



Article

Effects of Restricted Irrigation and Straw Mulching on Corn Quality, Soil Enzyme Activity, and Water Use Efficiency in West Ordos

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Abstract: Groundwater overexploitation in West Ordos necessitates sustainable irrigation practices. This study evaluated three irrigation levels—W1 (3300 m³ · ha^{−1}), W2 (2850 m³ · ha^{−1}), and W3 (2400 m³ · ha^{−1})—by modifying the wide-width planting pattern of maize. Additionally, two levels of straw mulch were analyzed: F1 (9000 kg · ha^{−1}) and F2 (no mulch). The study aimed to investigate the effects of these treatments on corn growth dynamics, soil water temperature, soil enzyme activity, yield, grain quality, and water use efficiency. The results indicated a decline in growth indices, enzyme activities, grain quality, and yield under the limited irrigation levels W2 and W3 compared to W1. The highest corn yields were observed with W1F1 (6642.54 kg · ha^{−1}) and W2F1 (6602.38 kg · ha^{−1}), with the latter showing only a 0.6% decrease. Notably, water use efficiency in the W2F1 treatment improved by 4.69%, 12.08%, 10.27%, 12.59%, and 12.96% compared to W1F1, W3F1, W1F2, W2F2, and W3F2, respectively. Straw mulch (F1) significantly elevated the soil temperature, increasing the effective accumulated temperature during the growth period by 10.11–85.79 °C, and boosted the soil enzyme activity by 10–25%. Under limited irrigation, the W2 (2850 m³ · ha^{−1}) and F1 (9000 kg · ha^{−1} straw) treatments achieved the highest water productivity of 2.48 kg · m^{−3}, maintaining a high yield of 6602.38 kg · ha^{−1} while preserving nutrients essential to the corn's quality. This approach presents a viable strategy for wide-width corn planting in groundwater-depleted regions, offering a scientifically grounded and sustainable water management solution for efficient corn production in West Ordos.

Keywords: groundwater overexploitation area; irrigation restriction; straw mulch; corn yield and quality; water use efficiency



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1. Introduction

Groundwater irrigation is extensively employed in Chinese agriculture, particularly in the northern agricultural and pastoral regions. Due to the relative scarcity of surface water resources, groundwater has emerged as a crucial source of irrigation water [1]. However, prolonged and excessive extraction has exacerbated the issue of groundwater overexploitation, especially in areas with intensive agricultural activity, such as the North China Plain and Ordos [2,3]. Groundwater plays a crucial role in agricultural irrigation across China, particularly in regions experiencing significant water scarcity, such as North China

and Northwest China. Extensive agricultural areas depend on groundwater for irrigation, which is vital for maintaining food production stability and fostering agricultural development [4]. To accommodate the rising demands of agricultural irrigation, the extraction of groundwater has been escalating annually [5]. In several key agricultural regions, the utilization of groundwater resources has reached or surpassed their renewable capacity. Agricultural production in the Ordos region is heavily reliant on groundwater for irrigation. As agricultural operations expand and irrigation demands escalate, the exploitation of groundwater resources has correspondingly intensified [6]. Prolonged overexploitation has led to a persistent decline in groundwater levels in Ordos, exacerbating the issue of groundwater depletion. This unsustainable utilization of water resources poses a significant threat to the long-term stability of agricultural production. The relentless extraction of groundwater results in a continuous decrease in water levels, escalating the difficulty and cost of water retrieval. Additionally, it risks the depletion of well water, rendering agricultural irrigation unfeasible [7–9]. Continuous overexploitation of groundwater has precipitated land subsidence and structural damage to surface infrastructures, subsequently impairing agricultural productivity and the living conditions of residents. Additionally, the declining groundwater levels may facilitate the intrusion of pollutants into the aquifers, thereby exacerbating the degradation of water quality [10]. Using polluted water for irrigation can severely damage crop and soil health. Furthermore, groundwater overexploitation results in water shortages, directly reducing agricultural irrigation efficiency and potentially causing crop yield reductions or even crop failures. This situation presents significant challenges to agriculture-dependent regional economies. In response to the unsustainable use of water resources, some regions have begun to modify their agricultural practices by reducing the cultivation of high-water-demand crops, shifting to drought-resistant varieties, and adopting water-saving agricultural technologies. To address groundwater overexploitation, the Chinese government and relevant authorities are actively promoting water-efficient irrigation technologies, adjusting agricultural water usage policies, enhancing groundwater resource management and protection, and fostering the sustainable development of agriculture [11–13]. In recent years, the escalating global water scarcity crisis has heightened the importance of sustainable groundwater resource management within agricultural research. The Ordos region, characterized by its arid climate and limited surface water availability, relies heavily on groundwater irrigation to sustain agricultural productivity [13]. Research on maize cultivation in this region, particularly that focusing on the impacts of deficit irrigation and straw mulching on maize yield, water use efficiency, quality, and soil enzyme activity, has garnered significant attention in academic circles [14,15]. Limited irrigation, defined as an insufficient water supply, enhances crop water use efficiency by regulating the irrigation volume [16]. Domestic and international research predominantly centers on investigating the impacts of varying irrigation levels on maize yield, water utilization efficiency, and quality [17]. Research indicates that moderately restricting irrigation can markedly enhance the water use efficiency of maize, with negligible effects on both yield and quality [18]. Common research methodologies often involve field experiments. In this study, various irrigation treatments were applied to maize, including full irrigation, 75% irrigation, and 50% irrigation. The study assessed multiple parameters related to growth, yield, quality indicators (such as grain protein and starch content), as well as soil enzyme activity [19–22]. As an agricultural management practice, straw mulching plays a pivotal role in enhancing soil moisture retention, crop yield, and quality. Recent research indicates that straw mulching effectively mitigates soil moisture evaporation, augments soil organic matter levels, and stimulates soil microbial activity, consequently elevating soil enzyme dynamics. To evaluate the effects of straw mulching on maize growth, yield, quality parameters, and soil enzyme activities, a field experiment with and without straw mulching was conducted. [23]. Furthermore, farmyard manure is an excellent organic fertilizer and a traditional mulch material widely used for conserving soil fertility [24]. Domestic research, exemplified by experiments conducted in the Ordos region, has demonstrated that straw mulching can markedly enhance the water use efficiency of maize. Furthermore, it

augments soil enzyme activity, thereby culminating in heightened yield and improving the quality of the crop [25]. Current research is focusing significantly on investigating the synergistic impacts of irrigation and straw mulching on maize yield, water use efficiency, quality parameters, and soil enzyme activity [26]. Typically, such studies employ a field experimental design incorporating multiple treatment groups, such as full irrigation combined with straw mulching, limited irrigation combined with straw mulching, and separate treatments for irrigation and straw mulching. This approach enables a comprehensive assessment of the interactions among various factors and their impacts on maize growth. Research has demonstrated that combining limited irrigation with straw mulching enhances water use efficiency and soil enzyme activity, while concurrently sustaining high maize yield and quality [27]. Field experiment design is frequently employed in studies aimed at monitoring and analyzing maize growth performance, yield, quality, and soil enzyme activity through the implementation of various treatment combinations. Specific methodologies encompass controlling irrigation amounts, applying straw mulching treatments, monitoring soil moisture, determining crop growth parameters, analyzing yield and quality, and assessing soil enzyme activity [28–30]. Applying these methods enables a comprehensive evaluation of the effects of various agricultural management practices on maize production, thereby establishing a scientific foundation for the formulation of rational strategies in agricultural water resource management. Despite significant advancements in existing research, certain deficiencies persist. Primarily, numerous studies exhibit shortcomings in systematic experimental design and the configuration of treatment groups, thereby neglecting to fully account for the synergistic impacts arising from diverse environmental conditions and management practices [31]. Current research on the correlation between soil enzyme activity and crop growth remains inadequate, and the mechanistic investigations are notably underdeveloped. Addressing these deficiencies necessitates a heightened emphasis on multifactorial comprehensive experiments and the exploration of synergistic effects arising from diverse management strategies. Concurrently, intensifying investigations into the mechanisms governing soil enzyme activity and crop growth is imperative for a more profound understanding of how agricultural management practices influence crop yields [32]. A comprehensive investigation into the impacts of restricted irrigation and straw mulching on maize yield in the Ordos region can furnish crucial insights for optimizing agricultural water management practices and fostering sustainable agricultural development in the area.

Previous studies have predominantly examined the individual impacts of irrigation techniques and straw mulching on maize growth, yield, and resource utilization efficiency. However, limited research has explored their combined and interactive effects on these parameters. This study aims to advance water-saving strategies and management practices in agricultural irrigation. Emphasizing the efficient utilization of water resources without compromising yield, the project rigorously investigates deep water-saving methods tailored for large-scale corn cultivation under controllable groundwater conditions. The establishment of a water-saving management demonstration area serves to provide scientific and technological support for sustainable development in Ordos. A field experiment was conducted to assess the effects of wide planting with straw mulching and restricted irrigation on maize yield, water use efficiency, and grain quality under varying irrigation levels achieved through different water and straw mulch application rates. The research objectives are as follows: (1) elucidate the impact of limited irrigation and straw mulching on soil enzyme activity and soil temperature, (2) examine alterations in maize water use efficiency, yield, and grain quality under these conditions, and (3) propose optimal schemes for limited irrigation and straw mulching in areas experiencing groundwater overexploitation in Western Ordos. Additionally, this study investigates the effects of reduced irrigation and straw mulching on soil enzyme activity in maize fields, thereby laying a theoretical foundation for enhancing profound water-saving management of agricultural groundwater in Western Ordos. This research offers theoretical insights for implementing more efficient and water-conserving cultivation methods in severely depleted plateau groundwater regions.

