, \quad \alpha_2, \ldots, \alpha_L\} \tag{13}$$

Where n is the number of evaluation indicators; L is the number of methods to determine the weights; $u_k$ is the set of basic weight vectors; and $\alpha_k$ is the linear combination coefficient.

(2) Arbitrary linear combination of the set of basic weight vectors with the linear combination coefficients:

$$u = \sum_{k=1}^{L} \alpha_k u_k^T, \quad \alpha_k > 0, \quad (k = 1, \quad 2, \quad \ldots, \quad L) \tag{14}$$

(3) Seeking consistency and compromise between different weights, the objective is to minimize the deviation of *u* and $u_k$, and the linear weight combination coefficient $\alpha_k$ in Eq.14 is optimized to obtain the most satisfactory weights in *u*. The objective function and a system of linear equations with its equivalent derivative condition are obtained as follows:

$$\min \left\| \sum_{k=1}^{L} \alpha_k u_k^T - u_k \right\|_2 (\mathrm{k} = 1, \quad 2, \quad \ldots, \mathrm{L}) \tag{15}$$

$$\begin{bmatrix} u_1 \bullet u_1^T & u_1 \bullet u_2^T & \cdots & u_1 \bullet u_L^T \\ u_2 \bullet u_1^T & u_2 \bullet u_2^T & & u_2 \bullet u_L^T \\ \vdots & & \ddots & \vdots \\ u_L \bullet u_1^T & u_L \bullet u_2^T & \cdots & u_L \bullet u_L^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_L \end{bmatrix} \begin{bmatrix} u_1 \bullet u_1^T \\ u_2 \bullet u_2^T \\ \vdots \\ u_L \bullet u_L^T \end{bmatrix} \tag{16}$$

And the calculated optimal combination coefficients are then normalized:

$$\alpha_k^* = \alpha_k \Big/ \sum_{k=1}^{L} \alpha_k, \quad (\mathrm{k} = 1, \quad 2, \quad \ldots, \mathrm{L}) \tag{17}$$

(4) The combined weights of the evaluation indicators are obtained according to the game-theoretic combination assignment:

$$u^* = \sum_{k=1}^{L} \alpha_k^* u_k^T, \quad (\mathrm{k} = 1, \quad 2, \quad \ldots, \mathrm{L}) \tag{18}$$

TOPSIS is a common method for evaluating the degree of advantage and disadvantage of a limited number of evaluation objects (Gholizadeh, 2016). This method has no strict restrictions on data distribution and sample content, and the data are simple to calculate, so it is widely used at present. TOPSIS was used for the comprehensive evaluation of the target indicators in this study, and its specific steps can be found in Wang et al. (2019c).

### 2.4. Data analysis

Basic experimental data were processed by Excel 2016. Analysis of variance (ANOVA) was performed using SPSS Statistics 22.0 and multiple comparisons were performed using the least significant difference (LSD) method. We generated plots with Origin 2021 and ArcMap 10.5.

## 3. Results

### 3.1. Physiological growth parameters, and overwintering ability

In the two-year experiment, the leaf area index (LAI) and chlorophyll content (Chl) of winter oilseed rape increased first and then decreased with the advancement of growth period (Fig. 3 and Fig. 4). From sowing to the end of overwintering stage, the growth of winter oilseed rape was extremely slow. The budding stage was the most vigorous growth period of winter oilseed rape, and the LAI and Chl were increased sharply. Entering the flowering stage, LAI showed an overall increasing trend,

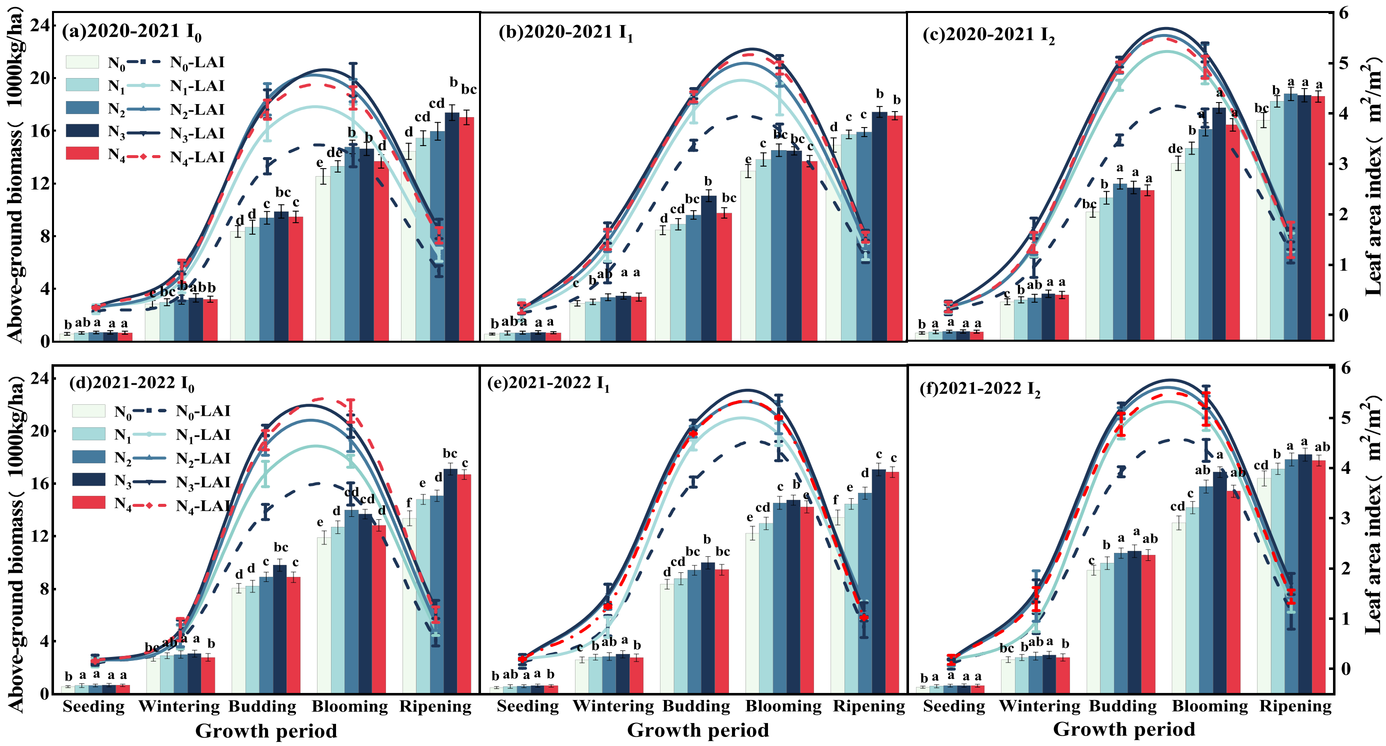

Fig. 3. Above-ground biomass and leaf area index of winter oilseed rape at whole growth period under different levels of nitrogen and supplemental irrigation in 2020–2021 and 2021–2022.

