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Optimizing Irrigation Regimes for Peanuts in Water-Scarce Regions: A Case Study in Western Liaoning, China

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Abstract: Scientific irrigation scheduling is crucial for conserving agricultural water resources, as excessive irrigation diminishes crop yield and imprecise water application can equally reduce water use efficiency (WUE). In Western Liaoning Province, China, where water scarcity is critical, traditional irrigation regimes are commonly used for peanut cultivation, with local farmers applying water without considering actual crop water demands, thereby reducing water efficiency and yield. In this study, field experiments on peanuts were conducted from May to October during 2021 and 2022 in Heishan County, Western Liaoning Province, China. Four irrigation regime treatments for micro-sprinkler irrigation, with different lower limits of soil water content, were applied: T1 (55% field capacity), T2 (65% field capacity), T3 (75% field capacity), and T4 (85% field capacity). The plant height, stem thickness, root length, dry matter weight, yield, WUE, and net return were measured. Different irrigation regimes had significant effects on peanut growth. The yield was highest in the T3 treatment in 2021 at 5574 kg·hm^{-2}. Moderate irrigation could improve the yield, but it was difficult to simultaneously achieve a high WUE. The WUE of the T3 treatment was 5% lower than that of the T2 treatment in 2022, where the WUE was the highest at 1.62 kg·m^{-3}. The highest net return was observed in the T3 treatment at 27,307 yuan·hm^{-2}. The T3 treatment, with the highest similarity degree of 0.83 as determined with the entropy value and TOPSIS method, was evaluated as the optimal irrigation regime. This regime not only exhibited a favorable balance of water use efficiency and yield but also maximized economic benefits, making it a recommendable practice for local peanut irrigation.

Keywords: optimal irrigation regimes; peanut; entropy value and TOPSIS method; water use efficiency; net return; water-scarce regions

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1. Introduction

Irrigation is a critical factor in agricultural productivity, significantly enhancing both crop yield and quality while promoting efficient water resource management [1,2]. Well-designed irrigation regimes not only support optimal crop growth but also substantially reduce water consumption, which is increasingly important in the context of global water scarcity [3–5]. Approximately 70% of the world's fresh water supply is consumed by agricultural irrigation [6]. As water resources become progressively limited worldwide, ensuring water availability for agriculture has become increasingly challenging [7–9]. In response to these challenges, extensive research has explored innovative irrigation practices aimed at improving water efficiency in crop production. Numerous studies from various regions, including rice cultivation in Tanzania [10], maize in northern Italy [11], cucumbers in Pakistan [12], and maize in southeastern Spain [13], have demonstrated the potential of water-saving techniques to enhance water productivity and reduce water usage across different crops.

Peanuts, a critical oilseed crop that has significantly benefited from advancements in irrigation technology, play a vital role in global food security as both a staple food and industrial raw material [14]. Peanut cultivation heavily depends on efficient irrigation techniques and irrigation regimes to ensure optimal yield, quality, and resource utilization, particularly in regions prone to water scarcity [14–16]. Traditional surface irrigation remains widely practiced due to its simplicity and low cost, yet it often results in uneven water distribution, higher evaporation losses, and inefficient water use [17]. In contrast, modern water-saving techniques such as sprinkler irrigation, drip irrigation, and micro-sprinkler irrigation have shown significant promise in enhancing water productivity and reducing water consumption. Sprinkler irrigation has demonstrated significant advantages in managing deficit irrigation for peanut cultivation, allowing precise water application and supporting macromanagement strategies for water-scarce regions [18]. Economic analyses further reveal that adopting sprinkler irrigation in peanut production enhances profitability by optimizing resource utilization and reducing labor costs [19]. Drip irrigation, another advanced technique, not only improves water use efficiency but also regulates soil nitrogen dynamics, photosynthesis, and root activity, significantly boosting peanut yields in arid regions [20,21]. Among the emerging techniques, micro-sprinkler irrigation has gained attention for its ability to combine the precision of drip irrigation with the uniformity of sprinkler irrigation. Comparative studies indicate that micro-sprinkler irrigation outperforms traditional surface irrigation in improving peanut growth and yield, particularly under challenging climatic conditions [17]. Additionally, irrigation practices and schedules have been shown to influence peanut oil concentration and overall crop performance, highlighting the critical role of tailored irrigation regimes [22].

Irrigation frequency and levels, which ultimately determine crop yield, quality, water use efficiency and economic benefit, are pivotal factors in optimizing irrigation regimes. For example, in Turkey, a study on drip irrigation for peanuts found that the IF2I125 irrigation regime (irrigation frequency of 25 mm and 125% of cumulative pan evaporation) produced the highest peanut yields [23]. Similarly, another study indicated that irrigation intervals and levels significantly impact peanut production, with a two-day irrigation interval at 50% cumulative evaporation yielding the highest oleic acid content in peanut cultivars 'Halisbey' and 'NC-7' [24]. Moderate continuous regulated deficit irrigation (CRDI) is beneficial to enhancing the water use efficiency and drought resistance of peanut through an experiment in China [25]. In addition, different irrigation regimes significantly influence the yield for peanuts, which in turn affects the economic benefit above variable and total cost [26,27]. A study on rabi groundnut under micro-irrigation methods reported notable improvements in yield and water productivity, while achieving higher profitability compared with traditional irrigation methods [28]. Furthermore, peanut-based cropping systems have been evaluated for their agronomic and economic responses to different irrigation strategies. Studies integrating irrigation regimes with crop rotation revealed that optimal water management not only enhanced peanut yields but also improved net returns by reducing water and energy input costs [26].