2. Materials and Methods

2.1. Experimental Site Description

The experimental area is located in the Inner Mongolia Autonomous Region of the People's Republic of China Ordos Etuoke Banner Agricultural and Animal Husbandry Technology Extension Station (39°06' N, 107°30' E, altitude 1151 m), Figure 1. This area belongs to the typical temperate continental monsoon climate, and the temperature difference between day and night is 16 °C. There is less precipitation, and the multi-year distribution is uneven, and is mainly concentrated in July to September. The average annual rainfall is 168.22 mm and the annual evaporation is over 3000 mm. When the light and heat in the area are sufficient, the yearly sunshine hours can reach 3000 h, the annual accumulated temperature above 0 °C is 3650 °C, and the frost-free period is about 122 d. The groundwater depth in this area is greater than 20 m, the average field capacity is 22.22%, the soil is brown calcic soil, and the soil bulk density is 1.49 g·cm⁻³.

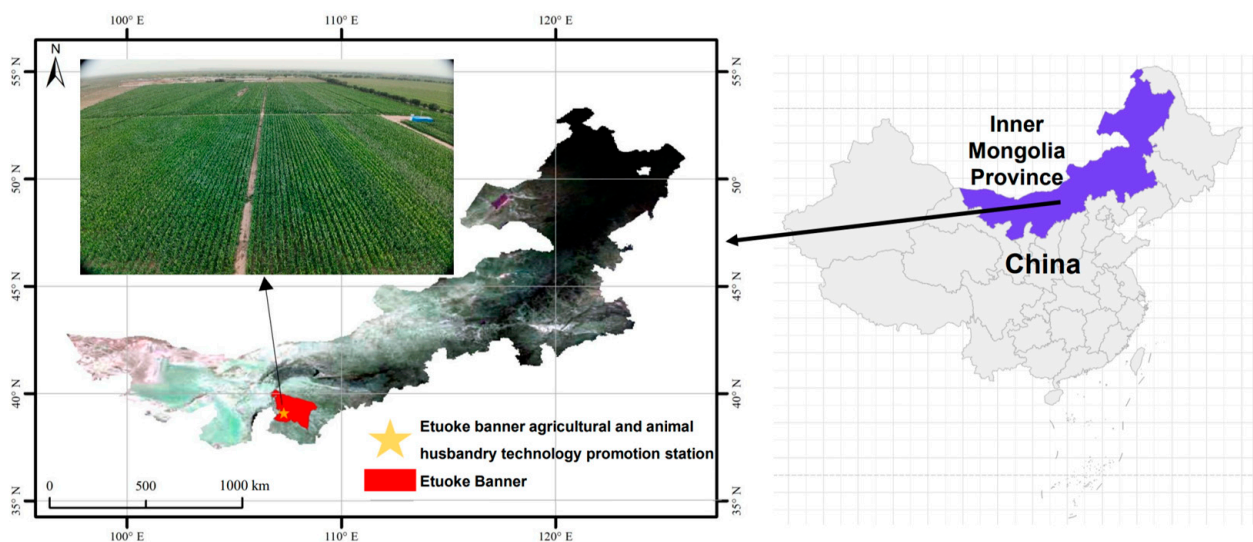


Figure 1. Location of the trial.

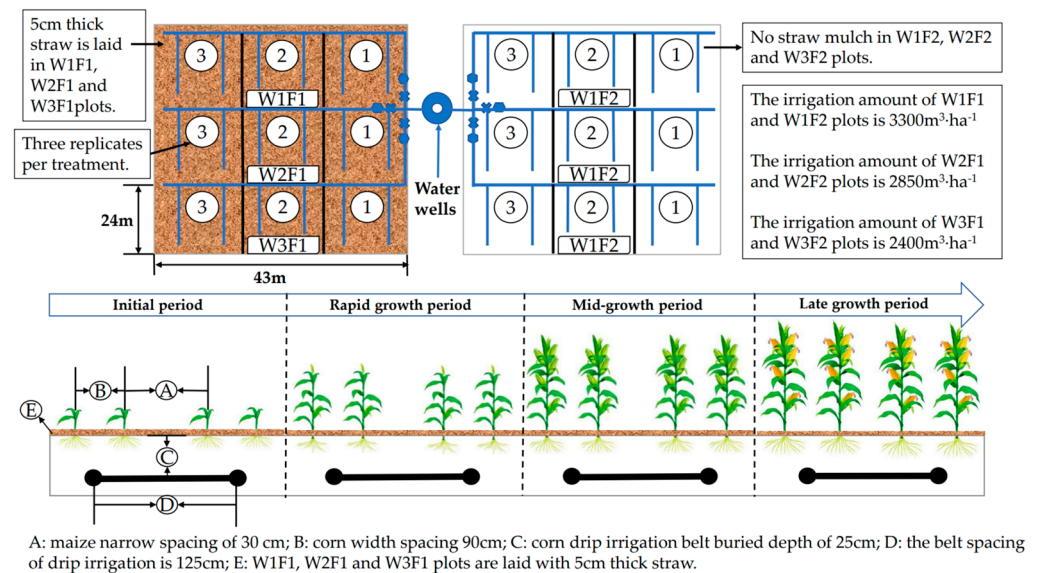
2.2. Experimental Design and Field Management

Aiming at the problem of groundwater overexploitation in Western Ordos, according to the local standard DB15/T 385-2020 [33] water quota of the Inner Mongolia Autonomous Region, two variables of irrigation amount and straw coverage were designed. The irrigation amounts were 3300 m³ · ha⁻¹ (W1), 2850 m³ · ha⁻¹ (W2), and 2400 m³ · ha⁻¹ (W3), respectively. The two straw coverage treatments were 9000 kg · ha⁻¹ (F1) and 0 kg · ha⁻¹ (F2). A randomized block design was used in the experiment, and each treatment was repeated in 3 groups. The test plan is shown in Table 1. As shown, the experimental plot is 40 m long and 25 m wide, and a 90 cm protection line is set up between the plots. The irrigation water is extracted from the high-standard farmland hydropower double control base well. Each plot is equipped with independent pipes and water meters to ensure that the plot is irrigated and fertilized separately. The irrigation adopts buried drip irrigation, and the corn ground shallow buried drainage root anti-negative pressure rat-avoiding buried drip irrigation pipe developed by Dayu Water Saving Group is selected. The drip irrigation belt is buried at a depth of 20 cm, the dripper flow rate is 2 L·h⁻¹, the dripper spacing is 30 cm, and the drip irrigation belt spacing is 125 cm. During the whole growth period, irrigation took place 12 times, and the detailed irrigation plan is shown in Table 1. The straw in the test area was crushed and covered in a broad and narrow row of corn, with a coverage of 9000 kg · ha⁻¹ and a coverage thickness of 5 cm, Table 1.

Table 1. Test treatment design scheme.

Treatment	Irrigation Frequency (Times)	Single Irrigation Amount ($\text{m}^3 \cdot \text{ha}^{-1}$)	Total Irrigation ($\text{m}^3 \cdot \text{ha}^{-1}$)	Straw Mulching ($\text{kg} \cdot \text{ha}^{-1}$)
W1F1	12	275	3300	9000
W1F2	12	275	3300	0
W2F1	12	237.5	2850	9000
W2F2	12	237.5	2850	0
W3F1	12	200	2400	9000
W3F2	12	200	2400	0

The test maize variety was ‘Guorui 188’. The maize was sown on 1 May 2023 and harvested on 18 September 2023. The planting method was wide and narrow row planting, a narrow row laying drip irrigation belt, wide row spacing of 90 cm, and narrow row spacing of 30 cm, and the plant spacing was 20 cm, Figure 2. Fertilization was determined according to local planting and production experience, and water-soluble fertilizer was applied in each growth period of maize. The agronomic measures such as weeding and spraying pesticides were based on local production experience.

**Figure 2.** Experimental layout.

2.3. Data Collection and Methods

2.3.1. Meteorological Data

The standard automatic HOBO-U30 weather station (Onset Computer Corp., Bourne, MA, USA) was installed at 10 m on the right side of the test plot to collect meteorological data during the fertility period, throughout the entire experimental period. Figure 3 shows the average temperature and precipitation in 2023. During the growth period in 2023, the temperature was between 10.3 °C and 26.9 °C and the precipitation was 216.3 mm.