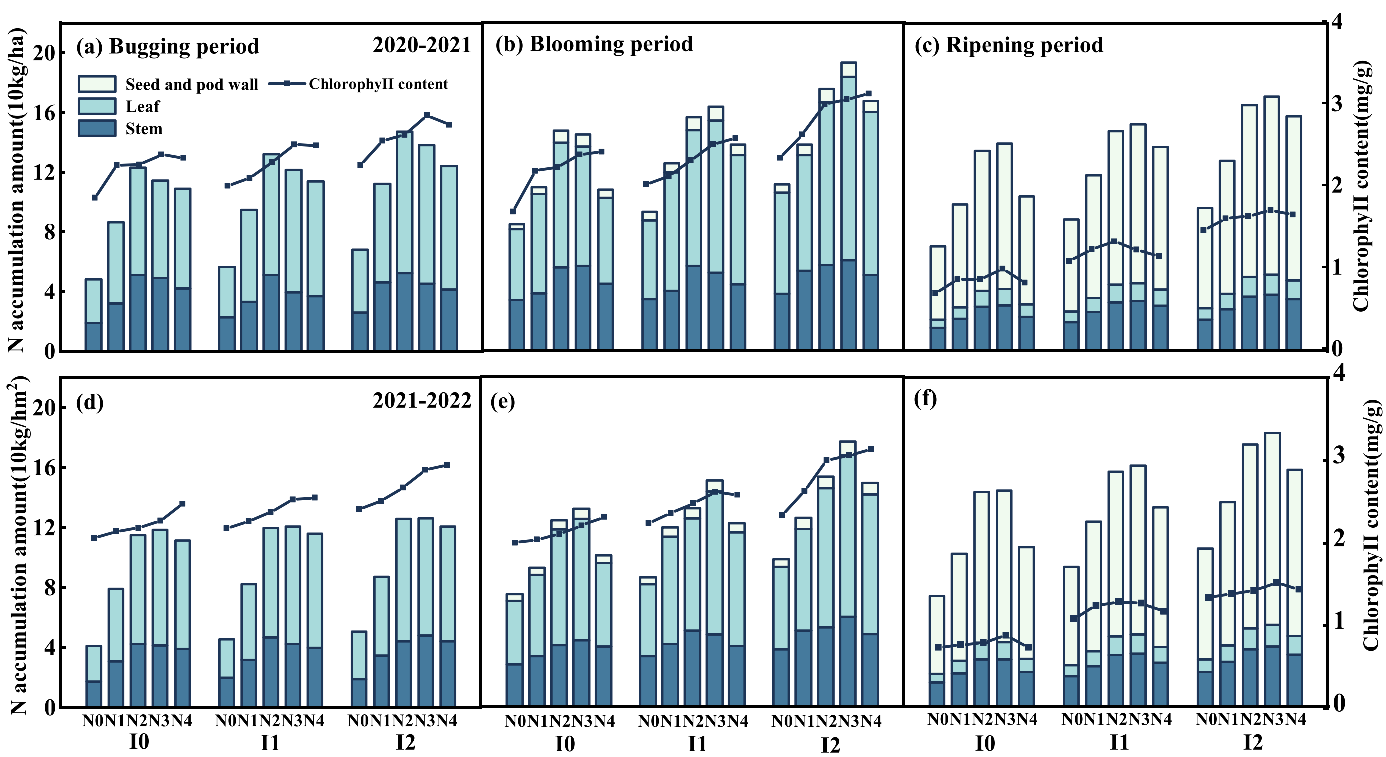

Fig. 4. N accumulation amount and chlorophyll content of winter oilseed rape at bugging, blooming and ripening period under different levels of nitrogen and supplemental irrigation in 2020–2021 and 2021–2022.

but the rate of increase was slowing down, and LAI was maximized under N3I2, but there was no significant difference between N3I2 (5.210 and 5.409) and N2I2 (5.049 and 5.215) in the two-year experiment. Chl didn't change much from the budding stage, under the same supplementary irrigation levels, Chl increased with the increase of N rate. Under the same N levels, except N4 in the first year, Chl was slightly lower than that in the budding stage under I0 and I1 levels, while Chl under I2 increased slightly. After the flowering stage, the leaves of winter oilseed rape began to senesce and turn yellow, the leaves fell in a large area, resulting in a sharp decline in Chl and LAI of winter oilseed rape.

As shown in Fig. 3, above-ground biomass (AGB) of winter oilseed rape increased with the advancement of growth period, and reached the maximum at the ripening stage. At the ripening stage, under the same N levels, the AGB under I2 was significantly higher than I1 and I0, and increased by 6.31–22.75% (I0) and 5.21%-22.02% (I1), respectively. The AGB of winter oilseed rape under I2 increased first and then decreased with the increase of N rate, but there was no significant difference between N2, N3, and N4. Compared with N0, the AGB of winter oilseed rape increased by 4.38%-10.78% (N1), 8.78%-13.69% (N2), 10.98%-28.14% (N3) and 8.29%-25.60% (N4), respectively. Supplementary irrigation during the overwintering stage can significantly improve the overwintering rate of winter oilseed rape ($P<0.01$), and the effect of N on the overwintering rate of winter oilseed rape did not reach a significance level ($P>0.05$) (Table 2). In the two-year experiment, the overwintering rate of winter oilseed rape with supplemental irrigation during overwintering stage increased by 47.73% (2020–2021) and 55.25% (2021–2022) compared with the treatment without supplemental irrigation.

### 3.2. Winter oilseed rape quality, yield and its components

The interactive effects of supplementary irrigation and nitrogen (IxN) had significant effects on oil content and oleic acid content ($P<0.05$), but it had no significant effects on thioside acid and erucic acid content (Table 3). The oil content was inversely proportional to the protein content ($R_{2020–2021}$=-0.891**, $R_{2021–2022}$=-0.944**), with the increase of N application rates, oil content showed a decreasing trend, while protein content showed an increasing trend. Thioside acid and erucic acid content increased first and then decreased with the increase of N application rates, but there was no clear pattern of different supplementary irrigation levels. The oleic acid content was inversely proportional to the erucic acid content ($R_{2020–2021}$=-0.647**, $R_{2021–2022}$=-0.699**), under the same supplementary irrigation levels, the oleic acid content showed a single-peak trend with the increase of N application rates, but there were no significant differences between N1, N2, and N3. Under the same N levels, the oleic acid content was higher under the supplementary irrigation levels (I2 and I1) than non-supplementary irrigation (I0).

As shown in Table 4, under different water and nitrogen supply conditions, the range of winter oilseed rape grain yield in two years was 1332.60–2460.40 kg/hm$^2$ (2020–2021) and 1437.20–2668.98 kg/hm$^2$ (2021–2022), respectively. Under the same supplementary irrigation conditions, the grain yield of winter oilseed rape increased first and then decreased with the increase of N application rate in two years, and reached the maximum at N3 level, but there was no significant difference between N2 and N3 levels. Under the same nitrogen application rate, the grain yield of winter oilseed rape under I2 was significantly higher than that under I1 and I0 levels. In the two-year experiment, compared with I0 and I1, the grain yield of winter oilseed rape under I2 increased by 15.90% −48.52% (N0), 20.34% −55.04% (N1), 19.34% −55.17% (N2), 14.03% −50.65% (N3) and 22.47% −61.50% (N4), respectively.

### 3.3. ET, RUE, and WUE

In the two-year experiment, the interactive effects of supplementary irrigation and nitrogen (IxN) on WUE was significant ($P<0.05$), but the interactive effects of IxN on ET and RUE were not significant ($P<0.05$) (Table 5). Under I0 and I1 supplemental irrigation conditions, the evapotranspiration (ET) of winter oilseed rape was in descending order: N2>N3>N1>N4>N0. Under the I2 supplemental irrigation condition, the ET of winter oilseed rape was in descending order: N3>N2>N4>N1>N0, and the ranges were 354.0–357.4 mm (2020–2021) and 362.4–373.3 mm (2021–2022), respectively. Under the same supplementary irrigation conditions, the RUE increased first and then decreased with the increase of N application rate, and the RUE reached maximum at N3 level. Under the medium and high N application levels, except for N4 in 2020–2021, RUE decreased with the increase of irrigation amount, but there was no significant difference between different supplementary irrigation conditions.

The effect of supplementary irrigation (I) on WUE was extremely significant ($P<0.01$), and the effect of nitrogen (N) on WUE of winter oilseed rape was significant over the two growing periods ($P<0.05$) (Table 5). Under the same supplementary irrigation conditions, WUE showed the trend of first increasing and then decreasing with the increase of N application rate, and reached the maximum at N3 level. Compared to other N application rate, the WUE of winter oilseed rape under N3 increased by 15.25–23.53% (N0), 7.94–16.67% (N1), 1.49–8.06% (N2), and 6.78–17.54% (N4), respectively. Under the same N application rate, the WUE was maximized under I2 level during the two growing periods. In 2020–2021, compared to I1 and I0, the WUE under I2 increased by 0.3–0.9 kg/hm$^2$·mm (5.08%-16.67%) and 0.1–0.6 kg/hm$^2$·mm (1.49%- 10.53%), respectively; in 2021–2022, compared to I1 and I0, WUE under I2 increased by 0.7–1.0 kg/hm$^2$·mm (11.86%-18.52%) and 0.2–0.6 kg/hm$^2$·mm (3.51%-9.52%), respectively.