China is the world's largest producer of peanuts, as reported by the Food and Agriculture Organization (FAO) of the United Nations [29,30]. In 2022, China produced 18.32 million tons of peanuts, accounting for nearly 40% of global production. With a peanut planting area of 4.63 million hectares, China ranks second globally in terms of sown area for oil crops [31]. Liaoning Province, situated in northeastern China, is a significant peanut-growing region, contributing approximately 330,000 hectares of planting area and producing 1.1549 million tons of peanuts annually [32]. Western Liaoning, a key peanut-growing area within the province, is particularly challenged by its semi-arid monsoon climate characterized by limited and unevenly distributed rainfall. The region receives an annual average precipitation of approximately 450 mm, significantly below the provincial average, and faces severe water shortages further aggravated by high evaporation rates. Combined with sandy loam soil and frequent droughts, these conditions impose significant constraints on agricultural production. Despite these challenges, peanuts remain a critical crop in Western Liaoning, supporting local livelihoods and substantially contributing to the regional economy. Addressing water scarcity is essential for sustaining peanut production in this region. Nevertheless, a large proportion of farmers still rely on surface irrigation. This situation reflects the broader trends in Liaoning Province, where statistics show that only about 26% of irrigable farmland is equipped with facilities for sprinkler, drip, or subsurface irrigation, suggesting that over 60% of irrigated farmland relies on surface irrigation. With the development of efficient water-saving irrigation projects in Western Liaoning, micro-sprinkler irrigation has become one of the key promoted high-efficiency water-saving irrigation technologies for local peanut cultivation. However, due to the lack of reasonable irrigation regimes, the application of micro-sprinkler irrigation in peanut farming within Western Liaoning remains limited. Farmers are primarily concerned with peanut yield and economic returns, while government water resource managers in water-scarce regions prioritize water use efficiency. Balancing these demands to determine the optimal irrigation regime through comprehensive evaluation is critical for the large-scale promotion of micro-sprinkler irrigation.

Based on the aforementioned background, this study employed a holistic methodology, synthesizing agronomic, water management, and economic dimensions to devise optimized irrigation strategies that align with the distinctive environmental and resource attributes of the region. Over a two-year field experiment (May to October, 2021 and 2022) in Heishan County, four irrigation treatments were applied using micro-sprinkler systems, with lower soil water content limits of T1 (55% field capacity), T2 (65%), T3 (75%), and T4 (85%). Key agronomic and economic parameters, including plant growth, yield, WUE, and net return, were measured. Using the entropy value and TOPSIS method, we identified the optimal irrigation regime for maximizing yield, improving water resource utilization, and enhancing economic benefits. This research provides robust evidence for developing scientifically optimized irrigation strategies, ensuring sustainable peanut production in water-scarce regions like Western Liaoning and supporting local farmers' livelihoods.

2. Materials and Methods

2.1. Site Conditions

Field experiments were conducted over two years, from May to October in 2021 and 2022, in Heishan County, Western Liaoning Province, China. The location of Heishan County is illustrated in Figure 1. The region experiences a semi-arid monsoon continental climate, with critically constrained water resources. The annual per capita water availability is as low as 672 m^3, approximately one-third of the national average in China. The average annual precipitation is 568 mm, while the average annual evaporation reaches 1737.9 mm, further exacerbating the existing water deficit. The average annual temperature is 6.8 °C. The soil is classified as sandy loam, with a bulk density of 1.41 g·cm^{-3} and a field capacity of 21% (by volume). The organic matter content of the soil is 15.1 g·kg^{-1}.

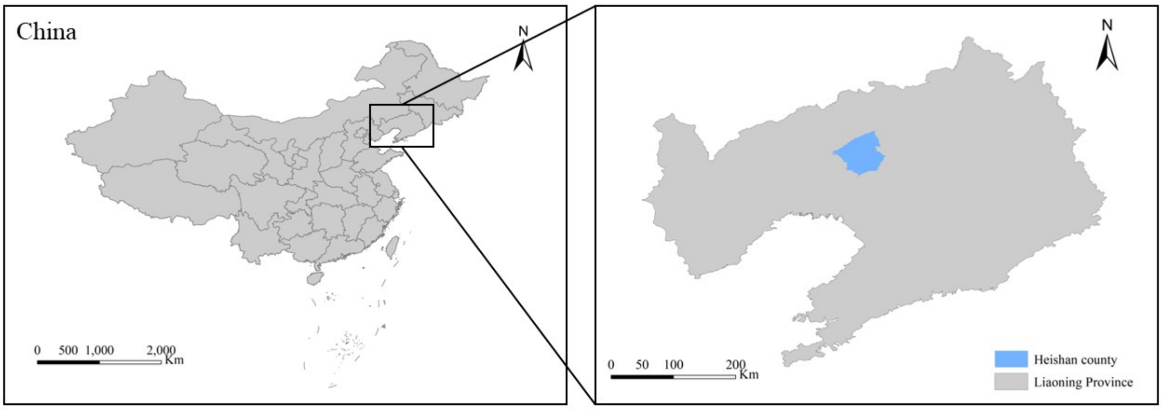


Figure 1. Location of Heishan County.

2.2. Experimental Design

The peanut variety Shandong-30 was selected for the experiment because it is commonly used in this region. Micro-sprinkler irrigation was used under electric awnings set up on double ridges of the experimental plots. Each plot was sized 2 m by 2.5 m. Four treatments (T1–T4) representing four irrigation regimes were set up, with the lower limits of soil water content set at 55% field capacity (θf), 65% θf, 75% θf, 85%θf. The upper limit of soil water content was set at 90% θf. Each treatment was replicated ten times, resulting in a total of 40 experimental plots. The test area layout and experiment processing are shown in Figure 2.

