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Coupling effect of water and nitrogen on olive (*Olea europaea* L.) using NSGA-II algorithm in hilly areas of Southwest China

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Abstract

Water scarcity and improper nitrogen management are major constraints affecting the sustainability of olive cultivation in the hilly regions of Southwest China. This study investigated the effects of different levels of supplemental irrigation and nitrogen application on olive yield, oil quality, and water–nitrogen use efficiency. A two-year field experiment (2020-2021) was conducted in Jintang County (Sichuan, China) using a randomized complete block design with three irrigation levels (W1: 60% FC, W2: 75% FC, W3: 90% FC) and three nitrogen rates (2020: 180, 360, and 540 kg ha^{-1}; 2021: 150, 300, and 450 kg ha^{-1}). A multi-objective optimization model was developed integrating yield, irrigation water use efficiency (IWUE), nitrogen partial factor productivity (NPFP), and olive oil quality indicators. The NSGA-II algorithm was applied to identify Pareto-optimal solutions. Results showed that nitrogen application significantly increased olive yield under all irrigation conditions, with yield following the trend N1 < N2 < N3. Palmitic acid content initially increased and then decreased with increasing nitrogen rates, whereas oleic acid showed an opposite trend. IWUE increased with nitrogen application, while NPFP decreased. Comprehensive quality evaluation using the VIKOR method indicated that excessive nitrogen reduced oil quality under higher irrigation levels. The optimal treatment identified by the NSGA-II model was W2N2, corresponding to moderate irrigation and nitrogen input. Under these conditions, the predicted yield reached 12,045 kg ha^{-1}, with a quality index (Qi) of 0.209, IWUE of 39.89 kg m^{-3}, and NPFP of 47.48 kg kg^{-1}. These findings demonstrate that balanced water–nitrogen management can simultaneously improve yield, oil quality, and resource use efficiency. The study provides a theoretical and practical basis for optimizing irrigation and fertilization strategies in olive orchards in mountainous regions of Southwest China.

Key words: supplemental irrigation and nitrogen application; olive (*Grossanne*); yield quality; NSGA-II algorithm; multi-objective optimization model

Introduction

The olive (*Olea europapea* L.) tree is a perennial evergreen broadleaf species belonging to the subfamily Oleoideae of the family Oleaceae, and it is indigenous to the coastal regions of the Mediterranean (Pierantozzi *et al.,* 2020; Liu *et al.,* 2022). Cold pressing the fresh fruit of the olive tree yields olive oil is renowned for its rich content of unsaturated fatty acids, squalene, polyphenols, and other natural bioactive compounds. As of 2018, the cultivation area of olives in the southwestern region of China, including Sichuan, Yunnan, Guizhou, and Chongqing, reached a substantial of 39,067 ha. The annual yield amounted to 7,900 tons of fresh fruit and 759 tons of olive oil, demonstrating significant economic viability (Liu *et al.,* 2019). In the hilly regions of Southwest China, various factors such as substantial inter-annual variability in rainfall, uneven temporal and spatial distribution within a year, recurrent seasonal droughts, and significant arbitrariness in field water and fertilizer management severely disrupt the complete flowering of olive trees during the flowering period, resulting in sluggish tree growth. Additionally, these factors contribute to an increased incidence of shriveled and smaller fruits during the kernel hardening phase, and premature fruit drop, exacerbating the natural tendency of olive trees towards alternate bearing (Freihat *et al.,* 2021). Thus, the optimization of nitrogen application and supplemental irrigation management are crucial for increasing and stabilizing olive yields, enhancing quality, improving efficiency, and fostering sustainable development in the hilly regions.

Moisture content stands as a pivotal factor influencing the absorption of nutrients in crops, as soil nutrients can only be utilized by crops when dissolved in water (Cheng *et al.,* 2023). Moderate water deficit has been shown to enhance the vitality of olive tree root systems, accelerate root respiration rates, and promote photosynthesis in leaves along with the accumulation of dry matter (Santos, 2018; Fdil *et al.,* 2023; Iglesias *et al.,* 2023). However, excessive water supply may diminish soil aeration and impede soil respiration, reducing soil oxygen levels and inducing hypoxia stress in the root zone. This stress inhibits aerobic respiration in roots, while intensifying anaerobic respiration, accumulating substantial anaerobic by-products (such as ethanol, lactic acid, etc.). Cells at the root tips rapidly perish under low oxygen conditions, causing loss of root elongation function and reduced energy synthesis in roots. Consequently, these triggers wilting of aboveground leaves, diminished photosynthetic activity, decreased plant metabolic rates, and a deceleration in plant growth and development (Herzog *et al.,* 2016; Ghobadi *et al.,* 2017; Lou *et al.,* 2023; Ben-Noah *et al.,* 2021).

Nitrogen (N) is an essential component of organic compounds element that plays a pivotal role in the growth and development of various plants (Cui *et al.,* 2019). Moderate nutrient deficiency can significantly enhance the yield of individual olive trees. However, excessive nitrogen application leads to a significant reduction in total polyphenols and monounsaturated fatty acid content in olive oil. It results in increased acidity levels, elevated levels of polyunsaturated fatty acids, overall declining quality, and decreased oxidative stability, consequently shortening the shelf life of olive oil. Excessive application of nitrogen, phosphorus, potassium can induce nutrient imbalances in crops, resulting in increased nitrate levels in fruits, decreased fruit quality, and reduced fertilizer utilization efficiency (Liu *et al.,* 2019). Excessive nitrogen leads to the accumulation of nitrate with some nitrogen leaching into deeper soil layers and groundwater, causing degradation of surface water and groundwater resources. Excessive nitrogen disrupts the balance between crop vegetative growth and reproductive growth, resulting in overly vigorous crop growth, delayed maturity, and reduced yield and quality (e.g., causing a decrease in polyphenol content and oxidative stability of olive oil) (Li *et al.,* 2015; Guo *et al.,* 2023; Christopoulou *et al.,* 2021; Zhou *et al.,* 2019; Li *et al.,* 2018). Indiscriminate overuse of phosphorus fertilizer leads to excessive phosphorus accumulation in the soil, resulting in wastage of resources. This accumulation triggers environmental issues such as nutrient enrichment in water bodies through surface runoff and leaching losses (Zhang *et al.,2023*; Aberathna *et al.,* 2022; Denison *et al.,* 2020). Therefore, the significance lies in the application of supplementary irrigation and fertilization during the critical growth stages of olive trees. This practice aims to increase olives yield, enhance the levels of functional nutrients in olive oil (such as polyphenols, oxidative stability, bitterness intensity, and fatty acid composition), and improve the water-nitrogen utilization efficiency.