2.3.2. Growth Index Data

- Three plants with the same growth and size were selected in each plot to observe the plant height, stem diameter, and leaf number. The plant height refers to the distance from the root to the highest point of the top leaf when it is naturally stretched on the ground; the stem diameter is the width of the second section of corn on the ground measured by a vernier caliper, and the average value is calculated [34,35].
- Leaf area index and canopy coverage of maize [34]:

$$L_a = \sum_{i=1}^n (0.74 * L_i * D_{iMAX}) \quad (1)$$

$$LAI = L_a / L_b \quad (2)$$

$$CC = 1.005(1 - \exp(-0.6LAI))^{1.2} * 100\% \quad (3)$$

n is the number of leaves per plant; L_a is the leaf area of a single plant (cm^2); L_b is the area occupied by plants (cm^2); D_{iMAX} is the maximum width (cm) of the i -th leaf; L_i is the length (cm) of the first leaf.

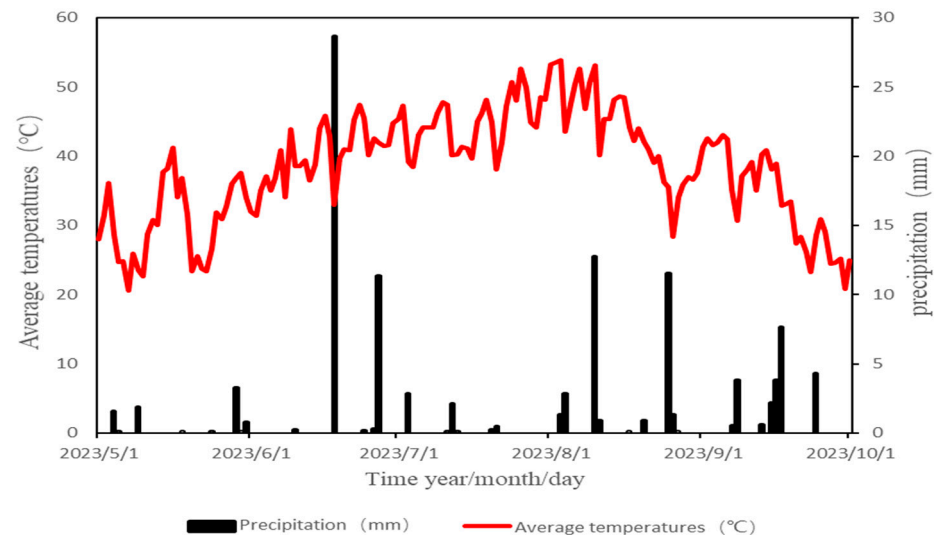


Figure 3. Average temperature and precipitation during the growth period in 2023.

2.3.3. Soil Enzyme Activity

Soil enzyme activities were measured on 19 August at the filling stage and on 12 September at the maturity stage of maize in 2023. The maize roots were dug out from the soil, and the sampling depth was 25 cm. The soil shaking method loosely combined with the origins separated the surface soil. Finally, the rhizosphere soil, combined closely with the roots, was brushed off with a brush, and the rhizosphere soil samples were collected. After the soil was naturally dried, the dried soil samples were sieved to 1 mm for enzyme activity analysis. Soil urease activity was measured using the indophenol blue colorimetric method. Catalase was determined by potassium permanganate titration; phosphatase content was determined by the disodium phenyl phosphate colorimetric method. Both sucrase and cellulase were determined by the 3,5-dinitrosalicylic acid colorimetric method [28].

2.3.4. Soil Moisture Content and Soil Temperature

The soil water content monitoring adopted the intelligent entropy + produced by Oriental Zhigang (Zhejiang) Science and Technology Co., Ltd., Hangzhou, China. The equipment observation adopted the FDR principle; the observation record step was one time/one hour. The equipment realizes the real-time upload of the observation data to the cloud server in GPRS mode and it is viewed through E ecology. The soil volumetric water content and soil temperature at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 cm depth of soil surface under different treatments of maize were continuously and dynamically monitored in real time.

The soil temperature of each treatment was recorded by intelligence entropy +, and the mean value of the two soil layers was taken. The position of each therapy was fixed, and the soil temperature measurement was set to be recorded every hour. In each plot, the soil temperature at 0–10, 10–20, and 20–30 cm was measured at 8:00, 10:00, 12:00, 14:00, 16:00, and 18:00 every day, and the average daily temperature was measured in the morning, middle and later parts of the day. The effective accumulated temperature of soil (AT , $^{\circ}\text{C}$) was calculated according to the following formula:

$$AT = \sum (T_m - T_b) \quad (4)$$

T_m is the average daily soil temperature ($^{\circ}\text{C}$); T_b is the effective accumulated temperature of corn, namely five $^{\circ}\text{C}$. When $T_m < T_b$, the adequate soil accumulated temperature is 0 $^{\circ}\text{C}$.

2.3.5. Soil Moisture Content and Soil Temperature

Each treatment was selected to harvest four rows of corn in the middle, and 0.5 m at both ends was removed to eliminate the influence of marginal effects. After air-drying, threshing was performed to determine yield (converted to yield according to 14% standard mass water content) and yield components (spike number, grain number, and thousand seed weight).

2.3.6. Corn Quality

After the corn was harvested, 1 kg of corn grains in each treatment was taken and measured according to the national food safety standards (GB5009.5-2016 [S] [36]) stipulated by the State Food and Drug Administration, including crude protein, crude fat, crude fiber, crude ash, and nitrogen-free extract. Among them, the crude protein was determined by the Kjeldahl method; crude fat was determined by the Soxhlet extraction method; crude fiber was determined by the acid–base decoction method; and crude ash was determined by the hot water extraction method. The difference in nitrogen-free extract was obtained by subtracting the percentage content of moisture, crude ash, crude protein, crude fat, and crude fiber from the material content of maize grain.2.

2.3.7. Water Use Efficiency

The following formula calculated water use efficiency:

$$WUE = \frac{Y}{ET} \quad (5)$$

where WUE is the water use efficiency, ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$); Y is the grain yield of maize, ($\text{kg} \cdot \text{ha}^{-1}$); ET is the water consumption of maize during the whole growth period, (mm).

2.3.8. The Comprehensive Score of Maize Growth Based on the Comprehensive Scoring Method

The comprehensive scoring method first scores each evaluation index according to the evaluation criteria of different indicators and then uses weighted addition to obtain the total score [27]. This experiment was based on the comprehensive score of maize yield, quality, water use efficiency, and soil enzyme activity. The calculation steps are as follows:

1. There are evaluation objects and b evaluation indexes. X_{ij} is the j -th index of the i -th treatment. In this experiment, $a = 6$, $b = 4$, and the normalized index Y_{ij} is obtained by eliminating the dimension of the measured values of each index.

$$Y_j = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)} \left(\begin{array}{l} i = 1, 2, \dots, a \\ j = 1, 2, \dots, b \end{array} \right) \quad (6)$$

2. We calculate the mean and variance of the index.

The average value of the index $\bar{X}_j$ is as follows:

$$\bar{X}_j = \frac{1}{a} \sum_{i=1}^a Y_{ij} \quad (7)$$

The variance S_j^2 of the i -index is

$$S_j^2 = \frac{1}{(a-1)} \sum_{i=1}^a (Y_{ij} - \bar{X}_j)^2 \quad (8)$$

3. We calculate the coefficient of variation Z_j of the index.

$$Z_j = \frac{S_j}{\overline{X_j}} \quad (9)$$

4. We calculate the index weight W_j

$$W_j = \frac{Z_j}{\sum_{j=1}^b Z_j} \quad (10)$$

5. The comprehensive score C_{si} of the processing is calculated.

$$C_{si} = \sum_{j=1}^b W_j Y_{ij} \quad (11)$$

2.4. Data Statistics

The data were collated and summarized by Microsoft Excel 2021, and the data were statistically analyzed by SPSS 22.0 software and plotted by GraphPad Prism 8 and Origin 2021 software. The statistical significance was determined using Tukey's pairwise.

3. Results

3.1. Effects of Limited Irrigation and Straw Mulching on Growth Indexes of Maize during the Whole Growth Period

3.1.1. The Dynamic Changes in Average Plant Height Stem Diameter and Leaf Number during the Whole Growth Period

During the 2023 growing season, the maize plant height in the W1F1 treatment group exhibited a significant increase compared to other treatments. Conversely, there were no significant differences in maize plant height among the W1F2, W2F1, and W2F2 treatment groups. However, the maize plant height in the W3F1 and W3F2 treatment groups was notably lower than in other groups. These findings suggest that incorporating some corn straw under the W2 irrigation treatment can effectively mitigate significant inhibition of maize plant height. Similarly, the leaf number and stem diameter in the W3F1 and W3F2 treatment groups were significantly reduced compared to those in other treatment groups. In contrast, there were no significant differences observed in the dynamics of leaf number and stem diameter among the W1F1, W1F2, W2F1, and W2F2 treatment groups, Figure 4. These results indicate that a judicious reduction in irrigation water does not result in undue adverse effects on maize growth and development.