**Table 2**
The overwinter rate of winter oilseed rape under different levels of nitrogen and supplementary irrigation in 2020–2021 and 2021–2022.

| Treatment | | 2020–2021 | | | 2021–2022 | | |
|---|---|---|---|---|---|---|---|
| | | Pre-winter plant counts (plants/m$^2$) | Post-winter plant counts (plants/m$^2$) | Overwinter rate (%) | Pre-winter plant counts (plants/m$^2$) | Post-winter plant counts (plants/m$^2$) | Overwinter rate (%) |
| No irrigation | N0 | 33.5 | 15.0 | 44.78 | 31.0 | 13.0 | 41.94 |
| | N1 | 29.0 | 14.5 | 50.00 | 30.5 | 13.0 | 42.62 |
| | N2 | 31.0 | 16.0 | 51.61 | 28.0 | 14.5 | 51.79 |
| | N3 | 30.5 | 16.5 | 54.10 | 26.5 | 14.0 | 52.8 |
| | N4 | 27.0 | 15.5 | 57.41 | 30.0 | 16.0 | 53.33 |
| Winter supplemental irrigation | N0 | 32.5 | 23.0 | 70.77 | 32.0 | 22.0 | 68.75 |
| | N1 | 28.5 | 21.5 | 75.44 | 27.5 | 20.5 | 74.55 |
| | N2 | 30.0 | 23.5 | 78.33 | 31.0 | 23.0 | 74.19 |
| | N3 | 29.0 | 22.0 | 75.86 | 32.0 | 25.5 | 79.69 |
| | N4 | 33.5 | 27.0 | 80.60 | 29.0 | 23.0 | 79.31 |
| Significant level (F value) | | | | | | | |
| I | | ns | ** | ** | ns | ** | ** |
| N | | ns | ns | ns | ns | * | ns |
| I×N | | ns | ns | ns | ns | ns | ns |

Note: Different lowercase letters in the same column indicate significance at $P < 0.05$, whereas the same letter indicates insignificance. * Means significant difference ($P<0.05$), ** means extremely significant difference ($P<0.01$).

**Table 3**
Quality indexes of winter oilseed rape under different levels of nitrogen and supplementary irrigation in 2020–2021 and 2021–2022.

| Treatment | 2020–2021 | | | | | 2021–2022 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Oil content (%) | Protein (%) | Thioside acid (μmol·g$^{-1}$) | Erucic acid (%) | Oleic acid (%) | Oil content (%) | Protein (%) | Thioside acid (μmol·g$^{-1}$) | Erucic acid (%) | Oleic acid (%) |
| I0N0 | 46.46±1.21$^{a}$ | 23.58±0.58$^{e}$ | 51.31±2.01$^{b}$ | 2.44±0.09$^{b}$ | 56.19±1.23$^{c}$ | 42.44±0.91$^{a}$ | 27.47±0.55$^{d}$ | 47.77±1.76$^{c}$ | 2.43±0.09$^{a}$ | 56.59±2.12$^{c}$ |
| I0N1 | 44.49±1.02$^{b}$ | 24.79±0.52$^{d}$ | 46.94±1.77$^{c}$ | 2.26±0.07$^{c}$ | 58.05±2.72$^{b}$ | 41.24±0.87$^{b}$ | 27.39±0.61$^{d}$ | 46.82±1.68$^{c}$ | 2.35±0.11$^{ab}$ | 51.08±2.09$^{b}$ |
| I0N2 | 43.76±0.97$^{b}$ | 25.75±0.61$^{c}$ | 51.34±1.96$^{b}$ | 2.45±0.11$^{ab}$ | 58.49±1.98$^{b}$ | 40.82±0.91$^{c}$ | 28.64±0.63$^{b}$ | 47.65±1.55$^{c}$ | 2.23±0.15$^{bc}$ | 55.32±3.01$^{b}$ |
| I0N3 | 41.85±1.11$^{c}$ | 27.95±0.49$^{b}$ | 54.27±2.21$^{a}$ | 2.63±0.12$^{a}$ | 57.89±1.78$^{bc}$ | 39.79±0.67$^{cd}$ | 28.69±0.71$^{b}$ | 52.19±1.69$^{ab}$ | 2.41±0.07$^{ab}$ | 58.08±1.38$^{ab}$ |
| I0N4 | 41.12±0.87$^{cd}$ | 28.05±0.76$^{a}$ | 56.40±2.17$^{a}$ | 2.66±0.06$^{a}$ | 54.80±1.66$^{c}$ | 37.94±0.54$^{d}$ | 31.37±0.67$^{a}$ | 52.50±1.87$^{ab}$ | 2.49±0.12$^{a}$ | 53.20±1.78$^{d}$ |
| I1N0 | 46.58±1.11$^{a}$ | 23.87±0.44$^{e}$ | 51.34±1.87$^{b}$ | 2.40±0.08$^{b}$ | 58.07±2.98$^{b}$ | 42.52±1.01$^{a}$ | 26.07±0.60$^{cd}$ | 49.07±1.88$^{bc}$ | 2.55±0.19$^{a}$ | 55.14±2.01$^{b}$ |
| I1N1 | 45.65±1.20$^{ab}$ | 24.24±0.51$^{d}$ | 50.79±1.74$^{b}$ | 1.92±0.14$^{c}$ | 61.95±3.21$^{a}$ | 41.34±0.99$^{b}$ | 27.42±0.66$^{cd}$ | 49.21±1.79$^{bc}$ | 2.27±0.20$^{bc}$ | 54.44±1.98$^{ab}$ |
| I1N2 | 43.10±0.77$^{b}$ | 24.88±0.77$^{cd}$ | 51.98±1.54$^{b}$ | 2.27±0.09$^{c}$ | 60.53±1.78$^{a}$ | 41.09±0.89$^{b}$ | 27.05±0.71$^{d}$ | 50.86±1.90$^{b}$ | 2.31±0.17$^{b}$ | 58.12±1.69$^{ab}$ |
| I1N3 | 41.98±0.81$^{c}$ | 27.77±0.71$^{b}$ | 56.34±2.44$^{a}$ | 2.45±0.10$^{ab}$ | 60.08±3.33$^{a}$ | 39.82±0.77$^{cd}$ | 28.63±0.72$^{bc}$ | 53.07±2.03$^{ab}$ | 2.32±0.09$^{b}$ | 62.56±0.98$^{a}$ |
| I1N4 | 40.95±0.69$^{cd}$ | 29.18±0.68$^{a}$ | 57.39±2.56$^{a}$ | 2.47±0.08$^{ab}$ | 57.88±4.01$^{bc}$ | 38.85±0.66$^{d}$ | 30.23±0.77$^{a}$ | 53.50±1.79$^{a}$ | 2.49±0.18$^{a}$ | 56.25±1.88$^{c}$ |
| I2N0 | 46.01±1.19$^{a}$ | 25.93±0.59$^{c}$ | 53.00±1.87$^{ab}$ | 2.48±0.12$^{b}$ | 60.59±3.79$^{a}$ | 42.51±1.11$^{a}$ | 26.62±0.64$^{d}$ | 49.51±1.88$^{bc}$ | 2.23±0.19$^{bc}$ | 53.26±2.09$^{a}$ |
| I2N1 | 45.05±1.13$^{ab}$ | 26.56±0.66$^{c}$ | 52.14±1.69$^{ab}$ | 2.23±0.06$^{c}$ | 62.60±2.07$^{a}$ | 40.99±0.88$^{bc}$ | 27.44±0.53$^{cd}$ | 49.87±1.67$^{bc}$ | 2.17±0.13$^{c}$ | 57.15±2.31$^{a}$ |
| I2N2 | 43.06±1.02$^{b}$ | 27.53±0.58$^{b}$ | 52.31±1.54$^{b}$ | 2.17±0.09$^{c}$ | 61.96±3.33$^{a}$ | 40.59±0.79$^{c}$ | 27.69±0.59$^{c}$ | 51.77±2.11$^{b}$ | 2.21±0.09$^{c}$ | 58.98±1.46$^{a}$ |
| I2N3 | 41.16±0.97$^{cd}$ | 28.98±0.78$^{a}$ | 57.30±2.45$^{a}$ | 2.54±0.13$^{a}$ | 61.23±2.45$^{a}$ | 38.47±0.45$^{d}$ | 29.85±0.49$^{b}$ | 54.64±2.65$^{a}$ | 2.36±0.12$^{ab}$ | 52.88±1.68$^{a}$ |
| I2N4 | 40.82±1.06$^{d}$ | 30.19±0.81$^{a}$ | 60.76±2.43$^{a}$ | 2.58±0.18$^{a}$ | 58.87±1.49$^{b}$ | 38.27±0.66$^{d}$ | 30.05±0.64$^{a}$ | 54.71±2.43$^{a}$ | 2.38±0.10$^{ab}$ | 57.62±2.03$^{a}$ |
| Significant level (F value) | | | | | | | | | | |
| I | * | * | ns | ns | ** | ** | * | ns | ns | ** |
| N | ** | ** | ** | * | * | ** | ** | ** | * | * |
| I×N | * | ns | ns | ns | * | * | * | ns | ns | * |

Note: Different letters in the same column indicate significance at P < 0.05, whereas the same letter indicates insignificance. * Means significant difference (P<0.05), ** means extremely significant difference (*P*<0.01).