To obtain an optimal water and fertilizer management strategy, various optimization methods such as binary quadratic regression models, Z-score analysis, and response surface methodology (Chen *et al.,* 2023) can be employed. However, empirical evidence substantiates the superiority of evolutionary algorithms over the mathematical optimization techniques to address multi-objective optimization problems. The NSGA-II algorithm has extensive applications in various scientific and engineering domains owing to its rapid computational speed and superior convergence performance. The current research on olive irrigation and fertilization predominantly focuses on elucidating the response patterns of young tree growth, fresh fruit yield, water-fertilizer utilization efficiency, and olive oil quality to the replenishment of nitrogen, phosphorus, and potassium elements. Previous studies often evaluate irrigation and fertilization schemes from a singular index perspective (Liu *et al.,* 2019; Zipori *et al.,* 2023; Gholami *et al.,* 2021). However, there is relatively limited reporting on the utilization of the NSGA-II algorithm to optimize irrigation and fertilization strategies for achieving high yield and quality of olive, as well as water-fertilizer utilization efficient.

Therefore the objectives of this study were to: i) explore the main and interaction effects of various supplementary irrigation levels and nitrogen application rates on the olive yield, olive oil quality, and the water-nitrogen utilization efficiency in hilly mountainous regions; ii) to conduct a comprehensive evaluation of olive oil quality indicators using the VIKOR method; iii) to establish a multi-objective optimization model for olive yield, olive oil quality, IWUE, and NPFP, to employ the NSGA-II algorithm to optimize supplemental irrigation and nitrogen application strategies, thereby determining the optimal levels for irrigation and nitrogen application. Findings from this study is provides theoretical foundations and technical support for the efficient integrated management of water-fertilization in local drip-irrigated olive orchards.

Materials and Methods

Experimental olive orchards

The field experiment was carried during olive growing seasons from March to October in 2020 and 2021 in Jintang County, Chengdu, China (104°34′E, 30°44′N;755 m above sea level) (Figure 1). The area has a subtropical monsoon climate with an average annual rainfall, temperature, evaporation, and sunshine duration of 820 mm, 16.6°C, 1169 mm, and 1268.7 h, respectively (Figure 2). The soil was classified as purple soil with 1.53 g cm^{-3} in bulk weight, 7.5 pH, 1.21 g kg^{-1} in total N, 9.43 mg kg^{-1} in available phosphorus, 91.67 mg·kg^{-1} in available potassium, and 0.246 cm^{3} cm^{-3} maximum volumetric water holding capacity in the 0-60 cm topsoil layer in the field.

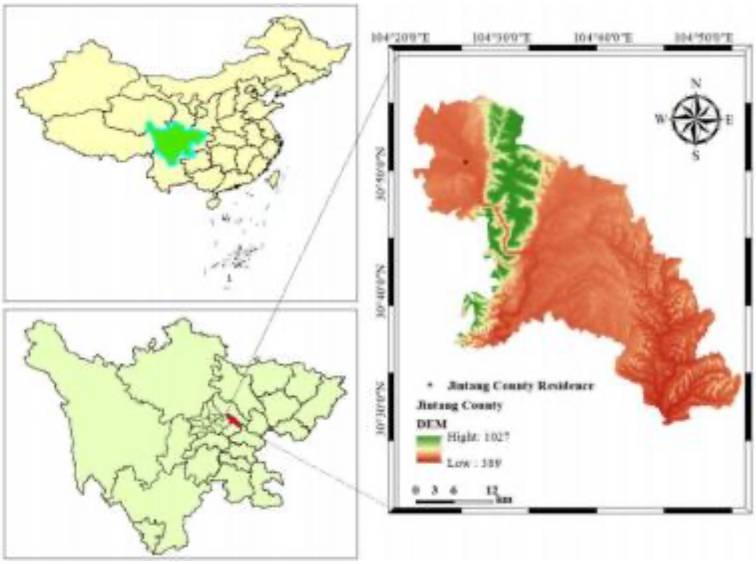


Figure 1. Study area.

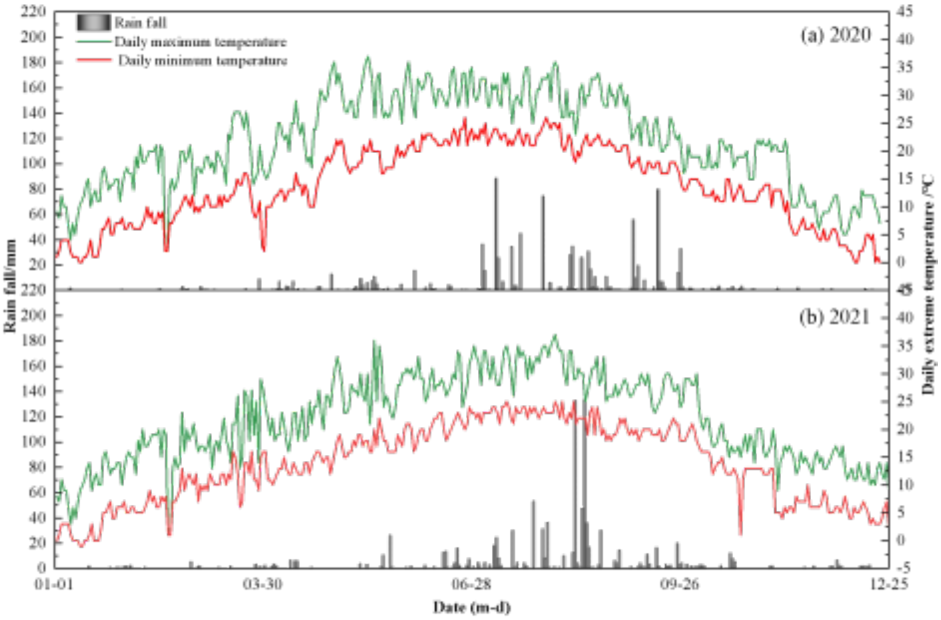


Figure 2. Seasonal trends in climate during two olive crop seasons.