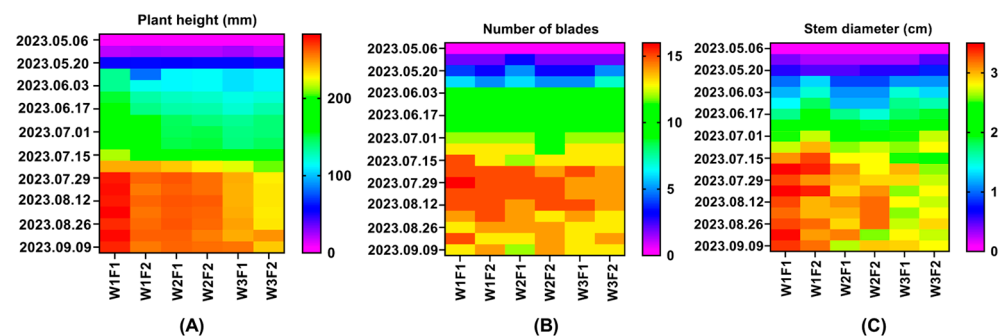


Figure 4. Plant height (A), blades number (B), and stem diameter (C) of maize under different treatments during the whole growth period. Note: Different colors represent significant differences ($p < 0.05$).

3.1.2. Leaf Area Index (LAI) and Canopy Cover (CC)

The results indicated no significant difference in canopy coverage between the W2F1 treatment group and the W1F1 and W1F2 treatment groups during the 2023 growth period. However, the canopy coverage in the W2F2, W3F1, and W3F2 treatment groups was

significantly lower than in the W2F1, W1F1, and W1F2 groups (Figure 5A) ($p < 0.05$). Similarly, no significant difference in leaf area index was observed at various developmental stages between the W2F1 treatment group and the W1F1 and W1F2 groups. Nonetheless, the leaf area index in the W2F2, W3F1, and W3F2 treatment groups was significantly lower than in the aforementioned three treatment groups (Figure 5B) ($p < 0.05$). These findings suggest that a moderate reduction in irrigation (W2, $2850 \text{ m}^3 \cdot \text{ha}^{-1}$) does not negatively impact the leaf area index or canopy coverage of straw-mulched maize.

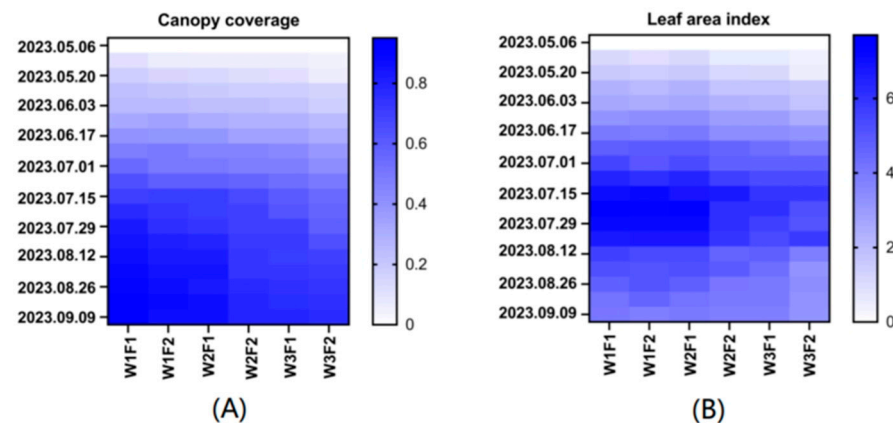


Figure 5. Canopy coverage (A) and leaf area index (B) of maize during the whole growth period under different treatments.

3.2. Response of Soil Enzyme Activity to Limited Irrigation and Straw Mulching at the Filling Stage of Maize

The enzyme activity analysis results (Figure 6) revealed that soil invertase, protease, cellulase, urease, catalase, and phosphatase activities were highest in the W1F1 treatment (irrigation volume of $3300 \text{ m}^3 \cdot \text{ha}^{-1}$ and $9000 \text{ kg} \cdot \text{ha}^{-1}$ straw mulching) during both the filling and mature stages. Relative to W1F1, the W1F2 treatment reduced the activities of soil invertase, protease, cellulase, and phosphatase by 18%, 12%, 24%, and 31%, respectively, and at the maturity stage, these reductions were 11%, 15%, and 9%, respectively. In the W2F1 treatment, soil sucrose activity decreased by 35% compared to W1F1, with no significant changes observed in the other enzyme activities. The activities of soil urease and catalase decreased by 17% and 19%, respectively, with no significant changes in other enzyme activities. Furthermore, treatments W2F2, W3F1, and W3F2 significantly reduced the activities of sucrose, protease, cellulase, urease, catalase, and phosphatase in the soil at both the irrigation and maturity stages compared to W1F1. These findings indicate that straw mulching can significantly enhance soil enzyme activity. Specifically, straw mulching can generally increase invertase activity by 10–25%, protease activity by 12–22%, cellulase activity by 5–17%, urease activity by 12–41%, catalase activity by 9–16%, and phosphatase activity by 14–22%, thereby improving soil fertility. Notably, the W2F1 treatment demonstrates that a moderate reduction in irrigation can effectively mitigate the decline in soil enzyme activity and fertility that may result from reduced irrigation levels.

3.3. Effects of Limited Irrigation and Straw Mulching on Water Use Efficiency and Effective Accumulated Temperature of Maize

After correcting the automatic monitoring data for soil moisture, the absolute error was reduced to less than 5%, meeting the required measurement standards. Based on these corrected data, the effects of limited irrigation and straw mulching on water use efficiency (WUE) and the effective accumulated temperature of maize were investigated. The findings indicated that reducing irrigation did not significantly influence the soil temperature, whereas straw mulching notably increased the soil temperature and provided heat insulation (Figure 7A). Compared with the non-mulching treatment (F2), applying $9000 \text{ kg} \cdot \text{ha}^{-1}$ of straw in treatment F1 significantly increased the soil temperature, raising

the effective accumulated temperature by 10.11 to 85.79 °C during the growth period. Moreover, straw mulching did not have a significant impact on the soil water content, while reduced irrigation significantly lowered the soil water content (Figure 7B).

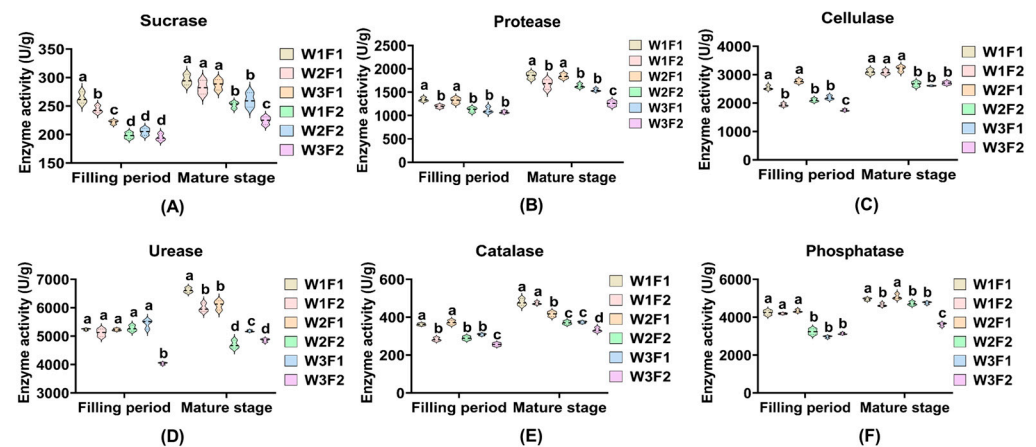


Figure 6. Enzyme activity analysis of sucrose (A), protease (B), cellulase (C), urease (D), catalase (E), and phosphatase (F) in different treatment groups at the filling stage and mature stage. Other letters in the exact figure represent significant differences at the 0.05 level.

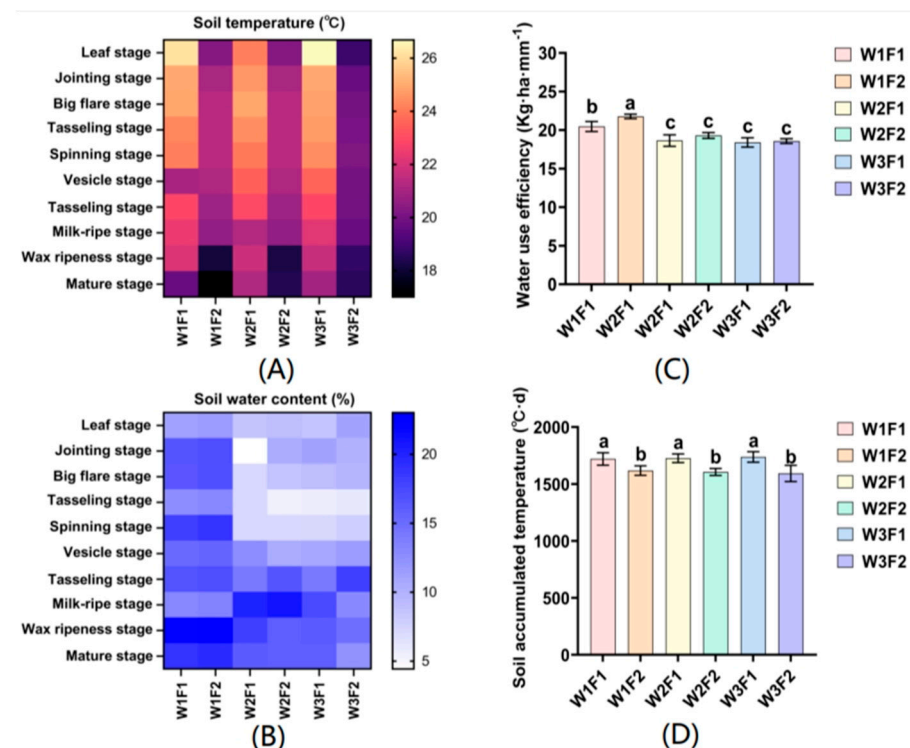


Figure 7. Effects of reduced irrigation and straw mulching on soil temperature (A), soil water content (B), water use efficiency (C), and maize effective accumulated temperature (D). Soil temperature and humidity measurements are based on soil conditions of soil layers 0–10 cm. Different letters in the exact figure represent significant differences at the 0.05 level.