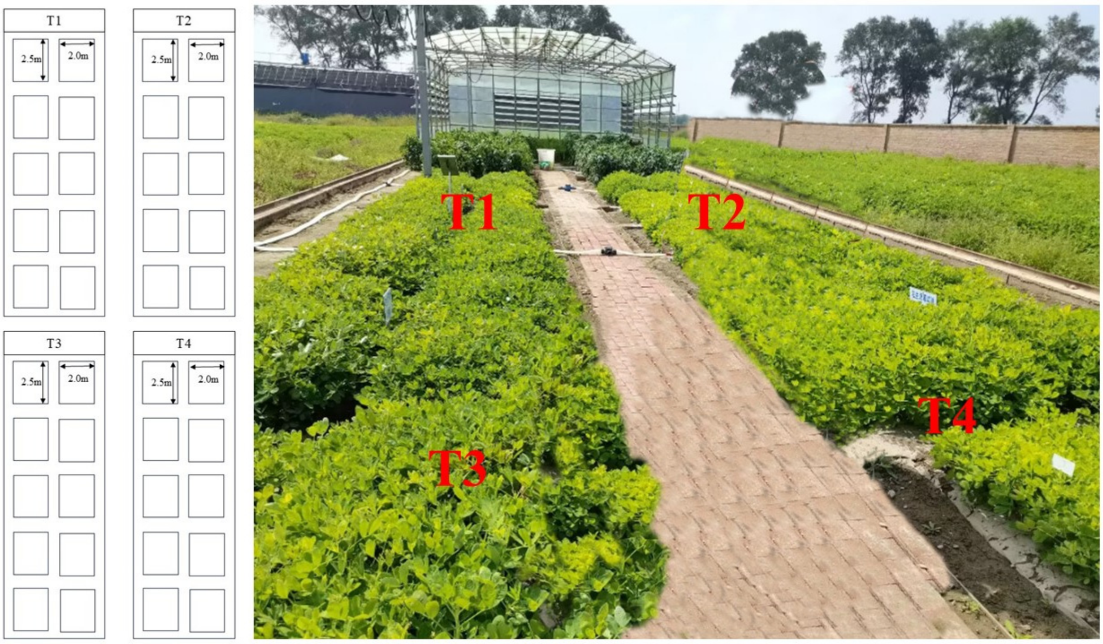


Figure 2. Test area layout and experiment processing.

The entire growth period for the peanuts lasted from 20 May to 1 October. Two measurement points were selected in each experimental plot, and soil moisture content at depths of 0–60 cm was measured every 5 days using a Trime instrument (IMKO Micromodultechnik GmbH, Ettlingen, Germany). Measurements were also taken before and after irrigation, as well as at the beginning and end of each peanut growth stage. Meteorological data, including evaporation, temperature, and wind speed, were provided by the local weather station. Plant height and stem diameter were measured every 10 days using a ruler and caliper (Model 500-196-30, Mitutoyo Corporation, Suzhou, China). At the end of each growth stage, 3–5 randomly selected peanut plants were harvested from each plot to measure dry matter weight and root length. Specifically, the above-ground parts and roots of the selected plants were first killed at 105 °C for 0.5 h, then dried at 80 °C to constant weight to determine dry matter mass. The soil surrounding the roots was carefully excavated (sampling depths: 10 cm during the seedling stage, 20 cm during flowering and pod-setting, and 30 cm during fruit maturation). The roots were then soaked in a bucket of water for approximately 3 h until the soil was fully moistened. Afterward, the roots were gently washed while maintaining their integrity. Once cleaned, the roots were allowed to naturally droop and placed on a flat surface. The root length was measured using a ruler. During harvest, the seeds were air-dried outdoors for 10–13 days, and peanut yield was calculated based on 14% moisture content. The irrigation quota was calculated using the water balance equation. Additionally, a water meter was installed at the outlet of the micro-sprinkler irrigation pipeline to record the irrigation quota for each irrigation event. By integrating market surveys and farmer interviews, we collected data on various costs and returns associated with peanut cultivation to calculate the net returns.

2.3. Water Balance Equation

The irrigation method of peanuts is incomplete irrigation. Since the experimental plot was equipped with an electric canopy and there was no rainfall, the water balance equation of peanuts could be simplified as follows [33,34]:

$$\mathrm{ET} = \mathrm{W_0} - \mathrm{W_t} + \mathrm{W_T} + \mathrm{K} + \mathrm{M} \tag{1}$$

where ET is the crop water requirement (mm); $\mathrm{W_0}$ and $\mathrm{W_t}$ are the water storage in the planned wet layer of soil at the beginning and end of a growth period (mm); $\mathrm{W_T}$ is the water increase due to the increase of the soil wet layer; K is the groundwater recharge during time period, and the depth of groundwater is 9–12 m, so K = 0; and M is the irrigation water (mm).

The water use efficiency (WUE) of peanut adopts the formula [35,36]:

$$\mathrm{WUE} = \frac{\mathrm{Q}}{\mathrm{ET}} \tag{2}$$

where WUE is water use efficiency ($\mathrm{kg \cdot m^{-3}}$) and Q is yield (kg).

2.4. The Entropy Value and TOPSIS Method

The entropy value and TOPSIS method were used for the comprehensive evaluation of different irrigation regimes. The entropy value method was used to determine the weights of the indexes, and then the TOPSIS method was used to rank different irrigation regimes. The results are relatively objective, and the specific calculation method is as follows [37–39].

The original data matrix is established, with m irrigation regimes and n evaluation indexes. X_{ij} is the original index value of the j-th evaluation index for the i-th irrigation regime, and the original evaluation index matrix X is constructed as follows:

$$X = \begin{pmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{pmatrix} \tag{3}$$

Individual indexes have different scales and cannot be directly compared, so a standardized matrix is obtained by dimensionless processing of the original data matrix.