### *3.4. NA, NAE, and PFPN*

The accumulation and distribution of nitrogen in different organs of winter oilseed rape in budding stage, flowering stage, and harvesting stage were shown in Fig. 4. During the budding stage, N accumulation was mainly concentrated in stems and leaves, and the N accumulation in leaves was higher than that in stems. The N accumulation in leaves accounted for 57.15%-66.61% (2020–2021) and 56.18%-65.86% (2021–2022) of the total N accumulation, respectively. During the flowering stage, the N accumulation in each organ of winter oilseed rape was increased compared with that in the budding stage. The proportion of the N accumulation in leaves was still higher than that in stems and fruits, but the proportion of the N accumulation in leaves was slightly lower than that in the budding stage. During the harvesting stage, the N accumulation in different organ of winter oilseed rape was in descending order: fruit> stem> leaf, and the range of N accumulation in fruits were 49.20–119.76 kg/hm$^2$ (2020–2021) and 47.15–116.44 kg/hm$^2$ (2021–2022), respectively.

In the two-year experiment, the supplementary irrigation (I) and the interaction effects of IxN had significant effects on nitrogen agronomic efficiency (NAE) (*P*<0.05), and N had extremely significant effect on NAE (Table 5). Under the same supplementary irrigation conditions, NAE increased first and then decreased with the increase of N application rate, which reached the maximum at N3, but there was no significant difference between N2 and N3. Under the same N application rate, except for N3 in 2021–2022, NAE reached the maximum under I2. As shown in Table 5, the supplementary irrigation (I) had significant effect on nitrogen partial factor productivity (NPFP), and nitrogen (N), IxN had extremely significant effects on NPFP (*P*<0.01). Under the same supplementary irrigation levels, NPFP decreased with the increase of the rate of N application. Under the same N application rate, NPFP was maximized under I2.

### *3.5. Multi-objective decision making and evaluation based on TOPSIS with Nash equilibrium-combination weighting method*

The weight of each evaluation index calculated by the three methods were shown in Fig. 5a. Through the analytic hierarchy process (AHP), the yield accounted for the highest weight (31.48%), followed by the oil content (16.09%), and the third was WUE (15.74%). The yield obtained by entropy weight method (EWM) also accounted for the highest weight (23.03%), followed by nitrogen accumulation (20.44%), and the third was chlorophyll content (13.40%). There were differences in the weights calculated by the AHP and EWM, and there were certain defects in the separate use of the two methods. Therefore, the NASH equilibrium is used as an optimization goal to coordinate the subjective and objective weights, and according to the principle of game theory, the comprehensive weight was obtained by combination weighting. The combination weight of yield (26.59%) was the highest, followed by nitrogen accumulation (13.96%), and the third was WUE (12.72%). Based on the comprehensive weight, the comprehensive evaluation value of winter oilseed rape in two years was determined according to the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). Although there were differences in the evaluation results between the two years, the difference was not significant (Fig. 5b). The highest score was I2N2 (Si=0.867) in 2020–2021, followed by I2N3 (Si=0.838), while the highest comprehensive score in 2021–2022 was I2N2 (Si=0.857), followed by I2N1 (Si=0.821). The results showed that the multi-objective

**Table 4**
Yield and its component of winter oilseed rape under different levels of nitrogen and supplementary irrigation in 2020–2021 and 2021–2022.

| Treatment | 2020–2021 | | | | | 2021–2022 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Branches per plant | Corners per plant | Seeds per corner | 1000-seed weight(g) | Yield (kg ha$^{-1}$) | Branches per plant | Corners per plant | Seeds per corner | 1000-seed weight(g) | Yield (kg ha$^{-1}$) |
| I0N0 | 16.67±0.89$^{c}$ | 171.50 ±14.22$^{c}$ | 27.73 ±1.98$^{c}$ | 3.41±0.21$^{b}$ | 1332.60 ±97.02$^{e}$ | 15.83±0.34$^{c}$ | 197.75 ±14.89$^{d}$ | 28.27 ±1.19$^{c}$ | 3.55±0.13$^{b}$ | 1437.20 ±109.89$^{e}$ |
| I0N1 | 21.12±0.56$^{b}$ | 211.33 ±12.71$^{b}$ | 29.28 ±1.21$^{b}$ | 3.46±0.18$^{b}$ | 1420.00 ±105.78$^{e}$ | 19.17 ±0.55$^{bc}$ | 210.75 ±10.98$^{d}$ | 28.40 ±0.98$^{c}$ | 3.61±0.21$^{ab}$ | 1493.10 ±69.08$^{d}$ |
| I0N2 | 25.50±0.21$^{a}$ | 274.83 ±11.98$^{ab}$ | 29.87 ±0.77$^{ab}$ | 3.57±0.15$^{a}$ | 1624.80 ±79.21$^{d}$ | 22.25±0.68$^{b}$ | 256.17 ±9.01$^{c}$ | 29.50 ±1.78$^{ab}$ | 3.63±0.16$^{ab}$ | 1650.40 ±98.23$^{c}$ |
| I0N3 | 24.33±0.64$^{a}$ | 291.33 ±14.23$^{ab}$ | 29.92 ±1.34$^{ab}$ | 3.47±0.22$^{b}$ | 1691.93 ±88.25$^{d}$ | 24.00±0.49$^{a}$ | 296.08 ±11.56$^{b}$ | 29.42 ±1.89$^{b}$ | 3.59±0.18$^{ab}$ | 1771.70 ±110.91$^{bc}$ |
| I0N4 | 23.50±0.42$^{b}$ | 237.22 ±10.32$^{b}$ | 29.37 ±1.11$^{b}$ | 3.25±0.17$^{c}$ | 1536.40 ±114.09$^{e}$ | 21.25±0.61$^{b}$ | 213.58 ±15.66$^{d}$ | 28.81 ±0.93$^{b}$ | 3.55±0.20$^{ab}$ | 1508.87 ±92.01$^{c}$ |
| I1N0 | 18.83±0.67$^{c}$ | 187.17 ±9.89$^{b}$ | 28.98 ±0.99$^{b}$ | 3.51±0.20$^{b}$ | 1788.07 ±89.65$^{c}$ | 18.83 ±0.44$^{bc}$ | 226.58 ±12.27$^{d}$ | 29.05 ±1.78$^{b}$ | 3.60±0.25$^{b}$ | 1841.80 ±82.10$^{c}$ |
| I1N1 | 23.00±0.39$^{b}$ | 255.50 ±13.98$^{ab}$ | 29.83 ±1.78$^{b}$ | 3.66±0.23$^{a}$ | 1800.73 ±90.21$^{c}$ | 20.50 ±0.56$^{bc}$ | 264.17 ±12.20$^{bc}$ | 29.60 ±1.09$^{ab}$ | 3.69±0.21$^{ab}$ | 1923.56 ±99.01$^{bc}$ |
| I1N2 | 26.33±0.81$^{a}$ | 285.67 ±10.90$^{a}$ | 30.73 ±1.56$^{a}$ | 3.78±0.13$^{a}$ | 2005.00 ±121.98$^{bc}$ | 22.08±0.60$^{b}$ | 299.67 ±16.09$^{b}$ | 30.75 ±0.98$^{a}$ | 3.77±0.14$^{a}$ | 2145.67 ±88.25$^{b}$ |
| I1N3 | 25.83±0.65$^{a}$ | 321.00 ±12.74$^{a}$ | 31.03 ±1.21$^{a}$ | 3.76±0.11$^{a}$ | 2157.73 ±79.01$^{b}$ | 24.92±0.81$^{a}$ | 334.33 ±10.98$^{a}$ | 29.95 ±0.78$^{a}$ | 3.72±0.22$^{a}$ | 2298.06 ±103.42$^{ab}$ |
| I1N4 | 24.83±0.71$^{a}$ | 291.50 ±15.67$^{ab}$ | 29.87 ±0.69$^{ab}$ | 3.66±0.14$^{a}$ | 1804.87 ±89.67$^{c}$ | 23.75±0.30$^{a}$ | 253.33 ±16.57$^{c}$ | 29.30 ±1.31$^{b}$ | 3.67±0.17$^{a}$ | 1989.70 ±72.01$^{b}$ |
| I2N0 | 20.83±0.63$^{b}$ | 210.67 ±16.66$^{b}$ | 29.02 ±1.45$^{b}$ | 3.62±0.21$^{a}$ | 2094.40 ±90.23$^{b}$ | 19.17 ±0.59$^{bc}$ | 246.58 ±13.87$^{c}$ | 29.15 ±0.99$^{b}$ | 3.69±0.09$^{ab}$ | 2134.56 ±104.81$^{b}$ |
| I2N1 | 24.33±0.59$^{a}$ | 294.83 ±15.98$^{a}$ | 30.67 ±1.21$^{a}$ | 3.70±0.26$^{a}$ | 2236.00 ±108.41$^{ab}$ | 23.75±0.79$^{a}$ | 305.08 ±12.67$^{b}$ | 30.35 ±1.77$^{a}$ | 3.75±0.18$^{a}$ | 2314.87 ±66.72$^{ab}$ |
| I2N2 | 27.67±0.67$^{a}$ | 312.28 ±16.01$^{a}$ | 30.97 ±0.77$^{a}$ | 3.87±0.28$^{a}$ | 2404.87 ±65.43$^{a}$ | 24.92±0.61$^{a}$ | 325.17 ±10.66$^{a}$ | 31.25 ±0.78$^{a}$ | 3.90±0.19$^{a}$ | 2560.89 ±87.90$^{a}$ |
| I2N3 | 26.00±0.29$^{a}$ | 333.17 ±11.09$^{a}$ | 31.35 ±1.89$^{a}$ | 3.82±0.10$^{a}$ | 2460.40 ±101.09$^{a}$ | 25.25±0.58$^{a}$ | 354.75 ±9.89$^{a}$ | 30.49 ±1.13$^{a}$ | 3.83±0.26$^{a}$ | 2668.98 ±72.12$^{a}$ |
| I2N4 | 25.33±0.53$^{a}$ | 302.89 ±8.97$^{a}$ | 30.52 ±1.22$^{a}$ | 3.73±0.19$^{a}$ | 2231.40 ±65.57$^{ab}$ | 24.25±0.66$^{a}$ | 297.75 ±11.89$^{b}$ | 30.15 ±1.47$^{a}$ | 3.84±0.20$^{a}$ | 2436.87 ±70.98$^{a}$ |
| Significant level (F value) | | | | | | | | | | |
| I | * | * | ** | ns | ** | * | * | * | ns | ** |
| N | * | ns | * | * | ** | ns | ns | * | * | * |
| I×N | ns | * | * | ns | * | ns | * | ns | ns | * |