Experimental design

8-year-old olive trees ('Grossanne') were selected as the experimental trees. The trees were planted at a spacing of 5m×5m (400 plants ha^{-1}). Olive trees are 2.5-3.0 m high and grow evenly. The field experiment was conducted using a completely randomized block design (CRBD) with three replications in the olive growing seasons (Figure 3). Reference to the management of local olive orchard and previous studies (Aïachi Mezghani *et al.,* 2019). A two-factorial design was applied with three levels of supplementary irrigation, W1:60% FC, W2:75% FC, W3:90% FC, and three levels of N fertilizer (urea), N1:180 kg ha^{-1}, N2:360 kg ha^{-1}, N3:540 kg ha^{-1} in 2020; N1:150 kg ha^{-1}, N2:300 kg ha^{-1}, N3:450 kg ha^{-1} in 2021. This formed nine treatments: W1N1, W1N2, W1N3, W2N1, W2N2, W2N3, W3N1, W3N2, and W3N3.

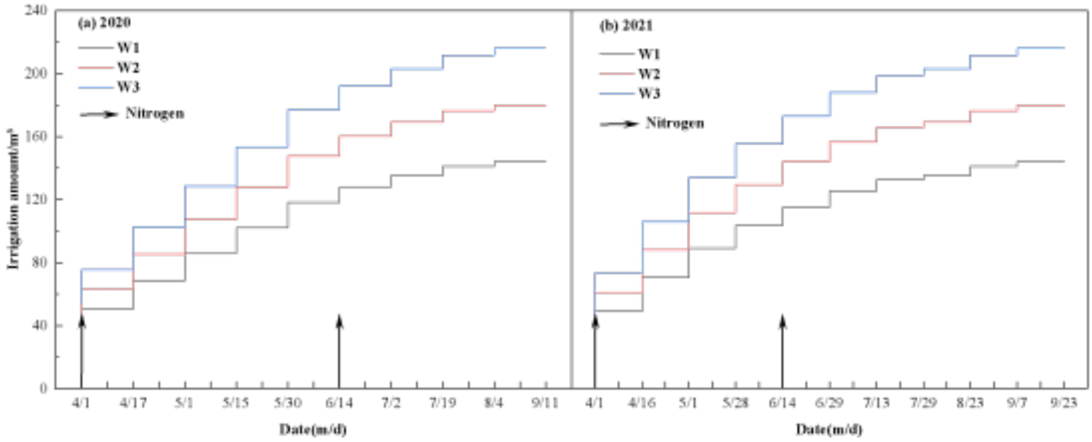


Figure 3. Scheduling of irrigation during the olive growing seasons of 2020 (a) and 2021 (b).

Field management

The underground water depth in the experimental area exceeds 15 m, which has no influence on the experiment. All treatments were performed with the same cultivation, disease, and insect control, and were consistent with local olive orchard. The soil moisture content was measured every 15 days as the lower limit of irrigation, and the rainfall was not irrigated and postponed. The irrigation quota for each drip irrigation treatment was determined by the following equation (He *et al.,* 2022):

$$M = 10 \times Y \times P \times H \times (\theta 1 - \theta 2) \qquad \text{(Eq. 1)}$$

Where M is the irrigation requirement of olive trees (mm); H is the planned wetted soil depth (h=0.60 m); γ is the average soil bulk density (1.53 g cm^{-3}); ρ is the design soil moisture ratio (economic fruit forest, drip irrigation, take 0.35); $\theta 1$ is the upper limit of irrigation soil moisture content; $\theta 2$ is the measured soil moisture content.

Nitrogen fertilizer (46.6% N) was applied to the field by Venturi fertilizer through drip irrigation system before flowering and fruit expanding stage; basic manure (organic fertilizer, N + P2O5 + K2O ≥5%, organic matter ≥45%, 10 kg $plant^{-1}$) was applied in annular furrow in January. The drip irrigation pipeline system was arranged in a row and one pipe, with a capillary spacing of 5 m and a pipe diameter of 20 mm. Each tree was equipped with four drippers, which was arranged around the tree. The type of drippers was pressure compensated, and flow rate of the dripper was 4.0 L·h-1 (Figure 4).

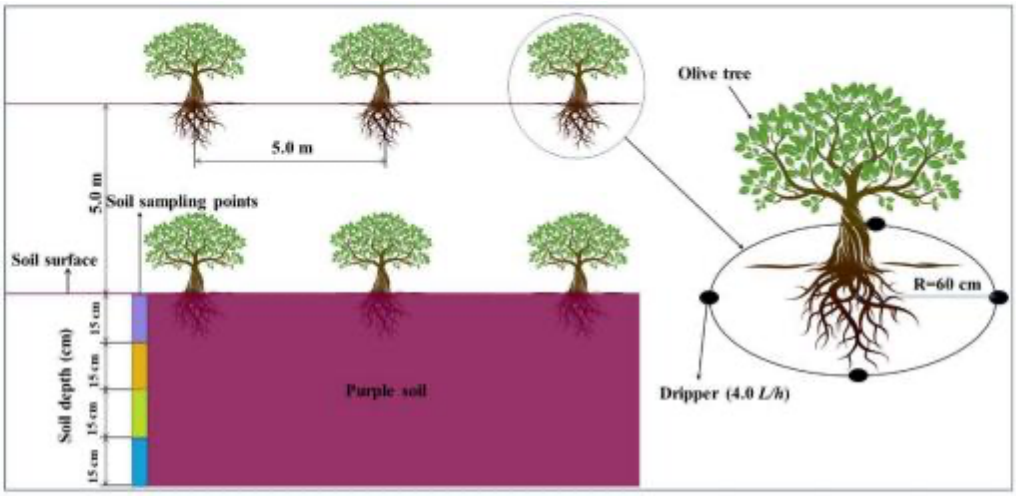


Figure 4. An experimental treatment layout.

Fruit yield and quality measurement

At maturity, the olive production of each monitored tree was weighed individually, then the average yields and the corresponding standard deviations were evaluated for the three trees of each treatment. Yield per hectare was determined by multiplying the average production by the tree density (400 plants·ha^{-1}). The harvest time was consistent with the local olive orchard. The determination of acid value (AV) and peroxide value (PV) of olive oil was carried out according to the methods (Marcelić *et al*., 2022). Fatty acid composition was determined by GC-MS (Cherif *et al*., 2023).

IWUE and NPFP

IWUE and NPFP were calculated according to the method (Lin *et al*., 2019).