The larger the value of some indexes, the better. The data are positively oriented. The smaller the value of some indexes, the better. The data are negatively oriented.

$$X_{ij}{}' = \frac{X_{ij} - min\ X_j}{max\ X_j - min\ X_j} \tag{4}$$

$$X_{ij}{}' = \frac{max\ X_j - X_{ij}}{maxX_j -\ min\ X_j} \tag{5}$$

The entropy, differentiation coefficient and weight of the *j*-th indicator of the *i*-th scenario are calculated with the following steps. The proportion of the *j*-th index for the *i*-th irrigation regime is determined as follows:

$$P_{ij} = \frac{X_{ij}{}'}{\sum_{i=1}^{m} X_{ij}{}'} \tag{6}$$

Calculate the entropy of the *j*-th index, where $k = 1/lnm$.

$$e_j = -k\sum_{i=1}^{m} p_{ij} lnP_{ij} \tag{7}$$

Calculate the differentiation coefficient of the *j*-th index.

$$g_j = 1 - e_j \tag{8}$$

Calculate the weight of the *j*-th index.

$$w_j = \frac{g_j}{\sum_{i=1}^{n} g_j} \tag{9}$$

Construct a weighted standardized decision matrix and multiply the standardized matrix by the index weight to obtain the comprehensive evaluation matrix Y.

$$Y = \begin{pmatrix} X_{11}{}'\omega_1 & X_{12}{}'\omega_2 & \cdots & X_{1n}{}'\omega_n \\ X_{21}{}'\omega_1 & X_{22}{}'\omega_2 & \cdots & X_{2n}{}'\omega_n \\ \vdots & \vdots & \ddots & \vdots \\ X_{m1}{}'\omega_1 & X_{m2}{}'\omega_2 & \cdots & X_{mn}{}'\omega_n \end{pmatrix} \tag{10}$$

Calculate the optimal and worst solutions for each indicator, where the optimal solution is the set of each index value reaching the overall optimal, and the worst solution is the set of each index value reaching the overall worst.

$$Y^+ = \max_{1\le i\le m} Y_{ij} | j = 1,2,\ldots,n \tag{11}$$

$$Y^- = \min_{1\le i\le m} Y_{ij} | j = 1,2,\ldots,n \tag{12}$$

Calculate the distance to the optimal solution d_i^+ and the distance to the worst solution d_i^- for each evaluation object.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (Y_{ij} - Y_j^+)^2 (i = 1,2,\ldots,m)} \tag{13}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (Y_{ij} - Y_j^-)^2} (i = 1,2,\ldots,m) \tag{14}$$

Calculate the similarity degree of each evaluation object to the optimal solution.

$$S_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{15}$$

where S_i refers to the degree to which each evaluation object is close to the optimal solution; the value range is 0~1. The larger S_i is, the higher the overall evaluation of the irrigation regime is [40,41].