Note: Different letters in the same column indicate significance at P < 0.05, whereas the same letter indicates insignificance. * Means significant difference (P<0.05), ** means extremely significant difference (*P*<0.01).

**Table 5**
Evapotranspiration (ET), rainfall utilization efficiency (RUE), water use efficiency (WUE), nitrogen agronomic efficiency (NAE), and nitrogen partial factor productivity (NPFP) under different levels of nitrogen and supplementary irrigation in 2020–2021 and 2021–2022.

| Treatment | 2020–2021 | | | | | 2021–2022 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ET (mm) | RUE (kg ha$^{-1}$·mm$^{-1}$) | WUE (kg ha$^{-1}$·mm$^{-1}$) | NAE (kg kg$^{-1}$) | NPFP (kg kg$^{-1}$) | ET (mm) | RUE (kg ha$^{-1}$·mm$^{-1}$) | WUE (kg ha$^{-1}$·mm$^{-1}$) | NAE (kg kg$^{-1}$) | NPFP (kg kg$^{-1}$) |
| I0N0 | 259.8 | 5.4$^{b}$ | 5.1$^{c}$ | – | – | 256.3 | 5.8$^{c}$ | 5.1$^{d}$ | – | – |
| I0N1 | 262.4 | 5.8$^{b}$ | 5.4$^{bc}$ | 0.73$^{d}$ | 11.83$^{b}$ | 260.9 | 6.1$^{b}$ | 5.4$^{d}$ | 0.47$^{e}$ | 12.44$^{d}$ |
| I0N2 | 265.8 | 6.6$^{a}$ | 6.1$^{b}$ | 1.46$^{a}$ | 10.12$^{bc}$ | 264.3 | 6.7$^{ab}$ | 6.1$^{bc}$ | 1.07$^{c}$ | 11.25$^{de}$ |
| I0N3 | 266.9 | 6.9$^{a}$ | 6.3$^{a}$ | 1.48$^{a}$ | 9.40$^{c}$ | 263.5 | 7.2$^{a}$ | 6.3$^{b}$ | 1.67$^{a}$ | 9.63$^{e}$ |
| I0N4 | 261.7 | 6.3$^{a}$ | 5.9$^{bc}$ | 0.57$^{d}$ | 5.27$^{e}$ | 258.7 | 6.1$^{b}$ | 5.9$^{c}$ | 0.34$^{f}$ | 6.72$^{f}$ |
| I1N0 | 315.5 | 5.6$^{b}$ | 5.7$^{c}$ | – | – | 321.1 | 5.8$^{c}$ | 5.7$^{d}$ | – | – |
| I1N1 | 318.7 | 5.7$^{b}$ | 5.7$^{c}$ | 0.91$^{c}$ | 15.01$^{a}$ | 327.5 | 6.1$^{b}$ | 5.9$^{c}$ | 0.68$^{d}$ | 16.03$^{b}$ |
| I1N2 | 323.2 | 6.3$^{a}$ | 6.2$^{b}$ | 1.58$^{a}$ | 11.03$^{b}$ | 339.5 | 6.8$^{ab}$ | 6.3$^{bc}$ | 1.52$^{b}$ | 13.73$^{c}$ |
| I1N3 | 322.2 | 6.8$^{a}$ | 6.7$^{a}$ | 1.62$^{a}$ | 9.71$^{c}$ | 337.3 | 7.3$^{a}$ | 6.8$^{a}$ | 1.83$^{a}$ | 12.02$^{d}$ |
| I1N4 | 317.1 | 5.7$^{b}$ | 5.7$^{c}$ | 0.75$^{d}$ | 6.01$^{d}$ | 326.4 | 6.3$^{b}$ | 6.1$^{c}$ | 0.41$^{e}$ | 7.05$^{f}$ |
| I2N0 | 354.0 | 5.2$^{c}$ | 5.9$^{bc}$ | – | – | 362.4 | 5.3$^{d}$ | 5.9$^{c}$ | – | – |
| I2N1 | 356.0 | 5.6$^{b}$ | 6.3$^{b}$ | 1.18$^{b}$ | 18.63$^{a}$ | 364.1 | 5.7$^{c}$ | 6.4$^{b}$ | 1.00$^{c}$ | 19.29$^{a}$ |
| I2N2 | 369.5 | 6.0$^{a}$ | 6.7$^{a}$ | 1.60$^{a}$ | 12.02$^{b}$ | 370.9 | 6.3$^{b}$ | 6.9$^{a}$ | 1.63$^{a}$ | 14.80$^{bc}$ |
| I2N3 | 360.9 | 6.1$^{a}$ | 6.8$^{a}$ | 1.71$^{a}$ | 10.79$^{b}$ | 373.3 | 6.6$^{ab}$ | 7.1$^{a}$ | 1.81$^{a}$ | 13.53$^{c}$ |
| I2N4 | 357.4 | 5.5$^{b}$ | 6.2$^{b}$ | 1.38$^{b}$ | 6.72$^{d}$ | 368.5 | 6.0$^{b}$ | 6.6$^{b}$ | 0.64$^{d}$ | 7.91$^{f}$ |
| Significant level (F value) | | | | | | | | | | |
| I | * | ns | ** | * | ** | * | ns | ** | * | * |
| N | ns | * | * | ** | ** | ns | * | * | ** | ** |
| I×N | ns | ns | * | ns | ** | ns | ns | * | * | * |

Different lowercase letters in the same column indicate significance at P < 0.05, whereas the same letter indicates insignificance. * Means significant difference (P<0.05), ** means extremely significant difference (P<0.01