Analysis of WUE showed the average values for each treatment group as follows: 20.51 kg · ha⁻¹ · mm⁻¹, 21.52 kg · ha⁻¹ · mm⁻¹, 18.92 kg · ha⁻¹ · mm⁻¹, 19.31 kg · ha⁻¹ · mm⁻¹, 18.81 kg · ha⁻¹ · mm⁻¹, and 18.73 kg · ha⁻¹ · mm⁻¹. There was no significant difference in WUE among the W1F1, W1F2, and W2F1 groups, but the WUE of the W2F2, W3F1, and W3F2 groups was significantly lower compared to that of the W1F1, W1F2, and W2F1

groups (Figure 7C). Additionally, the application of 5 cm straw mulching has a thermal insulation effect. The soil temperature increased by 0.68~1.53 °C during the maize growth period compared with the uncovered treatment (Figure 7D).

Significant analysis revealed that the amount of irrigation substantially affected irrigation water use efficiency ($p < 0.05$). Reducing the irrigation volume significantly improved the irrigation water use efficiency. The W2F1 treatment exhibited the highest irrigation water use efficiency at $21.52 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$. The lowest water use efficiency of W3F2 treatment was $18.73 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$. Compared with W1F1, W3F1, W1F2, W2F2, and W3F2, the water use efficiency of the W2F1 treatment increased by 4.69%, 12.08%, 10.27%, 12.59%, and 12.96%, respectively.

In conclusion, the W2F1 treatment ($2850 \text{ m}^{-3} \cdot \text{ha}^{-1}$ irrigation and $9000 \text{ kg} \cdot \text{ha}^{-1}$ straw mulching) was found to enhance the water use efficiency of maize. Furthermore, the accumulated temperature in the W2F1 treatment was the highest, being 2.17%, 3.05%, 13.66%, 15.27%, and 16.74% higher than that in W1F1, W3F1, W1F2, W2F2, and W3F2, respectively. The increased water use efficiency and accumulated temperature positively influenced maize growth. Enhancing water use efficiency can improve maize drought resistance, yield, and quality while reducing production costs. Increased accumulated temperature can accelerate maize growth and development, enhance nutrient absorption and metabolism, and improve yield and quality. Therefore, in maize production, it is crucial to focus on improving the management of water use efficiency and accumulated temperature to promote healthy growth and yield.

3.4. Effect of Limited Irrigation and Straw Mulching on Maize Yield

This study investigated the impacts of reduced irrigation and straw mulching on key yield components of maize, including the total yield, grain number, effective ear number, and 1000-grain weight. The findings revealed that the yield, grain number, effective ear number, and 1000-grain weight in the W2F1 treatment group did not differ significantly from those in the W1F1 group, yet they were markedly different from those of other four treatment groups ($p < 0.05$). Specifically, the W2F1 group exhibited 59.71×10^3 ears per hectare and 538.12 grains per ear, while the W1F1 group had the highest 1000-grain weight at 247.48 g. Additionally, the yields of W1F2, W2F1, W2F2, W3F1, and W3F2 were significantly lower than W1F1 by 9.6%, 0.6%, 9.8%, 28.7%, and 34.1%, respectively. The hierarchy of maize yields under various irrigation and mulching treatments was W1F1 > W2F1 > W1F2 > W2F2 > W3F1 > W3F2. The results indicated that straw mulching significantly enhances yield under full irrigation (W1: $3300 \text{ m}^3 \cdot \text{ha}^{-1}$). The yield and yield components of maize under different treatments are shown in Table 2. The effect of the irrigation amount on the maize yield, ear number, and 1000-grain weight was highly significant ($p < 0.01$). With the decrease in the irrigation amount, the necessary water required by maize decreased, and the yield, ear number, and 1000-grain weight of maize also reduced. There was no significant difference in grain number among treatments. The effect of straw mulching on maize yield and 1000-grain weight was also substantial ($p < 0.01$), the number of maize ears was significant ($p < 0.05$), and the number of grains per ear was substantial. In general, the effect of irrigation combined with straw mulching on maize yield was highly significant ($p < 0.01$), as it was 10 % higher than that of uncovered straw treatment. Furthermore, a moderate reduction in irrigation (W2: $2850 \text{ m}^3 \cdot \text{ha}^{-1}$) combined with straw mulching only marginally decreased the yield by 0.6%, achieving $6602.38 \text{ kg} \cdot \text{ha}^{-1}$. This approach does not negatively impact farmers' production income. Improving water use efficiency in this manner ensures that each unit of water consumption yields higher returns in agricultural production, industrial water use, and residential life. Consequently, this reduces the demand for groundwater extraction, thereby mitigating the pressures of groundwater overexploitation [16–18].

Table 2. Maize yield under different irrigation and straw treatments.

Treatment	Yield/(kg·ha ⁻¹)	Number of Panicles/(10 ³ ·ha ⁻¹)	Grain Number	Thousand Seed Weight/g
W1F1	6642.54 ± 57.12 a	59.12 ± 0.43 a	534.12 ± 9.12 a	247.48 ± 2.91 a
W1F2	6018.54 ± 98.14 b	57.09 ± 1.28 b	541.66 ± 4.61 a	229.97 ± 4.87 b
W2F1	6602.38 ± 96.87 a	59.71 ± 0.91 a	538.12 ± 6.05 a	241.74 ± 4.28 a
W2F2	5987.88 ± 89.64 b	55.67 ± 1.56 b	540.88 ± 8.95 a	233.88 ± 1.91 b
W3F1	4728.54 ± 71.29 c	53.28 ± 0.85 c	538.91 ± 7.91 a	193.74 ± 2.11 c
W3F2	4321.71 ± 62.19 d	54.12 ± 2.01 c	529.24 ± 1.98 b	177.51 ± 1.86 d
ANOVA				
Irrigation W	**	**	NS	**
Mulching F	**	*	NS	**
Irrigation × Mulching W × F	**	*	NS	*

Irrigation level: W1 was 3300 m³ · ha⁻¹, W2 was 2850 m³ · ha⁻¹, W3 was 2400 m³ · ha⁻¹; the straw mulching level F1 was (9000 kg · ha⁻¹); f2 was (0 kg · ha⁻¹). Different letters in the figure indicate significant differences between different treatments at $p < 0.05$. * and ** mean significant variable effect at the 0.05 and 0.01 probability levels, respectively. NS means no significant effect.

3.5. Effects of Reducing Irrigation and Straw Mulching on Grain Quality of Maize

The results indicate that the W2F1 treatment effectively reduced the irrigation demand while maintaining yield, demonstrating the water-saving benefits of straw mulching. Nutritional quality analysis revealed no significant differences in crude protein content among the W1F1, W1F2, W2F1, W2F2, and W3F1 groups. However, the W3F2 treatment group exhibited a significantly lower crude protein content compared to the other groups ($p < 0.05$), with a 9% reduction relative to W1F1 (Figure 8A). In terms of fat content, there were no significant differences among the W1F1, W1F2, and W2F1 treatment groups. Conversely, the W2F2, W3F1, and W3F2 groups showed reductions of 16.1%, 16.0%, and 16.2%, respectively, compared to W1F1. For cellulose content, no significant difference was observed between the W1F1 and W1F2 groups (Figure 8B). However, the W2F1, W2F2, W3F1, and W3F2 groups displayed significantly lower cellulose content than W1F1 ($p < 0.05$), with reductions of 17.1%, 36.1%, 37.4%, and 36.7%, respectively (Figure 8C). The analyses of ash content and nitrogen-free extract did not exhibit a similar trend (Figure 8D,E). These findings suggest that the W2F1 treatment (irrigation amount 2850 m³ · ha⁻¹ and straw mulching 9000 kg · ha⁻¹) effectively preserves essential maize nutrients. This underscores the viability and sustainability of W2F1 as a cost-effective agronomic practice for conserving moisture and maintaining maize quality.