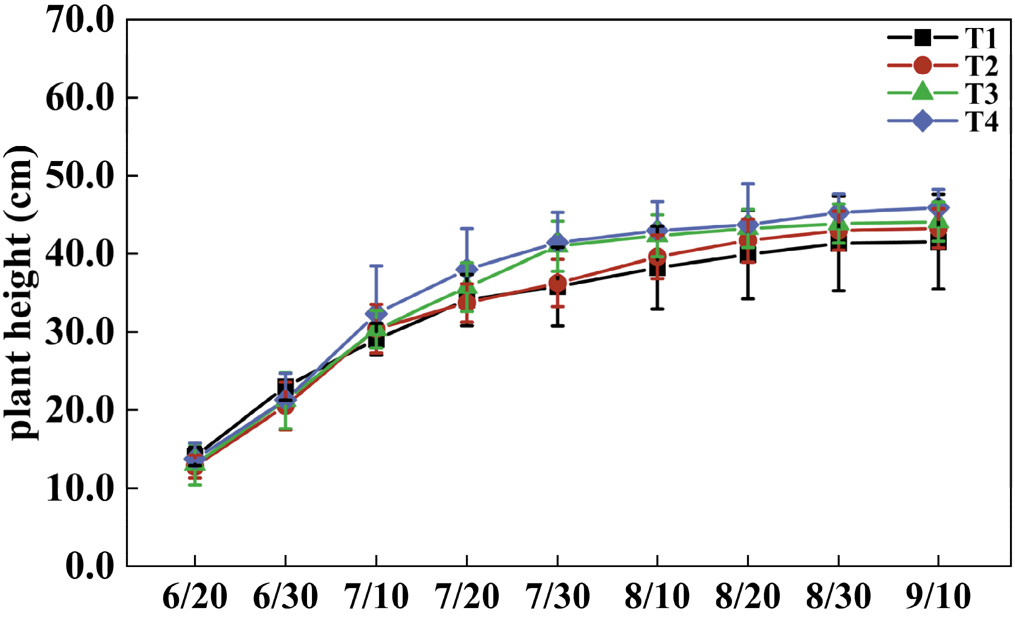
3. Results and Discussion

3.1. Effects of Different Irrigation Regimes on Growth Traits

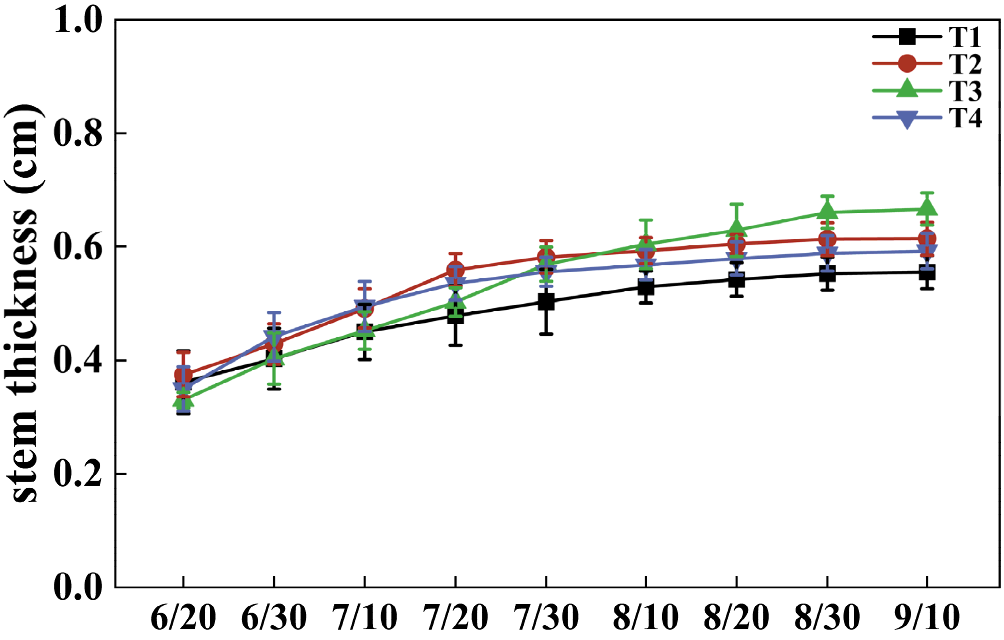
Due to the consistent experimental conditions and comparable results obtained in 2021 and 2022, the measured data from both years were averaged to enhance data accuracy and representativeness. Figure 3 illustrates the variations in the plant height, stem thickness, root length, and dry matter weight of the peanuts across different growth stages under varying irrigation regimes. These growth parameters were significantly influenced by the irrigation treatments, revealing distinct growth patterns. Plant height increased rapidly until 20 July, then plateaued, reflecting the natural progression of peanut development. The maximum observed plant height was 45.9 cm, whereas the minimum was 41.5 cm. The ranking of irrigation treatments regarding plant height was T4 > T3 > T2 > T1, directly correlating with the amount of water applied, indicating that an adequate water supply promotes optimal vegetative growth and results in taller plants. These findings align with those of Jinlong et al. [42], who reported that a sufficient water supply under drip irrigation significantly improves vegetative growth, particularly plant height, by maintaining optimal soil moisture levels.

Stem thickness exhibited a similar pattern to plant height, with rapid initial development tapering off as the plants matured. The maximum stem thickness was recorded at 0.67 cm, while the minimum was 0.56 cm. The ranking for stem thickness followed the order T3 > T2 > T4 > T1. This suggests that moderate irrigation, as seen in T3, promotes robust stem development, while both excessive and insufficient water supply negatively affect structural growth. These results are consistent with the findings of Cecilia et al. [43], who demonstrated that precise irrigation scheduling optimizes stem growth by ensuring water availability during critical developmental stages while avoiding the detrimental effects of over- or under-irrigation.

Root length and dry matter weight were measured at four growth stages: seedling, flower-pegging, pod setting, and pod filling. The maximum root length was 30.1 cm, whereas the minimum was 26.9 cm, and the most significant increase in root length occurred during the flowering stage. Root length exhibited the sequence T3 > T2 > T4 > T1, highlighting the importance of moderate irrigation in fostering deeper root systems for efficient nutrient and water uptake. This observation is also supported by Cecilia et al. [43], who found that optimal water supply enhances root development by mitigating drought stress and maximizing resource utilization. Dry matter weight experienced the greatest increase during the flower-pegging stage. The maximum and minimum dry matter weights were 27.1 g and 18.6 g, respectively. The ranking for dry matter weight was T3 > T4 > T2 > T1, underscoring the critical role of balanced water management in facilitating efficient biomass production. Treatment T1 consistently yielded the lowest values across all four indices, indicating that water-deficit conditions exerted a pronounced negative effect on peanut growth. As corroborated by Li et al. [44], irrigation strategies that avoid extreme moisture deficits or surpluses allow for the effective partitioning of assimilates into vegetative organs, optimizing dry matter accumulation. Collectively, these results indicate that both excessive and insufficient irrigation negatively affect peanut growth, while moderate irrigation, as evidenced in T3, achieves the optimal balance. These findings highlight the critical role of optimized irrigation in enhancing plant height, stem thickness, root length, and dry matter weight while ensuring efficient water use.