VIKOR method

Specific steps refer to the method (Parvin *et al*., 2019).

i) The standardization of data processing: $V_{ij} = \pm \frac{x_{ij} - E_j}{E_j} \#(2)$ (Eq. 2)

Where Ej is the target value of the jth index, and Vij is the target difference rate.

ii) Positive and negative ideal solutions:

$$R+ = (max_{i1}, max_{i2}, \dots \dots, max_{ij} \qquad \text{(Eq. 3)}$$

$$R- = (mini_{1}, min_{i2}, \dots \dots, min_{ij} \qquad \text{(Eq. 4)}$$

iii) Whole benefit value

$$S_i = \sum W_{ij}\left(\frac{R_j^+ - V_{ij}}{R_j^+ - R_j^-}\right) \qquad \text{(Eq. 5)}$$

Where W_{ij} represents the weight of each index.

iv) Individual regret value

$$R_i = max\left\{W_{ij}\left(\frac{R_j^+ - V_{ij}}{R_j^+ - R_j^-}\right)\right\} \qquad \text{(Eq. 6)}$$

v) Ratio of interest value (Qi)

$$Q_i = v\frac{S_i - S^-}{S^+ - S^-} + (1 - v)\frac{R_i - R^-}{R^+ - R^-} \qquad \text{(Eq. 7)}$$

Where Qi is the ratio of interest value for each treatment, and the smaller the value is, the better the scheme to be evaluated is. V is the decision-making mechanism coefficient of the 'most criteria' strategy; S+is the minimum values ofS, and S- is the maximum values ofS, respectively.

Multi-objective optimization model based on NSGA-II algorithm

Non-dominated sorting genetic algorithm-II (NSGA-II) uses crowding degree to measure the distribution of system elements and selects the genes with uniform distribution and the most information (Figure 5). There are six detailed steps: initialization population; non-dominated sorting; calculate crowding distance; selection crossover and mutation; and recombination and selection (Li *et al.*, 2021).

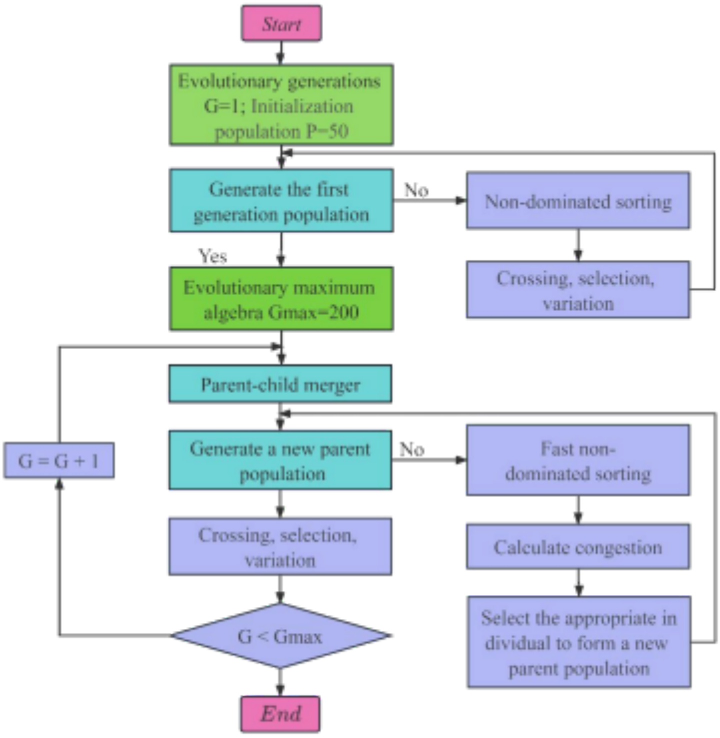


Figure 5. NSGA-II algorithm flow chart.

Data analysis

Experimental data were collected and analyzed by the Excel 365 and SPSS Statistics 27.0 software. Graphs were plotted with Origin 2021. The regression equation was established by MATLAB 2020 b, and the NSGA-II algorithm was used for multi-objective optimization. In this study, multiple comparisons were performed using the Duncan new compound difference method analysis. Significant differences between the detected parameters were compared by Tukey's honest significant difference (HSD) test at the 95% confidence level ($p<0.05$). In particular, the data used in the analysis of olive oil quality and the construction of multi-objective optimization model are the average of two years' data.

Results

Olive fruit yield

The supplementary irrigation and the interaction between water-nitrogen exhibited no significant impact on the fresh fruit yield of olives ($p>0.05$). Conversely, nitrogen application demonstrated a highly significant effect on the yield ($p<0.01$) (Figure 6).For identical irrigation conditions, the yield gradually increased with the application of nitrogen, following an ascending order (N1 < N2 < N3). In comparison to N1, the average yield under N2 and N3 treatments increased by 14.88% and 61.61%, respectively, in 2020; and by 21.41% and 60. 19%, respectively, in 2021. Under N1 conditions, the yield progressively increased with the nitrogen application. Conversely, under N3 conditions, the yield initially increased and then decreased with the increasing nitrogen application. The pattern of yield variation under N2 conditions was inconsistent. Across equivalent nitrogen application treatments, the yield in 2021 generally exceeded that of 2020.

Notably, the highest yield in 2020 reached 9586 kg·hm-2 (N3W2), which was 1.82 times greater than that of the N1W1 (5280 kg hm^{-2}). In 2021, the maximum yield peaked at 11027 kg·hm-2 (N3W2), which was 2.09 times higher than the N1W1 treatment (5280 kg hm^{-2}).

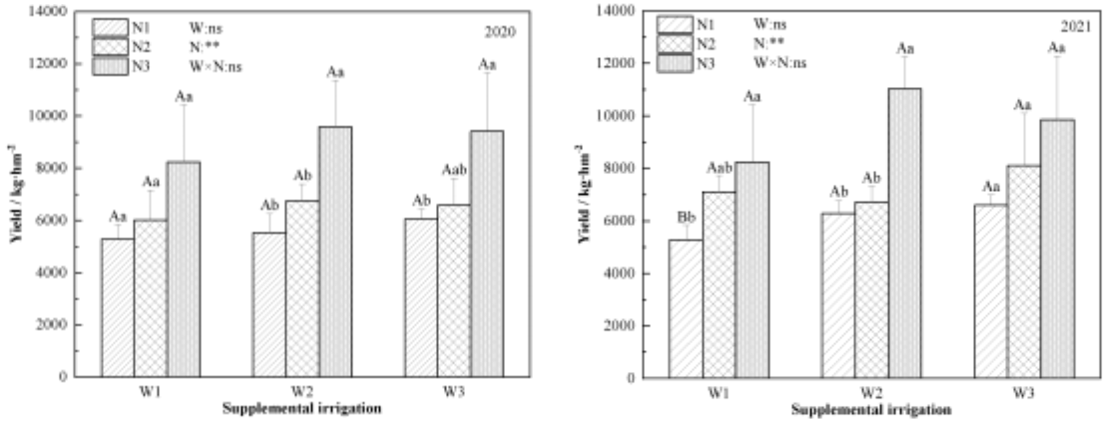


Figure 6. Effect of supplemental irrigation and fertilization on olive yield. The lowercase letters in the figure indicate that there are significant differences between different supplemental irrigation treatments under the same fertilization conditions. Capital letters indicate that under the same supplementary irrigation conditions, different fertilization treatments have significant differences. *, ** and ns indicate the effect significance at 0.05 level, 0.01 level, and no significant effect, respectively.