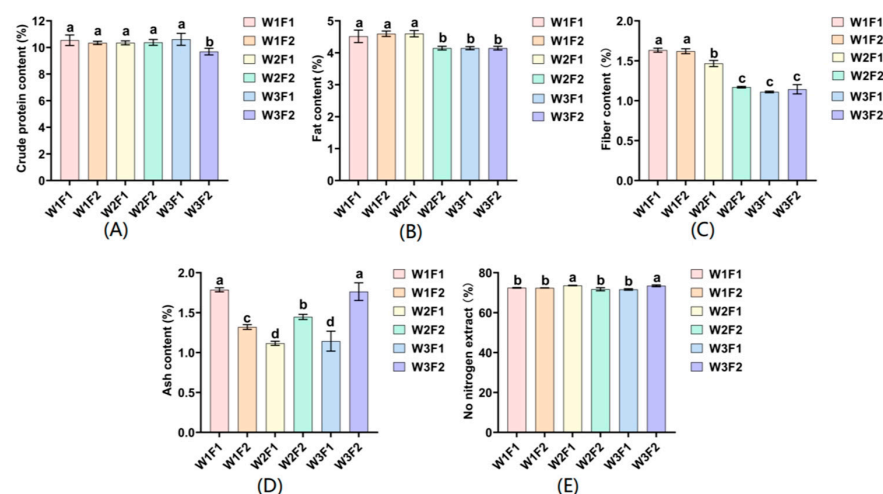


Figure 8. The nutritional components of maize in six treatment groups, including crude protein (A), fat (B), fiber (C), ash (D), and nitrogen-free extract (E). Different letters in the figure represent significant differences at the 0.05 level.

3.6. Comprehensive Evaluation of Maize Yield, Quality, Water Use Efficiency, and Soil Enzyme Activity under Different Treatments

Under varying water and fertilizer treatments, maize yield, quality, water use efficiency, and soil enzyme activity were employed as evaluation indices. A comprehensive evaluation method was utilized to assess each treatment. Initially, the weight of each evaluation index was determined using the coefficient of variation method for objective weighting. Yield was assigned the highest weight at 0.371, followed by water use efficiency at 0.288 and quality at 0.232, and soil enzyme activity had the smallest weight at 0.109. In the subsequent step, each index was scored separately to normalize the influence of different dimensions, and the corresponding membership degrees were calculated. Finally, the membership degree of each index was multiplied by its respective weight to compute the comprehensive score. A higher comprehensive score (Cs) indicates a more favorable treatment. The results, as presented in Table 3, demonstrate that the W2F1 treatment achieved the highest comprehensive score of 0.971, indicating that it was the most effective treatment.

Table 3. A comprehensive score of maize under different treatments based on the comprehensive score method.

Treatment	Membership				Comprehensive Score Cs	Rank
	Yield	Quality	WUE	Soil Enzyme Activity		
W1F1	0.92	0.96	0.89	0.95	0.952	2
W1F2	0.89	0.94	0.87	0.93	0.932	3
W2F1	0.98	0.96	0.98	0.96	0.971	1
W2F2	0.78	0.68	0.62	0.71	0.696	4
W3F1	0.62	0.59	0.48	0.50	0.542	5
W3F2	0.55	0.29	0.47	0.35	0.389	6

3.7. The Interaction between Irrigation and Straw Mulching

Through an analysis of the variance of the interaction between irrigation and straw mulching, the results showed that the effect of straw mulching on yield was more significant under irrigation conditions ($p < 0.01$), up to $6642.54 \text{ kg} \cdot \text{ha}^{-1}$, but the yield of straw mulching was $6602.38 \text{ kg} \cdot \text{ha}^{-1}$ under the condition of reduced irrigation, with a decrease of only 0.6%. As a result, irrigation helps to improve the quality characteristics of maize (such as increasing protein content), while straw mulching may have a positive effect on some specific quality indicators (such as increasing vitamin content). In general, straw mulching and irrigation also lead to significant differences in maize quality ($p < 0.05$). Straw mulching further improved water use efficiency under irrigation conditions by reducing soil water evaporation. The WUE of W2F1 treatment with an irrigation amount of $2850 \text{ m}^3 \cdot \text{ha}^{-1}$ and straw mulching treatment with an irrigation amount of $9000 \text{ kg} \cdot \text{ha}^{-1}$ combined with the mulching treatment group was up to $21.52 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$, which was significantly higher than that of the single irrigation or no mulching treatment group ($p < 0.01$). This shows that the treatment combination has the best performance with regard to effectively utilizing water resources and improving crop yield and quality, and that it is an effective strategy for sustainable agricultural production. Irrigation did not significantly improve the overall enzyme activity of maize, while straw mulching treatment significantly increased it by 10% compared with unmulched straw treatment. With straw mulching ($p < 0.05$), the activities of soil enzymes in the mature period were higher than those in the filling period. Straw mulching can promote the improvement of soil enzyme activity, which plays an important role in the soil nutrient cycle and organic matter decomposition. Irrigation provides a suitable water environment for soil microorganisms, while straw mulching provides a rich carbon source for microorganisms, and a combination of the two promotes the enhancement of soil enzyme activity, Table 4. Mulching corn straw under the condition of reduced irrigation water exhibits a synergistic effect between the two. Compared with other treatments, it has a significant impact on yield, quality, water use

efficiency, and soil enzyme activity. Given the problem of groundwater overexploitation in the Western Ordos region, this scheme is an effective strategy for sustainable agricultural production. In particular, the irrigation amount of W2F1 is $2850 \text{ m}^3 \cdot \text{ha}^{-1}$ and the straw mulch amounts to $9000 \text{ kg} \cdot \text{ha}^{-1}$, which provides a valuable reference and solution for sustainable agricultural production in Western Ordos.

Table 4. The interaction between irrigation and straw.

Treatment	Membership			
	Yield	Quality	WUE	Soil Enzyme Activity
Irrigation	**	**	*	NS
Mulching	*	*	**	**
Irrigation $\times$ Mulching	**	*	**	*

* and ** mean significant variable effect at the 0.05 and 0.01 probability levels, respectively. NS means no significant effect.

4. Discussion

4.1. Effects of Different Irrigation Amounts on the Growth and Development Indexes of Maize under Maize Straw Mulching

The Huang-Huai-Hai Plain, a critical region for summer maize production in China, is encountering an escalating water resource scarcity, with drought occurrences becoming increasingly frequent. Consequently, enhancing water use efficiency (WUE) and adopting effective irrigation practices are crucial for sustaining high yields of summer maize. Research indicates that moderate irrigation is more beneficial than full irrigation within the framework of ecological agriculture. Furthermore, optimizing tillage practices and employing plastic film mulching techniques can elevate soil temperature and moisture levels, thereby enhancing the absorption and utilization of water and nutrients [37,38], as described by Shen et al. [17]. The impact of various straw mulching quantities on water usage and dry matter accumulation in summer maize was investigated through field experiments. The findings indicated that water consumption was significantly higher in all straw mulching treatments compared to the control (CK). Moreover, an increase in the amount of mulch corresponded with greater water consumption. In arid and semi-arid regions, under ridge film furrow sowing conditions, a straw mulching amount of $7500 \text{ kg} \cdot \text{ha}^{-1}$ was identified as optimal. Zheng et al. [18] studied the effects of different irrigation and mulching conditions on maize yield and water use. The results showed that soil water consumption decreased with increased irrigation water, and mulching could reduce soil water consumption. Fu et al. [21] found that the more extensive the straw mulching, the more beneficial to improve the dry matter accumulation of summer maize within a specific lower limit of water, the more extensive the straw coverage, the more conducive it was to improving the dry matter accumulation of summer maize. Under consistent straw coverage, the accumulation of dry matter in summer maize increased with higher moisture levels at the lower limit. When the moisture lower limit remained constant, straw coverage of $7500 \text{ kg} \cdot \text{ha}^{-1}$ resulted in the greatest dry matter accumulation in summer maize. Previous research has predominantly examined the impacts of irrigation and maize straw on maize growth [39]. Despite extensive research on maize yield stability, few studies have addressed the challenge of maintaining yield while reducing irrigation. This study investigates the impact of moderate irrigation reduction combined with straw mulching on the growth of summer maize. Building upon previous research, this study enhances our understanding of the synergistic effects of straw mulching and reduced irrigation. By examining and comparing various irrigation and straw mulching treatments, we demonstrate that a moderate reduction in irrigation, when coupled with straw mulching, can effectively mitigate potential adverse effects without significantly impeding maize growth and development. This finding, underexplored in earlier research, introduces a novel sustainable farming method. Moreover, this study underscores the multifaceted benefits of straw mulching, such as

reduced water evaporation, regulated soil temperature, and increased soil organic matter, which are crucial under drought conditions. Previous studies have not fully examined the interaction between straw mulching and irrigation to determine the optimal strategy. Our experimental results highlight the advantages of combining straw mulching with moderate irrigation reduction, offering a more environmentally friendly, innovative, and sustainable approach to agricultural production. By supplementing and exploring the integration of straw mulching and reduced irrigation, this study provides new insights and solutions for maintaining the healthy growth and stable yield of summer maize under reduced irrigation. Our findings not only enhance the efficiency of water resource utilization but also promote sustainable agricultural development, significantly alleviating water resource pressure.