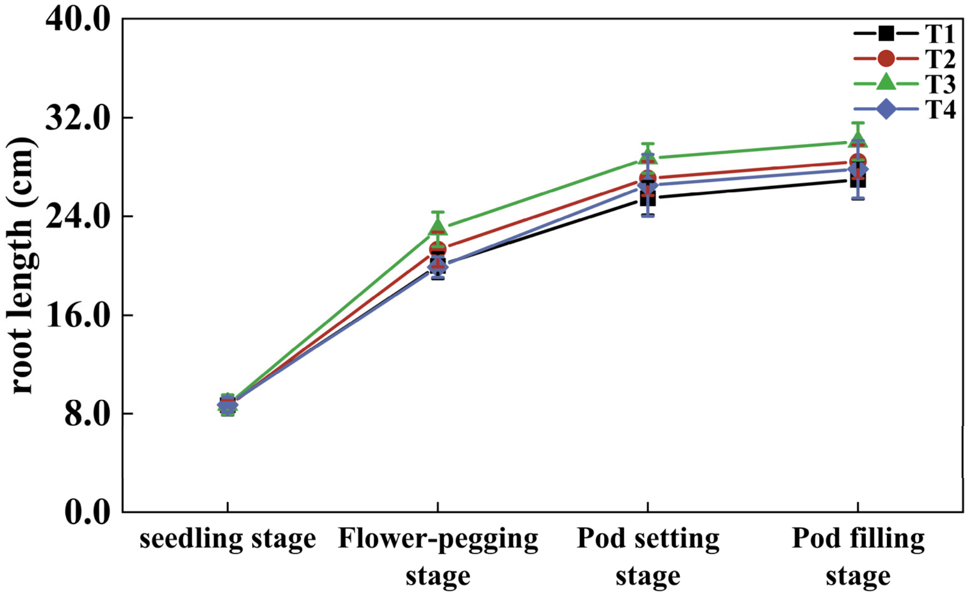


(**a**) plant height

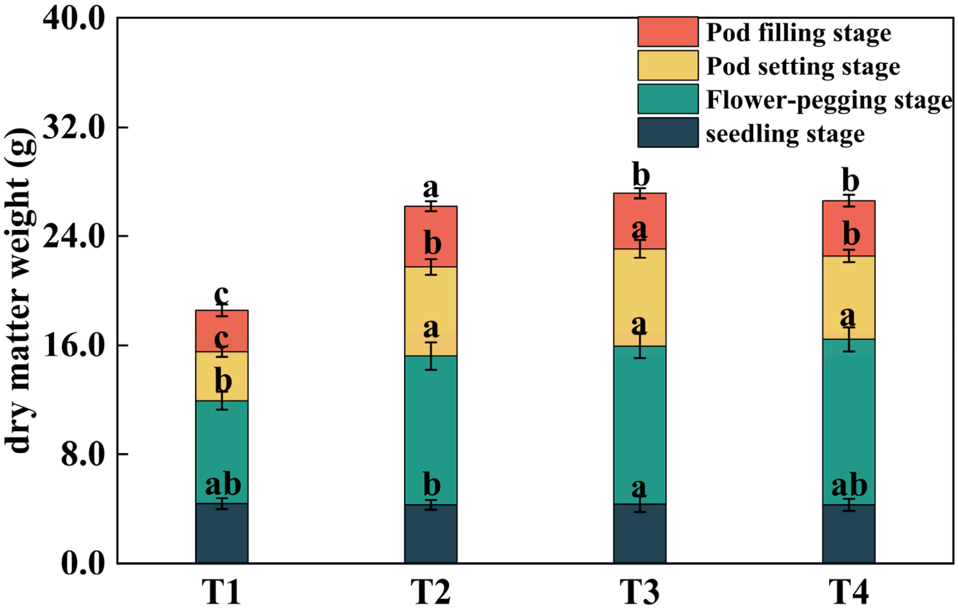


(**b**) Stem thickness

Figure 3. *Cont.*



(**c**) Root length



(**d**) Dry matter weight

Figure 3. Effects of different irrigation regimes on peanut growth and dry matter weight. Different lowercase letters (a, b, c) indicate significant differences between the data groups ($p < 0.05$).

3.2. Effects of Different Irrigation Regimes on Yield and WUE

The effects of various irrigation regimes on peanut yield and water use efficiency (WUE) were significant, as illustrated in Figure 4. In both 2021 and 2022, the ranking of yield among the treatments was T3 > T2 > T4 > T1, whereas WUE was ranked T2 > T3 > T1 > T4. The T1 treatment consistently yielded the lowest output, consistent with the peanut growth characteristics outlined in Section 3.1, where limited water availability adversely affected growth. Conversely, the elevated yields observed in the T2 and T3 treatments underscore the importance of maintaining appropriate soil moisture levels to enhance peanut productivity. This finding aligns with those of Ruier et al. [45], who demonstrated that excessive water application negatively impacts peanut yield by inducing waterlogging stress, which restricts root respiration and nutrient uptake during critical growth stages. These results suggest that achieving higher yields is not solely dependent on indiscriminately increasing irrigation levels but rather on carefully balancing water availability.