Olive oil quality

Acid value and peroxide value

The supplemental irrigation exhibited no significant impact on the AV of olive oil ($p > 0.05$) in the study. However, the interaction effect between nitrogen application and water nitrogen displayed an extremely significant influence on AV ($p < 0.01$), with nitrogen application exerting a greater influence compared to the interaction effect with water nitrogen. In 2020, supplementary irrigation, nitrogen application, and their interaction significantly impacted the PV of olive oil ($p < 0.01$), with the degree of influence ranked as follows: supplementary irrigation > nitrogen application >their interaction. In 2021, the interaction effect of water and nitrogen significantly affected the PV ($p < 0.05$), while the impact of supplementary irrigation-nitrogen application on AV showed no significant difference

(p>0.05) (Table 1).

The AV ranged from 0.20 to 0.58 mg g^{-1}, with the lowest value recorded in 2020 at 0.20 mg g^{-1} (N3W1), representing a 52.38% reduction compared to the N1W1 treatment (0.42 mg g^{-1}). In 2021, the minimum value was 0.22 mg g^{-1} (N3W1), showcasing a 52. 17% decrease from the N1W1 treatment (0.46 mg g^{-1}). In 2020, under the N1 treatment, AV gradually increased with increasing rehydration volume, whereas the N2 treatment exhibited an inverse trend. In 2021, under the N1 treatment, AV initially increased with rehydration volume before declining, reaching its peak at W2, whereas under the N2 treatment, AV decreased initially, then rose, reaching its nadir at W2. Over the two years, AV in the N3 treatment progressively increased with rising rehydration volumes. In 2020, AV under W1 and W2 treatments initially increased with nitrogen application before declining, reaching the maximum at N2; however, under the W3 treatment, AV decreased steadily with increasing nitrogen application. In 2021, AV under the W1 treatment decreased steadily with increasing nitrogen application; under W2 and W3 treatments, AV initially decreased before rising again, hitting the minimum at N2.

The PV of olive oil under the N1 gradually increases with the rise in irrigation amount (W1>W2>W3). Conversely, under the W2, the PV demonstrates an initial decrease followed by an increase with the augmentation of nitrogen application. In the N2 treatment, the PV exhibited a decrease followed by an increase with the augmentation of irrigation volume in 2020, whereas in 2021, the PV gradually increased with the rise in irrigation volume. Conversely, the N3 treatment displayed an inverse trend. In 2021, the PV exhibited an increase ranging from 4.38% to 56.83% compared to the values recorded in 2020. The PV for treatments other than N1W1 in 2020 was generally higher (5.69 mmol kg^{-1}). The maximum value recorded was 8.65 mmol kg^{-1} in the N2W3 treatment, representing a 52.02% increase compared to N1W1. In 2021, the highest recorded value was 9.66 mmol kg^{-1}in the N1W3 treatment with a 15.27% increase compared to the N1W1 treatment (8.38 mmol kg^{-1}).

Table 1. Effect of water-nitrogen application on free fatty acid and peroxide value of olive oil

Treatment	AV/mg g^{-1}		PV/mmol kg^{-1}	
	2020	2021	2020	2021
N1W1	0.42±0.05Bb	0.46±0.05Ba	5.69±0. 11Bb	8.38±0.22Bab
N1W2	0.45±0.02Ba	0.52±0.02Aa	7.54±0.43Aa	8.59±0.26Bab
N1W3	0.56±0.08Aa	0.40±0.02Ca	7.97±1.33Aab	9.66±0.53Aa
N2W1	0.58±0.08Aa	0.31±0. 10Ab	7.31±0.30Ba	7.63±0.60Ab
N2W2	0.47±0.05Aa	0.23±0.03Ac	6.16±0.16Bb	7.82±0.71Ab
N2W3	0.35±0.04Bb	0.27±0.05Ab	8.65±1.03Aa	9.44±1.25Aa
N3W1	0.20±0.02Bc	0.22±0.03Bb	5.86±0.10Ab	9. 19±0.84Aa
N3W2	0.21±0.01Bb	0.39±0.08Ab	6.46±0. 18Bb	9. 13±0.63Aa
N3W3	0.26±0.02Ab	0.46±0.06Aa	6.24±0.04Bb	8.33±0.75Aa

Water	0.444ns	2.573ns	11.768**	2.914ns
Nitrogen	88.323**	28.44**	9.678**	2.046ns
Water×nitrogen	13.743**	9.373**	7.364**	3.651*

Fatty acid composition

The influence of nitrogen application on palmitic acid content was statistically significant ($p<0.01$). Supplementary irrigation and nitrogen application, as well as their interactive effect on linoleic acid content, exhibited statistical significance ($p<0.05$ or $p<0.01$). In 2020, the impact of supplementary irrigation on oleic acid content was not statistically significant ($p>0.05$), while nitrogen application and the interaction effect of water-nitrogen showed statistical significance ($p<0.01$). In 2021, supplementary irrigation and nitrogen application demonstrated statistically significant effects on oleic acid content ($p<0.01$) as can be seen in Table 2.

In 2020, the highest observed content of oleic acid in olive oil reached 1.75% (N2W1 treatment), which was 1.9 times higher than that of the N1W1 treatment (0.92%). For similar supplementary irrigation conditions, the oleic acid content exhibited an initial increase followed by a decrease with the increment of nitrogen application, reaching its peak at N2. In N1 and N2 treatments, the oleic acid content displayed an initial rise followed by a decline with the increase in irrigation levels, peaking at W2. In 2021, the highest palmitic acid content recorded was 2.41% (in the N1W3 treatment), approximately 24.87% higher than that in the N1W1 treatment (1.93%). With the N2 and N3 treatments, the palmitic acid content exhibited a gradual decrease with an increase in irrigation levels (W1 < W2 < W3). Moreover, under the W2 and W3 treatments, the palmitic acid content displayed a gradual reduction with an increase in nitrogen application (N1 < N2 < N3).