4.2. Effects of Different Irrigation Amounts on Soil Enzyme Activity in the Critical Period of Maize Straw Mulching

Soil enzymes play a crucial role in catalyzing material cycles and biochemical reactions within soil. Their activity is indispensable for the transformation of nutrients in soil and the subsequent uptake of these nutrients by plants [11]. Currently, soil enzyme activity serves as a pivotal indicator for assessing soil microbial characteristics. Researchers have extensively explored the impacts of different enzymes on the incorporation of straw into soil. These enzymes include sucrase, urease, cellulase, phosphatase, and oxidoreductases such as catalase [40–44]. Numerous studies have demonstrated that incorporating straw into soil can stimulate microbial communities, enhance enzymatic secretion, and facilitate microbial proliferation. Farmlands treated with straw typically exhibit elevated soil enzyme activity compared to control plots lacking straw application [45,46]. Jin Yuting et al. researched paddy soil in Anhui Province, revealing that the activities of urease, phosphatase, and cellulase markedly increased following the incorporation of straw. Similarly, Ni et al. demonstrated a significant enhancement in soil enzyme activities after straw incorporation. Specifically, invertase, urease, catalase, and cellulase activities increased by 36.40%, 58.57%, 27.53%, and 98.22%, respectively, compared to the control group that did not receive straw incorporation [44,45]. Some studies have indicated that the incorporation of straw could lead to varying effects on the activity levels of different enzymes [46,47]. In the black soil of the Huaihe River Basin, the addition of straw resulted in heightened activities of glucosidase, lignin peroxidase, and manganese peroxidase. Conversely, the introduction of nitrogen fertilizer caused a decrease in phenol peroxidase activity [48–50]. These findings indicate that incorporating straw can significantly influence soil enzyme activity. Our study reinforces this assertion by demonstrating that straw treatment enhances the activities of protease, cellulase, and phosphatase in soil under reduced irrigation conditions, aligning with prior research outcomes. These results underscore the pivotal role of straw as a soil carbon substrate: integrating straw enriches the soil's carbon content, fostering microbial activity and thereby facilitating the uptake of essential nutrients like nitrogen and phosphorus. Moreover, optimizing the balance of chemical fertilizers can further boost microbial vitality and augment the synergistic interaction between straw and soil.

4.3. Effects of Different Irrigation Amount on Grain Yield and Quality of Maize under Maize Straw Mulching

Guo et al. [19] studied the effects of different water supplements on maize yield under mulching conditions. The findings indicated that maintaining soil water content between 75% and 80% of field capacity (FC) significantly enhanced crop yield. In this investigation, with consistent straw mulching levels, the yield, water use efficiency (WUE), and phosphorus use efficiency (PUE) of summer maize peaked at 70% FC, averaging 6602.07 kg · ha⁻¹, 1.98 kg · m⁻³, and 5.23 kg · m⁻³, respectively. Conversely, under identical moisture regimes, maximum yield, WUE, and PUE were achieved in summer maize at a straw mulching rate of 4500 kg · ha⁻¹, averaging 6257.69 kg · ha⁻¹, 1.97 kg · m⁻³, and 5.05 kg · m⁻³, respectively. Fu et al. [21] showed that the yield (6922.54 kg · ha⁻¹), WUE (2.09 kg · m⁻³), and PUE (5.48 kg · m⁻³) of summer maize were the highest when the lower limit of water control was 70% FC treatment. The straw mulching amount was

4500 kg · ha⁻¹, and the water consumption coefficient per unit maize yield was the smallest, significantly improving economic benefits. This provides a reference and technical support for formulating the coupling application scheme of straw mulching measures and water-saving irrigation in the high-yield and high-efficiency ridge planting mode in Northwest China and North China. Based on the results of this study, we found that reducing irrigation combined with straw mulching (as shown in the W2F1 treatment group) did not harm the maize yield or nutritional quality. This tillage method not only effectively prevents the decline in yield but also ensures the quality of maize and significantly reduces irrigation water use [51–53]. With the increasing shortage of global water resources, reduced irrigation has become an important strategy for promoting sustainable agricultural development. Measures aimed at reducing the use of irrigation water not only benefit the growth of crops but also reduce dependence on precious water resources, promoting sustainable agriculture development. In addition, as a multifunctional soil protection method, straw mulching can reduce water evaporation and effectively prevent soil erosion [42]. Straw forms a protective barrier on the soil's surface, which can resist weathering, improve the internal structure of the soil, and increase its organic matter content, thereby enhancing soil fertility and water retention performance [9,54]. At the same time, the use of reduced irrigation combined with straw mulching can also significantly improve the resistance of crops to drought and other environmental pressures [55]. Straw mulching can slow down the evaporation rate of soil moisture, maintain appropriate soil moisture, and create a stable growth environment for crops [56]. The adoption of reduced irrigation coupled with straw mulching enhances crops' resilience against drought and other natural adversities. Notably, this approach not only boosts agricultural productivity but also yields significant economic advantages. Reduced irrigation decreases production costs by conserving water, while straw mulching reduces expenses related to weed management and enhances soil fertility. These combined factors synergistically improve crop yields and quality, thereby fostering sustainable agricultural development.

5. Conclusions

The impact of restricted irrigation and straw mulching on maize growth, enzyme activity, water use efficiency, yield, and quality was investigated using correlation and comprehensive scoring methods. The findings indicated that the combination of W2 irrigation (2850 m³ · ha⁻¹) with F1 straw mulch (9000 kg · ha⁻¹) exerted minimal inhibitory effects on corn growth, with higher soil enzyme activity observed during the filling and mature stages. Moreover, the W2F1 treatment significantly enhanced soil enzyme activity and facilitated nutrient absorption by maize. In comparison to traditional irrigation methods, the W2F1 treatment showed the least reduction in corn yield, with negligible changes in crude protein, fat, and cellulose contents, suggesting its efficacy in sustaining both yield and quality. According to the comprehensive scoring method, the W2F1 treatment achieved the highest comprehensive score (0.971). Therefore, adopting the W2F1 treatment, involving 2850 m³ · ha⁻¹ of irrigation water and 9000 kg · ha⁻¹ of straw mulch is recommended for the Ordos region. This approach conserves water resources while enhancing water use efficiency and maize yield quality, offering valuable insights for local agricultural practices.

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References

- Mishra, B.K.; Kumar, P.; Saraswat, C.; Chakraborty, S.; Gautam, A. Water security in a changing environment: Concept, challenges and solutions. *Water* **2021**, *13*, 490. [\[CrossRef\]](#)
- Salehi, M. Global water shortage and potable water safety; today's concern and tomorrow's crisis. *Environ. Int.* **2022**, *158*, 106936. [\[CrossRef\]](#) [\[PubMed\]](#)
- Wang, S.; Hu, Y.; Yuan, R.; Feng, W.; Pan, Y.; Yang, Y. Ensuring water security, food security, and clean water in the north China plain—Conflicting strategies. *Curr. Opin. Environ. Sustain.* **2019**, *40*, 63–71. [\[CrossRef\]](#)
- Shu, G.; Cao, G.; Li, N.; Wang, A.; Wei, F.; Li, T.; Yi, L.; Xu, Y.; Wang, Y. Genetic variation and population structure in China summer maize germplasm. *Sci. Rep.* **2021**, *11*, 8012. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tuan, N.T.; Qiu, J.J.; Verdoodt, A.; Li, H.; Van Ranst, E. Temperature and precipitation suitability evaluation for the winter wheat and summer maize cropping system in the Huang-Huai-Hai plain of China. *Agric. Sci. China* **2011**, *10*, 275–288. [\[CrossRef\]](#)
- Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant acidification in major Chinese croplands. *Science* **2010**, *327*, 1008–1010. [\[CrossRef\]](#) [\[PubMed\]](#)
- Eekhout, J.P.C.; Hunink, J.E.; Terink, W.; de Vente, J. Why increased extreme precipitation under climate change negatively affects water security. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 5935–5946. [\[CrossRef\]](#)
- Yu, C.; Huang, X.; Chen, H.; Godfray, H.C.J.; Wright, J.S.; Hall, J.W.; Gong, P.; Ni, S.; Qiao, S.; Huang, G.; et al. Managing nitrogen to restore water quality in China. *Nature* **2019**, *567*, 516–520. [\[CrossRef\]](#)
- Hou, P.; Jiang, Y.; Yan, L.; Petropoulos, E.; Wang, J.; Xue, L.; Yang, L.; Chen, D. Effect of fertilization on nitrogen losses through surface runoffs in Chinese farmlands: A meta-analysis. *Sci. Total Environ.* **2021**, *793*, 148554. [\[CrossRef\]](#)
- Zhang, H. Production and quality of the sugar beet (*Beta vulgaris* L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. *Agric. Water Manag.* **2003**, *62*, 215–227.
- Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [\[CrossRef\]](#)
- Comas, L.H.; Trout, T.J.; DeJonge, K.C.; Zhang, H.; Gleason, S.M. Water productivity under strategic growth stage-based deficit irrigation in maize. *Agric. Water Manag.* **2019**, *212*, 433–440. [\[CrossRef\]](#)
- Wudil, A.H.; Ali, A.; Raza, H.A.; Hameed, M.U.; Jellason, N.P.; Ogbaga, C.C.; Singh, K.; Çiğ, F.; El Sabagh, A. Sustainable Solutions to Food Insecurity in Nigeria: Perspectives on Irrigation, Crop-Water Productivity, and Antecedents. In *Global Agricultural Production: Resilience to Climate Change*; Ahmed, M., Ed.; Springer: Cham, Switzerland, 2022.
- Ullah, H.; Santiago-Arenas, R.; Ferdous, Z.; Attia, A.; Datta, A. Chapter two—Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2019; pp. 109–157.
- Jovanovic, N.; Pereira, L.S.; Paredes, P.; Pôças, I.; Cantore, V.; Todorovic, M. A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods. *Agric. Water Manag.* **2020**, *239*, 106267. [\[CrossRef\]](#)
- Peng, Y.; Xiao, Y.; Fu, Z.; Dong, Y.; Zheng, Y.; Yan, H.; Li, X. Precision irrigation perspectives on the sustainable water-saving of field crop production in China: Water demand prediction irrigation scheme optimization. *J. Clean. Product.* **2019**, *230*, 365–377. [\[CrossRef\]](#)
- Shen, X.; Qiu, C. Research on the Mechanism of Corn Price Formation in China Based on the PLS-SEM Model. *Foods* **2024**, *13*, 875. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhao, Y.; Zhao, B.; Xie, Y.; Jia, H.; Li, Y.; Xu, M.; Wu, G.; Ma, X.; Li, Q.; Hou, M.; et al. The evening complex promotes maize flowering and adaptation to temperate regions. *Plant Cell* **2023**, *35*, 369–389. [\[CrossRef\]](#) [\[PubMed\]](#)
- Guo, Z.; Shi, Y.; Yu, Z.; Zhang, Y. Supplemental irrigation affected flag leaves senescence post-anthesis and grain yield of winter wheat in the Huang-Huai-Hai plain of China. *Field Crops Res.* **2015**, *180*, 100–109. [\[CrossRef\]](#)
- Liu, S.; Lin, X.; Wang, W.; Zhang, B.; Wang, D. Supplemental irrigation increases grain yield, water productivity, and nitrogen utilization efficiency by improving nitrogen nutrition status in winter wheat. *Agric. Water Manag.* **2022**, *264*, 107505. [\[CrossRef\]](#)