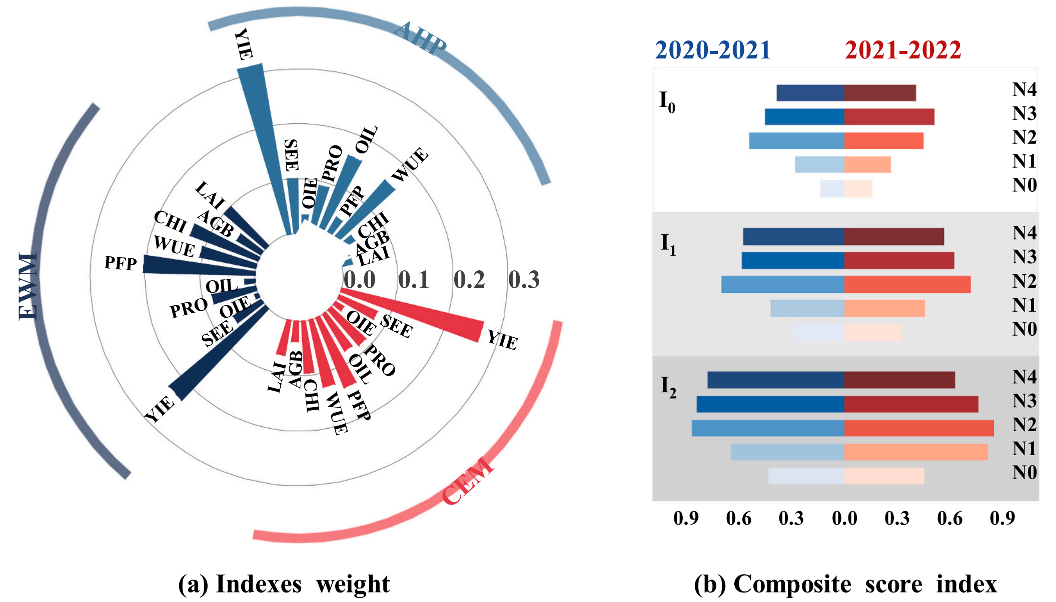


**Fig. 5.** The weight values of each index calculated by different methods and the comprehensive scores of different treatments. Notes: LAI, AGB, CHI, WUE, PFP, OIL, WUE, PFP, OIE, SEE, YIE means leaf area index, above-ground biomass, chlorophyll content, water use efficiency, nitrogen partial factor productivity, oil content, protein content, oleic acid content, 1000-seed weight, and yield, respectively.

comprehensive level was optimal under I2N2 in the two years.

## 4. Discussion

### *4.1. Effect of supplementary irrigation and N rate on winter oilseed rape physiological growth parameters, water/nitrogen utilization efficiency, yield and quality*

Water and nitrogen are the main factors affecting crop growth, yield. The main purpose of agricultural water and nitrogen management is to maximize the yield and quality of crops under unit water and N application (Trenberth et al., 2014; Yan et al., 2022c). Winter oilseed rape is a crop with large water demand. Supplementary irrigation during its critical growth period can increase crop overwintering rate, promote crop growth and development, and ultimately increase crop yield (Gu et al., 2018c; Moradi et al., 2022). Rainfall in Guanzhong region of Shaanxi Province is mainly concentrated from July to October, and the rainfall can meet the water demand of winter oilseed rape at seedling stage. In this study, under the same N application levels, the over-wintering rate of winter oilseed rape with winter supplementary irrigation increased by 28.94% −56.31% (Table 2). This's probably because the supplementary irrigation during the overwintering stage can stabilize the ground temperature to save sufficient water for root activity, increase the cold-resistant substances of crop rhizomes, and then reduce the degree of crop damage (Dai et al., 2022; Wang et al., 2022). The bugging stage is the key period for the growth of winter oilseed rape, and the crop water consumption is the largest during this period (Wu et al., 2019). Drought stress at the bugging period not only inhibit the formation of chlorophyll, but also cause the decomposition of chlorophyll in leaves (Urban et al., 2018). Chlorophyll is the main driving factor of the first link of crop photosynthesis, and the chlorophyll content can directly affect the crop photosynthesis efficiency, which in turn affects crop growth and biomass accumulation, and ultimately affects crop yield (Liao et al., 2022). Our study showed that under the same N rate, the chlorophyll content and grain yield of winter oilseed rape treated with supplementary irrigation at overwintering and budding stages were significantly higher than those treated with supplementary irrigation only during the overwintering stage and without supplementary irrigation. Dai et al., (2023) and Olesen et al., (2000) have found that supplementary irrigation at key growth stages can improve crop water and nitrogen use efficiency, which is generally consistent with the results of this study.

Improving water and nitrogen use efficiency can promote the absorption of nitrogen, ensure high crop yield, and effectively alleviate problems such as waste of resources and environmental pollution (Wang et al., 2023). Within a certain range, increasing the amount of N fertilizer can significantly increase the N accumulation and water & nitrogen use efficiency of winter oilseed rape (Gu et al., 2018). In this study, under the same irrigation level, N accumulation and WUE increased first and then decreased with the increase of N application rate, and reached the maximum at 200 kg/hm$^2$ or 280 kg/hm$^2$. The reason is that the appropriate amount of N can alleviate the adverse effects of water stress on plant growth, reduce the decline rate of chlorophyll content, prolong the leaf functional cycle, and improve its photosynthetic productivity, promote the accumulation of N (Wu et al., 2019; Li et al., 2019). At the same time, it promotes the number and density of winter oilseed rape flowers, ultimately increase its grain yield (Shi, 2022). Excessive applications of N fertilizer not only cause nutritional competition between vegetative organs, reduce the amount of N transported to seeds, but also cause stem weakness, resulting in large-scale lodging of winter oilseed rape in the later period, and large-scale lodging will easily lead to the aggravation of diseases and insect pests in the lower concealment (Yan et al., 2022; Su et al., 2014). Liu et al. (2016) showed that the application of N fertilizer is an important factor to increase yield, but excessive application will reduce the oil content of crop grain and affect its quality, which is consistent with the results of this study. Previous studies have shown that insufficient supply of N fertilizer will seriously affect the growth and development of winter oilseed rape, resulting in dwarf plants, making it impossible for crops to produce and store enough nutrients, which affect crop yield (Wang et al., 2019; Gu et al., 2018). According to the winter oilseed rape fertilizer demand characteristics and experimental results we put forward a reasonable strategy for combining supplementary irrigation and N fertilizer reduction, which reduced the production cost and improved the efficiency of N utilization. It is conducive to the green and efficient production, and improves its market competitiveness.

### 4.2. Multi-objective decision making and evaluation based on the TOPSIS with Nash equilibrium-combination weighting method

Multi-objective optimization decision making is very common and important in solving problems in agriculture and people's daily life, and has important scientific and practical significance. Scholars have established a variety of evaluation and analysis models for multi-objective optimization in agricultural production (Ning et al., 2018; Sun et al., 2022). Among them, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is widely used. Xiang (2017) took the yield, quality, water and nitrogen efficiency of sweet pepper as the target evaluation indexes and based TOPSIS to propose the best water and nitrogen application strategy to achieve high yield and quality of sweet pepper. Wang et al., (2019) conducted multi-objective optimization of potato management in northern sandy land through TOPSIS, and found that the multi-objective reached the optimal level when the irrigation frequency was once every 8 days, full irrigation (1.0ETc) and high fertilizer application. In the process of comprehensive evaluation, it is important to select the appropriate target evaluation index and determine its weight (Luo and Li, 2013; Hou et al., 2021). In this study, we selected these ten indicators for the following four reasons: (1) LAI, chlorophyll content and aboveground biomass can reflect the physiology and growth of the crop; (2) WUE and PFPN are the core contents of the efficient utilization of water and nitrogen (Yan et al., 2022); (3) With the improvement of living standards, people's demand for crop quality has gradually increased while pursuing high crop yield. Protein, oil content and oleic acid content are important quality indexes of winter oilseed rape.

Entropy weight method (EWM) is a typical objective weighting method based on data diversity, which can calculate weight attributes according to the diversity of data attributes (Li et al., 2012). However, EWM cannot reflect the decision-makers' understanding of the importance of each index, which may lead to the situation that the evaluation results are contrary to the facts (Deng et al., 2021). Analytic Hierarchy Process (AHP) refers to the decomposition of the elements related to decision-making into levels such as objectives, criteria and schemes, and on this basis, qualitative and quantitative analysis is carried out (Veisi et al., 2022). The weight calculated by AHP can better reflect the importance of decision makers for different attributes. However, this method has strong subjective arbitrariness, which increases the burden on decision analysts (Baviera-Puig et al., 2022). In this study, we invoke the Nash equilibrium coefficient and use game theory to combine subjective and objective empowerment methods. The combination of the two methods can take into account the decision maker's preference for attributes, but also reduce the subjective arbitrariness of the assignment, so that the decision-making results are more realistic and reliable (Hong et al., 2022). Through TOPSIS with Nash equilibrium-combination weight method, our study found that multi-objective comprehensive level was optimal under the combination of N application rate of 200 kg/hm$^2$ and supplementary irrigation at overwintering and budding stages.