The linoleic acid content ranged from 4.31% to 14.65%. Under various supplementary irrigation and nitrogen application treatments in 2021, the linoleic acid content exhibited an increase ranging from 6.34% to 188.77% compared to that of 2020.In 2020, the highest linoleic acid content recorded was 10.07% (N2W1 treatment), representing 2.17 times increase compared to the N1W1 treatment (4.63%). In 2021, the maximum linoleic acid content reached 14.65% (N2W1 treatment), marking a 9.57% increase over the N1W1 treatment (13.37%). The linoleic acid content decreased gradually with increased irrigation amount under N1 and N3 treatments (W1 < W2 < W3). Conversely, under W1 and W3 treatments, the linoleic acid content exhibited an initial increase followed by a subsequent decline with increasing nitrogen application.

The oleic acid content ranged from 69.87% to 81.72%. In 2020, the highest oleic acid content (81.72%) was observed in the N1W1 treatment, exhibiting an increase of 0.85% to 16.96% compared to other treatments. In 2021, oleic acid content was found to be below 80%. The maximum oleic acid value (78.71%) was 6.49% higher than that of the N1W1 treatment (73.91%). Oleic acid content increased gradually with the increment of irrigation volume under treatments N2 and N3 (W1 < W2 < W3). Within the same irrigation treatment, oleic acid content initially decreased and thereafter increased with the rise in nitrogen application at minimum for N2.

Table 2. Effects of water-nitrogen application on palmitoleic acid, oleic acid, and linoleic acid in olive oil.

Treatment	Palmitoleic acid (%)		Linoleic acid (%)		Oleic acid (%)	
	2020	2021	2020	2021	2020	2021
N1W1	0.92±0. 16Ab	1.93±0.08Bab	4.63±0.55Bb	13.37±0.47Aab	81.72±1.99Aa	73.91±1.99Ba
N1W2	1.48±0.42Aa	2.37±0.24ABa	9.83±1.84Aa	10.81±0.93Ba	71.67±3.44Bb	78.71±2.76Aa
N1W3	1.24±0.37Aa	2.41±0.30Aa	6.78±1. 14Ba	7.21±0.80Cb	75.39±2.88Ba	78.27±1.72ABa
N2W1	1.75±0.02Aa	2.05±0.09Aa	10.07±0.01Aa	14.65±0.51Aa	69.87±0.60Bb	69.94±2.35Ba
N2W2	1.62±0.23Aa	1.96±0.08Ab	8.33±1.23Ba	9.27±1.71Ba	73.35±3.88AB	73.95±2.05Aa
N2W3	1.36±0.35Aa	1.92±0.75Aab	5.76±0. 19Ca	9.37±1. 16Ba	77.31±1.29Aa	76.24±1.34Aa
N3W1	0.83±0. 12Bb	1.75±0. 11Ab	4.58±0.23Bb	12.50±1. 10Ab	79.90±2.01Aa	74.75±4.41Aa
N3W2	0.81±0.03Bb	1.63±0. 13Ac	4.31±0.32Bb	10.05±0.20Ba	81.03±1.65Aa	76.45±2.03Aa
N3W3	1.25±0. 16Aa	1. 17±0. 10Bb	6.32±0.39Aa	6.95±0.57Cb	77.03±2. 17Aa	76.47±2.06Aa
Water	0.846 ns	0.635 ns	5. 121*	84.386**	1.311 ns	7.445**
nitrogen	14.335**	13.970**	27.331**	4. 133*	12.976**	5.097*
Water×nitrogen	4.089 ns	2.678 ns	22.556**	4.024*	10.595**	0.835 ns

The impact of supplemental irrigation on the content of unsaturated fatty acids in olive oil showed no significant differences (p>0.05). However, in 2020, the nitrogen application and water-nitrogen interaction had a highly significant effect on the unsaturated fatty acid content (p<0.01). In 2021, nitrogen application exhibited a significant effect on the unsaturated fatty acid content (p<0.05), while the interaction effect of water-nitrogen showed no significant impact (p>0.05) (Figure 7).

The unsaturated fatty acid content in olive oil ranges from 77.23% to 91.89%. In 2021, the unsaturated fatty acid content for various supplementary irrigation and nitrogen application treatments surpassed that of 2020. Under treatments W1 and W2, the unsaturated fatty acid content exhibited a decrease followed by an increase with the incremental application of nitrogen, reaching its minimum at N2. In 2021, the highest unsaturated fatty acid content reached 91.89% in the N1W2 treatment, exhibiting a 3% increase compared to the N1W1 treatment (84.59%). In 2020, the peak unsaturated fatty acid content was observed in the N1W1 treatment (84. 15%), surpassing other supplementary irrigation and nitrogen application treatments by 2. 10% to 8.96%.

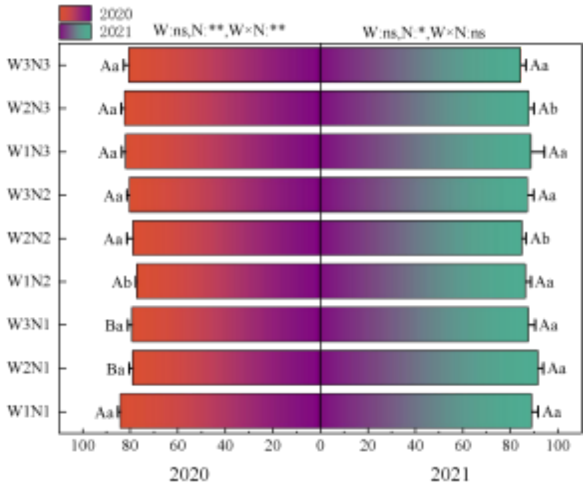
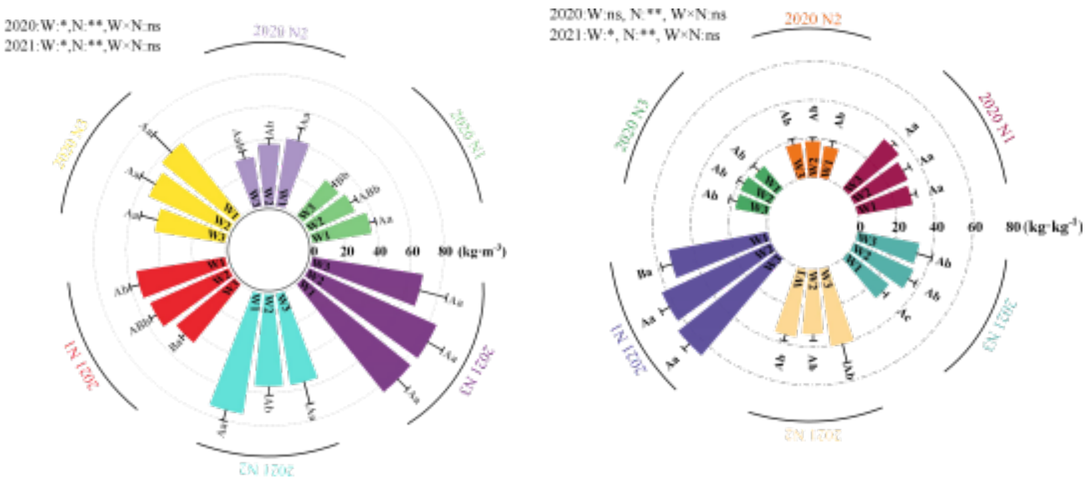