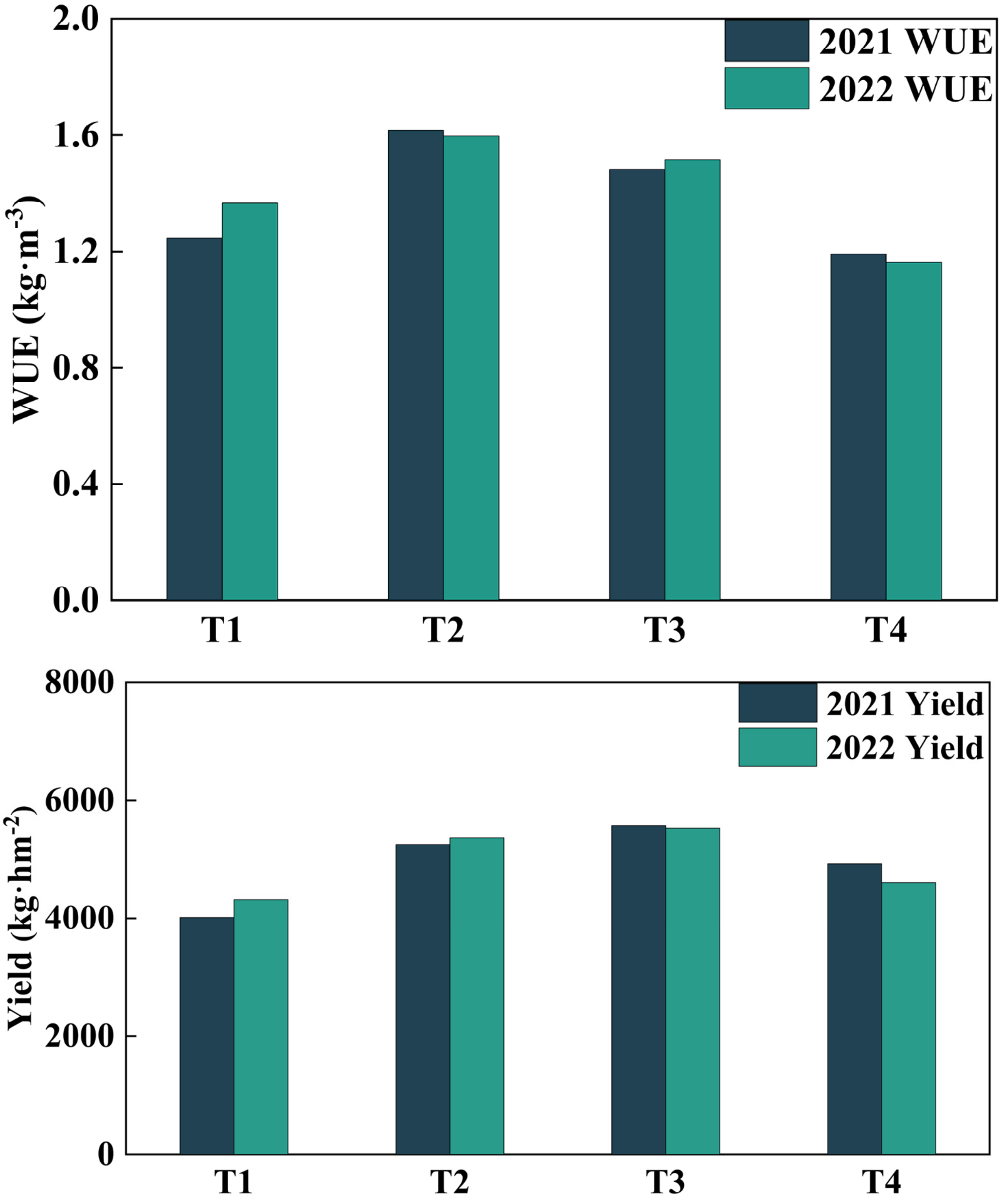


Figure 4. Effects of different irrigation regimes on yield and WUE.

The T3 treatment yielded the highest output in 2021, reaching 5574 kg·hm^{-2}; however, its WUE was 5% lower than that of T2, which achieved the highest WUE (1.62 kg·m^{-3}) in 2022. This trend highlights the inherent trade-off between maximizing yield and improving WUE. While T3 consistently achieved the highest yields, its lower WUE suggests that additional water input was required, leading to reduced water use efficiency. Similar trade-offs were observed by Junxiao et al. [25], who reported that irrigation strategies designed to maximize yield often reduce WUE, particularly under high water input conditions. Conversely, the T2 treatment, which prioritized WUE, demonstrated the effectiveness of moderate irrigation in achieving efficient water utilization, consistent with the findings of Songsri et al. [46], who emphasized the role of root distribution and stomatal conductance in optimizing WUE under different soil moisture regimes.

These results indicate that evaluating the superiority of irrigation regimes based solely on yield or WUE provides an incomplete perspective. Farmers typically prioritize maximizing yield to enhance profitability, whereas water resource managers focus on improving WUE to conserve resources and increase food production with less water. Abdrabbo et al. [18] highlighted the need for balanced irrigation practices that address both objectives, as deficit irrigation can enhance WUE while mitigating unnecessary water loss. Integrating both yield and WUE metrics into the decision-making process is crucial to reconciling these competing priorities. Such an integrated approach supports the development of irrigation strategies that optimize resource use and productivity under varying environmental and resource conditions.

3.3. Effects of Different Irrigation Regimes on Economic Benefit

Growth traits reflect the developmental conditions of peanuts throughout their entire growing period under various irrigation regimes, illustrating the growth process of these plants. Due to local drought conditions and water scarcity, irrigation quotas and WUE are of paramount concern for water resource management agencies. Yield directly determines gross returns. However, it is equally essential to consider total costs, as net return is a primary concern for farmers. Consequently, we conducted extensive market research, investigated the total costs and gross returns of peanuts across various irrigation regimes, and calculated the net returns [47].

The total cost encompassed equipment, plowing and planting, seed, fertilizer, weeding, water, electricity, and labor. Labor costs varied based on the irrigation frequency of the four regimes, necessitating adjustments to labor costs in accordance with irrigation cycles. Gross returns, derived from peanut sales, were influenced by both yield and the prevailing market price. The calculation of net return (averaged over 2021 and 2022) is presented in Table 1.

Table 1. Economic benefit of different irrigation regimes.

Treatments	**Gross Return (yuan·hm^{-2})**	**The Total Cost (yuan·hm^{-2})**								**Net Return (yuan·hm^{-2})**
		Equipment	**Plowing and Planting**	**Seed**	**Fertilizer**	**Weeding**	**Labor**	**Water**	**Electricity**	
T1	33,330	600	1050	3150	2700	525	5000	108	143	20,055
T2	42,474	600	1050	3150	2700	525	7500	126	168	26,655
T3	44,412	600	1050	3150	2700	525	8760	138	182	27,307
T4	38,130	600	1050	3150	2700	525	10,001	143	188	19,773

Different irrigation regimes significantly affected the economic benefit. Gross returns under the four irrigation regimes ranked in descending order as T3 > T2 > T4 > T1, with the T3 treatment yielding the highest gross return of 44,412 yuan·hm^{-2}. The total costs across the four irrigation regimes, ranked in descending order, were T4 > T3 > T2 > T1. The total cost of the T4 treatment was the highest (18,357 yuan·hm^{-2}), whereas the T1 treatment had the lowest cost (13,276 yuan·hm^{-2}). Considering both gross returns and total costs, the net returns of the various irrigation regimes, ranked in descending order, were as follows: T3 > T2 > T1 > T4. The net return from the T3 treatment was the highest (27,307 yuan·hm^{-2}), whereas that of the T4 treatment was the lowest (19,773 yuan·hm^{-2}). The ranking of net returns from the peanuts under the four treatments differed from the ranking of growth traits and yield. For instance, of the four treatments, the T1 treatment exhibited the lowest yield and growth traits, but its net return was not the lowest. This is because the T1 treatment used the least amount of water and had the lowest total cost, whereas the T4 treatment consumed the most water and had the highest total cost. As a result, the net return of the T1 treatment exceeded that of the T4 treatment. Additionally, the T3 treatment achieved relatively optimal water usage, reduced total costs, and increased peanut yield, thereby resulting in the highest net return.