## 5. Conclusions

Supplementary irrigation at overwintering and budding stages can improve the physiological growth indexes, overwinter ability, water-N utilization efficiency, main quality indexes, and yield of winter oilseed rape. Under the same supplementary irrigation level, the grain quality and yield of winter oilseed rape first increased and then decreased with the increase of N application rate, which maximum at the N application rate of 200 kg/hm$^2$ or 280 kg/hm$^2$. The result showed that the combination of supplementary irrigation at overwintering and budding stages and medium N application rate are suitable for winter oilseed rape cultivation in Northwest China. Based on the TOPSIS with Nash equilibrium-combination weighting method, the multi-objective optimal strategies were determined to be the combination of supplementary irrigation at overwintering and budding stages (I2) and N application rate of 200 kg/hm$^2$ (N2).

In our study, the optimal combination of supplementary irrigation and N application rate was determined based on crop physiological growth indexes, yield, quality, and water-N utilization efficiency. The other indicators, such as economy indicators, can be taken into account in future studies to further improve the evaluation results. Although meteorological factors such as rainfall may affect the water and N application strategies in actual cultivation, our results can provide a reference for winter oilseed rape cultivation in semi-arid areas of Northwest China and other regions with similar environments.

## CRediT authorship contribution statement

**Xiangyang Huang:** Formal analysis, Data curation. **Xueyan Zhang:** Visualization, Validation, Supervision. **Xin Wang:** Methodology, Investigation. **Fucang Zhang:** Validation, Supervision. **Zhenqi Liao:** Supervision, Methodology, Conceptualization. **Youzhen Xiang:** Methodology. **Li Feng:** Funding acquisition. **Han Wang:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 52179045).

## References

Ali, S., Ma, X.C., Jia, Q.M., Ahmad, I., Ahmad, S., Zhang, S., Yun, B., Muhammad, A., Ren, X.L., Sha, S.H., Akbar, H., Cai, T., Zhang, J.H., Jia, Z.K., 2019. Supplemental irrigation strategy for improving grain filling, economic return, and production in winter wheat under the ridge and furrow rainwater harvesting system. Agric. Water Manag. 226, 105842 https://doi.org/10.1016/j.agwat.2019.105842.

Baviera-Puig, A., Garcia-Melon., Lopez-Cortes, I., Ortola, M.D., 2022. Combining sensory panels with Analytic Hierarchy Process (AHP) to assess nectarine and peach quality. Cogent Food Agric. 9 (1), 2161184. https://doi.org/10.1080/23311932.2022.2161184.

Chun, Z., Dong, Z.Y., Guo, Q., Hu, Z.L., Wei, T., Ding, R.X., Cai, T., Ren, X.L., Han, Q.F., Zhang, P., Jia, Z.K., 2022. Ridge–furrow rainwater harvesting combined with supplementary irrigation: water-saving and yield-maintaining mode for winter wheat in a semiarid region based on 8-year in-situ experiment. Agric. Water Manag. 259, 107239 https://doi.org/10.1016/J.AGWAT.2021.107239.

Dai, Y.L., Fan, J.L., Liao, Z.Q., Zhang, C., Yu, J., Feng, H.L., Zhang, F.C., Li, Z.J., 2022. Supplemental irrigation and modified plant density improved photosynthesis, grain yield and water productivity of winter wheat under ridge-furrow mulching. Agric. Water Manag. 274, 107985 https://doi.org/10.1016/j.agwat.2022.107985.

Dai, Y.L., Liao, Z.Q., Lai, Z.L., Bai, Z.T., Zhang, F.C., Li, Z.J., Fan, J.L., 2023. Interactive effects of planting pattern, supplementary irrigation and planting density on grain yield, water-nitrogen use efficiency and economic benefit of winter wheat in a semi-humid but drought-prone region of northwest China. Agric. Water Manag. 287, 108438 https://doi.org/10.1016/j.agwat.2023.108438.

Deng, Z., Yi, J., Wu, J.B., Zhang, H.J., 2021. Comprehensive evaluation of water and fertilizer application for Lycium barbarum L. based on AHP and entropy weight method. J. IRRIG DRAIN ENG 39 (7), 712–719.

Erisman, J.W., Bleeker, A., Hensen, A., Vermeulen, A., 2008. Agricultural air quality in Europe and the future perspectives. Atmos. Environ. 42 (14), 3209–3217. https://doi.org/10.1016/j.atmosenv.2007.04.004.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320 (5878), 889–892. https://doi.org/10.1126/science.1136674.

Gao, Y., Zhang, M., Yao, C., Liu, Y., Wang, Z., Zhang, Y., 2021. Increasing seeding density under limited irrigation improves crop yield and water productivity of winter wheat