Figure 7. Effects of supplemental irrigation and fertilization on unsaturated fatty acids in olive oil (%)

Water-nitrogen use efficiency

The supplemental irrigation significantly affects IWUE and NPFP (except in 2020) at a significance level of $p<0.05$, nitrogen application exerts an extremely significant influence on both IWUE and NPFP ($p<0.01$). However, the interaction effect between water-nitrogen demonstrates no significant impact on either IWUE or NPFP ($p>0.05$) (Figure 8). For similar supplementary irrigation conditions, IWUE progressively increases with the escalation of nitrogen application. In 2020, IWUE under N2 and N3 treatments initially decreases before subsequently escalating with augmented irrigation levels, while under the N1 treatment, IWUE steadily declines with increased irrigation. Conversely, in 2021, following a corresponding reduction in nitrogen application, IWUE gradually diminishes with escalating irrigation levels. Notably, IWUE remains consistently lower in the high nitrogen (N1) treatment compared to other treatments.

For NPFP, the increment in irrigation amount (W1 < W2 < W3), under N1 treatment, exhibits a gradual increase in N1 processing. However, under N3 treatment, there is an initial rise followed by a subsequent decline with the escalation of irrigation. Under similar supplemental irrigation conditions, NPFP demonstrates a progressive decrease with the increase in nitrogen application (N1 > N2 > N3). In 2021, after the respective reduction in nitrogen application, NPFP surpassed that of 2020. In Experiment 2a, the highest NPFP were consistently observed in the high nitrogen-low water (N1W3) treatment with increments of 14.66% and 25% compared to the N1W1 treatment.



(a) Water use efficiency (kg m^{-3})　　(b) Nitrogen partial factor productivity (kg kg^{-1})

Figure 8. Effects of supplemental irrigation and fertilization on water-nitrogen use efficiency of olive trees.

Comprehensive evaluation of olive oil quality based on VIKOR method

The quality of olive oil was normalized by VIKOR method, and the ratio of interest value (Qi) of each treated olive oil quality was obtained (Table 3). The smaller the Qi value, the better the comprehensive quality of the corresponding treated olive oil. For Qi value, N3W1 treatment was the largest (1.00), N1W2 treatment was the smallest (0.00), and N2W1 treatment was the second (0.103), and the N2W1 treatment was the second (0.103). For the same nitrogen application rate, with the increase of supplementary irrigation amount, the Qi value showed a trend of increasing first and then decreasing or decreasing first and then increasing. Under the condition of W2 and W3, the Qi value gradually increased with the increase of nitrogen application rate, indicating that excessive nitrogen application rate would reduce the quality of olive oil with high amount of supplementary irrigation.

Table 3. Comprehensive evaluation of olive oil quality based on VIKOR method.

Treatments	Acid value mg g^{-1}	Peroxide value mmol kg^{-1}	Palmitoleic acid (%)	Linoleic acid (%)	Oleic acid (%)	Unsaturated fatty acid (%)	S	R	Qi	Rank (Qi)
N1W1	0.059	0. 154	0. 129	0.003	0. 144	0.000	0. 154	0.489	0.443	4
N1W2	0.000	0.075	0.000	0.013	0.087	0.008	0.087	0. 184	0.000	1
N1W3	0.006	0.018	0.027	0.007	0.230	0.020	0.230	0.307	0.267	3
N2W1	0.055	0. 120	0.006	0.032	0.000	0.030	0. 120	0.244	0. 103	2
N2W2	0. 172	0. 157	0.034	0.019	0. 153	0.030	0. 172	0.564	0.553	6
N2W3	0.224	0.000	0.073	0.007	0.206	0.017	0.224	0.528	0.546	5
N3W1	0.350	0. 116	0. 164	0.005	0. 164	0.008	0.350	0.807	1.000	9
N3W2	0.230	0.096	0. 182	0.000	0.222	0.009	0.230	0.739	0.821	7
N3W3	0. 160	0. 134	0. 185	0.007	0.245	0.026	0.245	0.758	0.858	8
$R+$	0.364	0.016	0.083	0.002	0.018	0.001				
$R-$	0. 156	0.013	0.052	0.001	0.010	0.001				

Multi-objective optimization of supplemental irrigation and nitrogen application of olive trees based on NSGA-II algorithm

Taking the coding value of nitrogen application rate (x1) and that of supplementary irrigation amount (x2) as independent variables, olive fruit yield (y1), Qi value (y2), IWUE (y3) and NPFP (y4) as dependent variables, regression analysis was carried out and a multi-objective optimization model was established (Table 4). The determination coefficient R2 was above 0.747, $p<$ 0.05, indicating that the regression relationship between the nitrogen application rate of supplementary irrigation and the above factors was significant. This study used NSGA-II for multi-objective optimization, with the individual numbers of 50 and the maximum generation of 50. Its computational flow was shown in Figure 5. In the final output of the optimal Pareto solution, the coding value of supplementary irrigation amount was 0.227, the coding value of nitrogen application amount was -0.374, and the actual value was 188 m^3 ha^{-1}and 268 kg ha^{-1}. The optimal yield was 12045 kg ha^{-1}, Qi value was 0.209, the optimal IWUE was 39.89 kg m^{-3}, and the optimal NPFP was 47.48 kg kg^{-1} .

Table 4. Regression relationship between the amount of supplementary irrigation and fertilization and olive yield, Qi value and water and nitrogen use efficiency.