These findings align with prior research, such as the study by Deng et al. [48], which demonstrated that optimized irrigation not only improved water use efficiency but also enhanced crop yields and economic returns in semi-arid regions. Similarly, Oweis et al. [49] reported that balancing irrigation water input with yield response is critical to maximizing net returns. The T3 treatment in our study reflects these principles, as moderate irrigation quotas effectively balanced water savings, yield improvement, and economic returns. In contrast, the T4 treatment demonstrated the economic impact of excessive water use, which significantly increased labor and energy costs without yielding proportionate economic benefits. This aligns with the findings of Cremades et al. [50], who highlighted the negative economic consequences of inefficient water management, such as a high irrigation frequency. However, while a high irrigation frequency may not fully define the T4 treatment, the cost implications of excessive water use observed in T4 resonate with their conclusions. Furthermore, our results support the conclusion by Zwart [51], emphasizing that irrigation efficiency is a key determinant in achieving sustainable agricultural practices. The T3 treatment exemplifies this, as it effectively optimized resource use to achieve a balance between economic benefits and water conservation.

3.4. Comprehensive Evaluation by the Entropy Value and TOPSIS Method

Based on the aforementioned study, the selection of an optimal irrigation regime varies depending on multiple factors affecting growth, yield, WUE and economic benefits. Therefore, plant height, stem thickness, root length, dry matter weight, yield, WUE, and net return were selected as key indicators for this study. Using the entropy value method, the weight of each indicator was calculated. The weight matrix for the indicators—plant height, stem thickness, root length, dry matter weight, yield, WUE, and net return—was as follows: (0.147, 0.158, 0.132, 0.118, 0.149, 0.135, 0.160). These weights reflect the relative importance of these indicators in optimizing irrigation practices. It was evident that net return, yield, and stem thickness received relatively higher weights, whereas dry matter weight and root length were assigned relatively lower weights. As the sole indicator reflecting water use, WUE was assigned a medium weight, underscoring its significant impact on the overall results. Subsequently, the TOPSIS method was employed to calculate the optimal and worst distances, along with the similarity degrees for the various irrigation regimes. The results matrix, as represented below, displays the values calculated for each treatment:

$$X = \begin{pmatrix} 0.33 & 0.08 & 0.20 \\ 0.15 & 0.24 & 0.62 \\ 0.07 & 0.32 & 0.83 \\ 0.21 & 0.22 & 0.51 \end{pmatrix}$$

A higher similarity score indicates a more favorable overall evaluation of the irrigation regime. The similarity ranking for different treatments was T3 > T2 > T4 > T1, with the T3 treatment achieving the highest similarity score of 0.83. In conclusion, the T3 treatment not only optimized peanut yield and net return but also exhibited a favorable balance of water use efficiency, making it the optimal choice for both farmers and water resource managers. This result is consistent with previous findings that optimal irrigation regimes are typically those that balance high yield with efficient water use and cost-effectiveness [49]. Nevertheless, to improve the representativeness and comprehensiveness of optimal irrigation regime assessments, future research should incorporate additional sustainability indicators. For instance, factors such as greenhouse gas emissions and energy efficiency, as recommended by Allen et al. [52], could provide a more holistic evaluation framework, ensuring that irrigation practices are not only economically and agronomically viable but also environmentally sustainable.

4. Conclusions

This study assesses the impact of different irrigation regimes on peanut growth, water use efficiency (WUE), and economic returns over two years (2021–2022) in Heishan County, China. The main conclusions are four-fold:

(1) Irrigation treatments significantly influenced peanut growth characteristics. While T4 resulted in the highest plant height, moderate irrigation (T3) promoted optimal growth in terms of stem thickness, root length, and dry matter weight, indicating that balanced water management is crucial for supporting biomass production. Both excessive (T4) and insufficient (T1) irrigation negatively impacted growth.

(2) The relationship between yield and WUE varied across treatments. T3 achieved the highest yield (5574 kg·hm^{-2}) and a WUE of 1.48 kg·m^{-3}. In contrast, T2 recorded the highest WUE (1.62 kg·m^{3}), although its yield (5251 kg·hm^{-2}) was slightly lower. This highlights the trade-off between maximizing yield and optimizing water use efficiency. In regions where water scarcity is a critical concern, T2 may represent a practical alternative, as it prioritizes water efficiency while maintaining reasonably high yields. Policymakers could support this transition by offering incentives such as subsidies or technical assistance to mitigate potential economic disadvantages for farmers prioritizing water efficiency.

(3) Different irrigation regimes significantly influenced economic returns. Moderate irrigation (T3) resulted in the highest net return (27,307 yuan·hm^{-2}), highlighting its cost-effectiveness. T3 provided the best balance between resource use and profit, outperforming both over-irrigation (T4) and under-irrigation (T1), which resulted in lower net returns. These results underscore the economic importance of optimizing irrigation practices to maximize profitability while ensuring efficient resource utilization.

(4) The entropy value and TOPSIS methods, which integrated growth traits, WUE, and economic returns, were used to identify the optimal irrigation regime. T3 emerged as the most favorable treatment, with a similarity degree of 0.83 supporting its classification as the best irrigation strategy. In the future, a portion of the peanut cultivation area in Heishan County could be transitioned to the proven optimal irrigation regime, T3, for pilot implementation. Further investigation into the long-term impacts and scalability of this irrigation regime across different crop varieties and regions could help extend these findings to other areas in Western Liaoning Province.

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