by constructing a reasonable population architecture. Agric. Water Manag. 253, 106951 https://doi.org/10.1016/J.AGWAT.2021.106951.
Gholizadeh, B.A., 2016. Modeling land suitability evaluation for wheat production by parametric and TOPSIS approaches using GIS, northeast of Iran. Model. Earth Syst. Environ. 2 (3).
Gu, X.B., Li, Y.N., Du, Y.D., 2018. Effects of ridge-furrow film mulching and nitrogen fertilization on growth, seed yield and water productivity of winter oilseed rape (Brassica napus L.) in Northwestern China. https://doi.org/10.1016/j.agwat.2018.01.001.
Guo, J.J., 2022. Effects of water and nitrogen regulation and slow-release nitrogen fertilizer combined with urea on growth, water and nitrogen utilization of winter wheat/summer maize. Northwest Agric. For. Univ. https://doi.org/10.27409/d.cnki.gxbnu.2022.000665.
Hong, T., Cai, Z., Li, R., Liu, J.C., Wang, Z., Zhang, Z., 2022. Effects of water and nitrogen coupling on watermelon growth, photosynthesis and yield under CO2 enrichment. Agric. Water Manag. 259 https://doi.org/10.1016/j.agwat.2021.107229.
Hou, X.H., Fan, J.L., Hu, W.H., Zhang, F.C., Yan, F.L., Xiao, C., Li, Y.P., Cheng, H.L., 2021. Optimal irrigation amount and nitrogen rate improved seed cotton yield while maintaining fiber quality of drip-fertigated cotton in northwest China. Ind. Crops Prod. 170, 113710 https://doi.org/10.1016/j.indcrop.2021.113710.
Huang, Z.B., Shan, K., 1998. Research progress on water use efficiency and its physiological and ecological mechanism. Chin. J. Ecol. 4.
Hwang, C.L., Yoon, K., 1981. Multiple Attributes Decision Making Methods and Applications . Berlin Heidelberg : Springe . .
Li, J., He, Z.B., Du, J., C, L.F., L, P.F., Z, X., F, S., Z, M.M., T, Q.Y., 2018. Effects of winter irrigation on soil water and heat status of desert oasis farmland in arid area during freeze-thaw period. Trans. Chin. Soc. Agric. Eng. 34 (11), 8 https://doi.org/CNKI:SUN:NYGU.0.2018-11-013.
Li, L., Jin, J.L., Zhu, Y.Z., 2012. Discussion on some problems in the application of TOPSIS method. Hydropower Energy Cust. Source 30 (3), 51–54 https://doi.org/CNKI:SUN:SDNY.0.2012-03-015.
Li, Y., Song, H., Zhou, L., Xu, Z., Zhou, Z., 2019. Vertical distributions of chlorophyll and nitrogen and their associations with photosynthesis under drought and rewatering regimes in a maize field. Agric. For. Meteorol. 272–273, 40–54. https://doi.org/10.1016/j.agrformet.2019.03.026.
Liao, Z., Zeng, H., Lai, Z., Zhang, C., Zhang, F., Wang, H., Cheng, M., Guo, J.J., Li, Z., 2022. Effects of plant density, nitrogen rate and supplemental irrigation on photosynthesis, root growth, seed yield and water-nitrogen use efficiency of soybean under ridge-furrow plastic mulching. Agric. Water Manag. 268 https://doi.org/10.1016/j.agwat.2022.107688.
Liu, Q.X., Ren, T., Zhang, M., Liao, S.P., Li, X.K., Chong, R.H., Lu, J.W., 2016. Effects of straw incorporation with nitrogen,phosphate and potassium fertilization on yield and yield components of direct-sown winter oilseed rape. Soil and Fertilizer Sciences in China.
Lu, J.S., Hu, T.T., Zhang, B.C., Wang, L., Yang, S.H., Fan, J.L., Yan, S.C., Zhang, F.C., 2021. Nitrogen fertilizer management effects on soil nitrate leaching, grain yield and economic benefit of summer maize in Northwest China. Agric. Water Manag 247, 106739. https://doi.org/10.1016/j.agwat. 2021.106739.
Lu, Q., Zhang, Y., 2022. A multi-objective optimization model considering users' satisfaction and multi-type demand response in dynamic electricity price. Energy 240. https://doi.org/10.1016/j.energy.2021.122504.
Luo, Y., Li, Y.L., 2013. Comprehensive decision-making of transmission on network planning based on entropy weight and grey relational analysis. Power Syst. Technol. 37 (1), 77–81. https://doi.org/10.13335/j.1000-3673.pst.2013.01.017.
Luo, N., Wang, X., Hou, J., Wang, P., Meng, Q., 2020. Agronomic optimal plant density for yield improvement in the major maize regions of China. Crop Sci. https://doi.org/10.1002/csc2.20000.
Moradi, L., Siosemardeh, A., Sohrabi, Y., Bahramnejad, B., Hosseinpanahi, F., 2022. Dry matter remobilization and associated traits, grain yield stability, N utilization, and grain protein concentration in wheat cultivars under supplemental irrigation. Agric. Water Manag 263, 107449. https://doi.org/10.1016/j.agwat. 2021.107449.
Ning, D., Yan, C., Zhao, Y., Yang, X., Yang, L., Li, N., Wang, Z., 2018. Study on agronomic, economic and qualitative characters of different peanuts varieties with TOPSIS method evaluation. J. Shanxi Agric. Sci. 46 (12), 1986–1989.
Olesen, J., Mortensen, J., Jørgensen, L., Andersen, M., 2000. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. I. Yield, yield components and nitrogen uptake. J. Agric. Sci. 134, 1–11. https://doi.org/10.1017/S0021859699007352.
Rady, M.O.A., Semida, W.M., Howladar, S.M., Abd El- Mageed, T.A., 2021. Raised beds modulate physiological responses, yield and water use efficiency of wheat (Triticum aestivum L) under deficit irrigation. Agric. Water Manag. 245, 106629 https://doi.org/10.1016/j.agwat.2020.106629.
Rathke, G.W., Behrens, T., Diepenbrock, W., 2006. Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (Brassica napus L.): a review. AGR ECOSYST ENVIRON 117 (2–3), 80–108. https://doi.org/10.1016/j.agee.2006.04.006.
Saaty, T.L., Kearns, K.P., 1985. The analytic hierarchy process. Anal. Plan. 1985 https://doi.org/10.1016/B978-0-08-032599-6.50008-8.
Shen, R.F., Wang, C., Sun, B., 2018. Soil science and technology problems in the implementation of grain storage technology strategy 2, 135–144. 10.16418/j.issn.1000-3045.2018.02.002.
Shi, P.C., 2002. The significance and technology of winter wheat irrigation, 7-7 Mod. Rural Sci. Technol. 10. https://doi.org/10.3969/j.issn.1000-6400.2002.11.004.
Shi, Y., 2022. Effects of nitrogen application rate on flowering traits and grain yield of plateau rapeseed. Agric. Eng. Technol. 42 (23), 33-33.
Su, W., Lu, J.W., Wang, W.N., Li, X.K., Ren, T., Cong, R.H., 2014. Influence of rice straw mulching on seed yield and nitrogen use efficiency of winter oilseed rape (*Brassica napus* L.) in intensive rice-oilseed rape cropping system. Field Crops Res 159, 53–61. https://doi.org/10.1016/j.fcr.2014.01.007.
Sun, X., Zhang, F.C., Yang, L., Zhang, S.H., Wang, H.D., Qiang, S.C., Guo, J.J., 2022. Optimal combination of potassium fertilizer and drip irrigation for potato production based on entropy weight method and TOPSIS analysis. J. Plant. Nutr. Soil Sci. 28 (2), 279–290.
The China Statistical, Yearbook. http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm.
Trenberth, K.E., Dai, A., Van Der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change 4, 17–22. https://doi.org/10.1038/nclimate2067.
Urban, O., Hlavacova, M., Klem, K., Novotna, K., Rapantova, B., Smutna, P., Horakova, V., Hlavinka, P., Skarpa, P., Trnka, M., 2018. Combined effects of drought and high temperature on photosynthetic characteristics in four winter wheat genotypes. Field Crops Res 223, 137–149. https://doi.org/10.1016/j.fcr.2018.02.029.
Veisi, H., Deihimfard, R., Hydarzadeh, Y., 2022. Application of the analytic hierarchy process (AHP) in a multi-criteria selection of agricultural irrigation systems. Agric. Water Manag. 267, 107619 https://doi.org/10.1016/J.AGWAT.2022.107619.
Wang, J., Cai, H., Li, H., Chen, X., 2006. Study and evaluation of the calculation methods of reference crop evapotranspiration in solar-heated greenhouse. J. Irrig. Drain. Eng. 25 (6) https://doi.org/11-14.10.13522/j.cnki.ggps.2006.06.003.
Wang, H., Fan, J., Fu, W., Du, M., Zhou, G., Zhou, M., Hao, M., Shao, M., 2022. Good harvests of winter wheat from stored soil water and improved temperature during fallow period by plastic film mulching. Agric. Water Manag 274, 107910 https://doi.org/107910.10.1016/j.agwat.2022.107910.
Wang, H.D., Wang, X.K., Bai, L.F., Wang, Y., Fan, J.L., Zhang, F.C., Hou, X.H., Cheng, M. H., Hu, W.H., Wu, L.F., Xiang, Y.Z., 2019. Multi-objective optimization of water and fertilizer management for potato production in sandy areas of northern China based on TOPSIS. Field Crops Res 240, 55–68. https://doi.org/10.1016/j.fcr.2019.06.005.
Wang, X., Xiang, Y.Z., Guo, J.J., Tang, Z.J., Zhao, S.T., Wang, H., Li, Z.J., Zhang, F.C., 2023. Coupling effect analysis of drip irrigation and mixed slow-release nitrogen fertilizer on yield and physiological characteristics of winter wheat in Guanzhong area. Field Crops Res 302. https://doi.org/10.1016/J.FCR.2023.109103.
Wu, X.M., Chen, B.X., Lu, G.Y., 2007. Description Standard and Data Standard of Rapeseed Germplasm Resources. China Agricultural Publishing House.
Wu, W., Ma, B.-L., Fan, J.-J., Sun, M., Yi, Y., Guo, W.-S., Voldeng, H.D., 2019. Management of nitrogen fertilization to balance reducing lodging risk and increasing yield and protein content in spring wheat. Field Crops Res 241, 107584. https://doi.org/10.1016/j.fcr.2019.107584.
Wu, L., Zhang, F., Zhou, H., Suo, Y., Liang, F., 2014. Effect of drip irrigation and fertilizer application on water use efficiency and cotton yield in North of Xinjiang. Trans. Chin. Soc. Agric. Eng. 30 (20), 137–146.
Xiang, Y.Z., 2017. Coupling Effects of Water and Nitrogen on Greenhouse Bell Pepper under Fertilization. Northwest A&F University.
Yan, F.L., Liu, X.Q., Bai, W.Q., Fan, J.L., Zhang, F.C., Xiang, Y.Z., Hou, X.H., Pei, S.Z., Dai, Y.L., Zeng, H.L., Wang, Y., 2022. Multi-objective optimization of water and nitrogen regimes for drip-fertigated sugar beet in a desert climate. Field Crops Res 288, 108703. https://doi.org/10.1016/j.fcr.2022.108703.
Zhang, Z., 2018. Analysis of Yield Difference and Nutrient Efficiency Difference of Winter Oilseed Rape in the Yangtze River Basin. Huazhong Agricultural University, Wuhan https://doi.org/CDMD:1.1018.192648.
Zhang, S.W., Chen, S.H., Hu, T.T., Cheng, C.M., 2023. Optimization of irrigation and nitrogen levels for a trade-off: Yield, quality, water use efficiency and environment effect in a drip-fertigated apple orchard based on TOPSIS method. Sci. Hortic. 309 https://doi.org/10.1016/J.SCIENTA.2022.111700.