Response variable	Regression equation	R^2	p
Olive fruit yield	$y1= 12207.22+2990x1+2743.33x2+3315x12+390x1x2-1890x2^2$	0.957	0.029
Qi value	$y2=0.2454+0.2456x1+0.3697x12+0.0792x2^2$	0.747	0.048
Irrigation water use efficiency	$y3=47.494+12.9465x1-7.3814x2-9. 1417x12-3.3324x1x2-1.5998x2^2$	0.971	0.016
Nitrogen partial productivity	$y4=33.3587-27. 1194x1+6. 1906x2+17.4413x12-2.6719x1x2-1.9313x2^2$	0.957	0.029

Discussion

Soil moisture and nutrients are crucial factors influencing crop yield and quality. Modulating the soil moisture and nutrient status through a judicious irrigation and fertilization regime is significant towards achieving high-yield and high-quality crops and serves as a key factor in enhancing the water-fertilizer use efficiency (Xu *et al.*, 2019; Zhou *et al.*,. 2023). Management of water and fertilizer is advantageous in promoting the normal growth of olive trees to mitigate the inherent inclination of alternate bearing in olive trees and stabilizing the fresh fruit yield of olives (Rufat *et al.*, 2014). Unscientific water and fertilizer management can inhibit the absorption, transportation, and utilization of soil moisture and nutrients by the root system, resulting in low productivity, low quality, and even wilting or death (Xing *et al.*, 2015).

Findings from this study indicate significant differences in the yield, quality, and water-nitrogen use efficiency of fresh olive fruits under varying supplemental irrigation and nitrogen application levels. It was observed that the amount of supplemental irrigation and the coupling effect of water and nitrogen was not significant on olive yield. However, nitrogen application demonstrated high significant influence on olive yield. Under similar supplemental irrigation conditions, the fresh fruit yield of olives increased concomitantly with the augmentation of nitrogen application. Centeno et al. (Centeno *et al.*, 2018) observed significant interannual variations in the responsiveness of olive fruit yield to varying fertilization levels, while detecting no significant intra-annual variations. Ahumada-Orellana *et al.* (2017) indicated that moderate or mild drought stress in super high-density olive orchards had no significant impact on fruit yield, while severe drought stress significantly affected both the yield and their constituent elements. This could be associated with the meteorological conditions of the research area, as well as the water retention capacity of the soil. Irrational application of water and fertilizers may counteract the increase in chlorophyll content. Severe soil moisture deficit can induce the production of exudates in plant roots, which, as water moves, transmit signals to the leaves. As a part of the plant's 'self-protection' mechanism, this prompts a reduction in stomatal aperture and a decrease in transpiration rates. Consequently, there is a reduction in the plant's photosynthetic products, a decline in photosynthetic rates, and a slowdown in overall plant growth, leading to diminished fruit yield and quality (Li *et al*., 2014; Pérez-Pasto *et al*., 2014; Abdelkhalik *et al*., 2019; Sun *et al*., 2018).

Water-fertilizer use efficiency stands is pivotal in determining whether crops qualify as green produce within agricultural practices. Within a certain range, increasing irrigation and fertilization levels significantly enhances IWUE and partial factor productivity. However, an excessive supply of water and nutrients can lead to a reduction in the efficiency of their utilization (Wang *et al*., 2023). The present study reveals that nitrogen application significantly impacts IWUE and NPFP. Additionally, the supplemental irrigation amount demonstrates a notable influence on both IWUE and NPFP. However, the interaction effect between water and nitrogen does not significantly affect IWUE or NPFP. Maintaining a constant supplemental irrigation amount, an increase in nitrogen application leads to a decrease in NPFP while enhancing IWUE. Similarly, with a constant nitrogen application, an increase in supplemental irrigation amount elevates NPFP while reducing IWUE. Some scholars argue that while maintaining a constant overall fertilization quantity, adjusting the proportion of fertilization during different growth stages can significantly enhance mango yield and fertilizer use efficiency (Liu *et al*., 2019). The water and nutrient requirements of various crops vary significantly during crucial growth stages. Additionally, the response patterns of crops to different nutrients exhibit considerable variation among elements. Potassium has been shown to enhance plant uptake and utilization of phosphorus while also strengthening nitrogen metabolism and the transport of photosynthetic products within plants. Nitrogen, on the other hand, plays a regulatory role in carbon metabolism in plants, actively participating in the formation and transportation of carbohydrates within plant systems (Cao *et al*., 2018; Li *et al*., 2021). Therefore, it is only through the appropriate application of water and nitrogen in tandem that a positive synergistic effect can be achieved. This synergy promotes enhanced absorption and utilization of both water and nutrients by plants, ultimately leading to an improved efficiency in water and fertilizer usage (Wei *et al*., 2020).

The quality of olive oil flavor and fruit yield serve as direct indicators reflecting economic profitability. The use of algorithms for comprehensive scientific assessment of fruit quality represents a prevailing trend in crop irrigation and fertilization management research. Song *et al.* (2018) employed the NSGA-II algorithm to conduct decision optimization on the developed Aqua Crop crop growth model, thereby establishing a scientifically sound irrigation regime for insufficiently irrigated conditions in arid regions. Qu *et al.* (2021) used the NSGA-II algorithm to optimize cucumber yield and quality, further corroborating the reliability and superiority of this algorithm in optimizing cucumber irrigation-fertilization schemes. The olive yield, as well as indicators related to water and nitrogen utilization efficiency and the quality of olive oil, are subject to numerous influencing factors. This study employs a multivariate regression analysis to establish regression models for yield, quality, and water-nitrogen utilization efficiency by incorporating supplementary irrigation and nitrogen application. The NSGA-II algorithm is utilized for multi-objective optimization, resulting in the determination of the optimal treatment of supplementary irrigation and nitrogen application as N2W2.

Conclusions

Irrigation and nitrogen application can modify the soil moisture content in the root zone of olive trees, facilitating the absorption, translocation, and utilization of nutrients by the root system. Consequently, this practice enhances the yield of fresh olives, improves water and nitrogen use efficiency, and contributes to enhancing the flavor profile and extending the shelf life of olive oil. In this study, the comprehensive evaluation of the flavor quality of extra virgin olive oil based on the VIKOR method reveals that the optimal treatment is N1W2, Qi value of 0. By considering fresh fruit yield, olive oil quality, IWUE, and NPFP, a multivariate regression model was constructed. The NSGA-II algorithm was employed to seek Pareto optimal frontier solutions, identifying the best supplementary irrigation and nitrogen application treatment as N2W2. Correspondingly, the optimal yield was determined to be 12045 kg hm^{-2}, with a profit ratio Qi value of 0.209, IWUE of 39.89 kg m^{-3}, and NPFP of 47.48 kg kg^{-1}. The conclusions drawn from this study offer theoretical support for the efficient and high-quality cultivation of olive trees in the hilly regions of the southwest China. Additionally, they contribute to the optimal use of water-fertilizers in this specific agricultural context.

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