21. Fu, Y.; Xiao, W.; Tian, L.; Guo, L.; Ma, G.; Ji, C.; Huang, Y.; Wang, H.; Wu, X.; Yang, T.; et al. Spatial transcriptomics uncover sucrose post-phloem transport during maize kernel development. *Nat. Commun.* **2023**, *14*, 7191. [\[CrossRef\]](#)
22. Srivastava, R.K.; Panda, R.K.; Chakraborty, A. Quantification of nitrogen transformation and leaching response to agronomic management for maize crop under rainfed and irrigated condition. *Environ. Pollut.* **2020**, *265*, 114866. [\[CrossRef\]](#)
23. Yi, J.; Li, H.; Zhao, Y.; Zhang, H.; Liu, M. Assessing soil water balance to optimize irrigation schedules of flood-irrigated maize fields with different cultivation histories in the arid region. *Agric. Water Manag.* **2022**, *265*, 107543. [\[CrossRef\]](#)
24. Ejaz, M.K.; Aurangzaib, M.; Iqbal, R.; Shahzaman, M.; Habib-ur-Rahman, M.; El-Sharnouby, M.; Datta, R.; Alzuaibr, F.M.; Sakran, M.I.; Ogbaga, C.C.; et al. The Use of Soil Conditioners to Ensure a Sustainable Wheat Yield under Water Deficit Conditions by Enhancing the Physiological and Antioxidant Potentials. *Land* **2022**, *11*, 368. [\[CrossRef\]](#)
25. Shui, W.J.; Li, G.S.; Hui, D.T. Mechanisms in the accumulation and movement of mineral N in soil profiles of farming land in a semi-arid region. *Acta Ecol. Sin.* **2003**, *23*, 2040–2049.
26. Yang, Y.; Wu, J.; Du, Y.L.; Gao, C.; Pan, X.; Tang, D.W.S.; Ploeg, M.V.D. Short- and Long-Term Straw Mulching and Subsoiling Affect Soil Water, Photosynthesis, and Water Use of Wheat and Maize. *Front. Agron.* **2021**, *3*, 708075. [\[CrossRef\]](#)
27. Qiao, Y.; Tie, J.; Wang, X.; Wei, B.; Zhang, W.; Liu, Z.; Zhang, G.; Lyu, J.; Liao, W.; Hu, L.; et al. Comprehensive evaluation on effect of planting and breeding waste composts on the yield, nutrient utilization, and soil environment of baby cabbage. *J. Environ. Manag.* **2023**, *341*, 117941. [\[CrossRef\]](#)
28. Peng, Z.; Fu, C. Effects of Straw Mulching Plus Nitrogen Fertilizer on Nitrogen Efficiency and Grain Yield in Winter Wheat. *Acta Agron. Sin.* **2008**, *34*, 1014–1018.
29. Kong-Cao, X.; Dao-You, H.; Shou-Long, L.; Han-Hua, Z. Response of Spatial and Temporal Variation of Upland Soil Moisture to Rice Straw Mulching in Different Cropping Rotation Systems. *J. Soil Water Conserv.* **2009**, *34*, e02013.
30. Lal, R. Mulching effects on soil physical quality of an alfisol in western Nigeria. *Land Degrad. Dev.* **2000**, *11*, 383–392. [\[CrossRef\]](#)
31. Govaerts, B.; Sayre, K.D.; Lichter, K.; Dendooven, L.; Deckers, J. Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. *Plant Soil* **2007**, *291*, 39–54. [\[CrossRef\]](#)
32. Xiangqian, Z.; Guoqin, H.; Xinmin, B.; Qiguo, Z. Effects of nitrogen fertilization and root interaction on the agronomic traits of intercropped maize, and the quantity of microorganisms and activity of enzymes in the rhizosphere. *Plant Soil* **2013**, *368*, 407–417.
33. DB15/T 385-2020; Local Standard of Inner Mongolia Autonomous Region (Industrial Water Quota). Market Supervision and Administration of Inner Mongolia Autonomous Region: Inner Mongolia Autonomous Region, China, 2020.
34. Liu, T.; Gu, L.; Dong, S.; Zhang, J.; Liu, P.; Zhao, B. Optimum leaf removal increases canopy apparent photosynthesis, ¹³C-photosynthate distribution and grain yield of maize crops grown at high density. *Field Crops Res.* **2015**, *170*, 32–39. [\[CrossRef\]](#)
35. Thomas, R.L.; Sheard, R.W.; Moyer, J.R. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agron. J.* **1967**, *59*, 240–243. [\[CrossRef\]](#)
36. GB5009-2016; National Food Safety Standards. Standards Press of China: Beijing, China, 2016.
37. Chen, L.; Chang, J.; Wang, Y.; Guo, A.; Liu, Y.; Wang, Q.; Zhu, Y.; Zhang, Y.; Xie, Z. Disclosing the future food security risk of China based on crop production and water scarcity under diverse socioeconomic and climate scenarios. *Sci. Total Environ.* **2021**, *790*, 148110. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Zhang, H. *Improving Water Productivity through Deficit Irrigation: Examples from Syria, the North China Plain and Oregon*; International Water Management Institute: Boston, MA, USA, 2003; pp. 301–309.
39. Tavakkoli, A.R.; Oweis, T.Y. The role of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. *Agric. Water Manag.* **2004**, *65*, 225–236. [\[CrossRef\]](#)
40. Lu, J.; Hu, T.; Geng, C.; Cui, X.; Fan, J.; Zhang, F. Response of yield, yield components and water-nitrogen use efficiency of winter wheat to different drip fertigation regimes in Northwest China. *Agric. Water Manag.* **2021**, *255*, 107034. [\[CrossRef\]](#)
41. Lyu, X.; Wang, T.; Song, X.; Zhao, C.; Rees, R.M.; Liu, Z.; Xiaotang, J.; Siddique, K.H.M. Reducing N₂O emissions with enhanced efficiency nitrogen fertilizers (EENFs) in a high-yielding spring maize system. *Environ. Pollut.* **2021**, *273*, 116422. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Mansouri-Far, C.; Sanavy, S.A.M.M.; Saberali, S.F. Maize yield response to deficit irrigation during low-sensitive growth stages and nitrogen rate under semi-arid climatic conditions. *Agric. Water Manag.* **2010**, *97*, 12–22. [\[CrossRef\]](#)
43. Meng, Q.F.; Yue, S.C.; Hou, P.; Cui, Z.L.; Chen, X.P. Improving yield and nitrogen use efficiency simultaneously for maize and wheat in China: A review. *Pedosphere* **2016**, *26*, 137–147. [\[CrossRef\]](#)
44. Jin, Y.T.; Li, X.F.; Cai, Y.; Hu, H.X.; Liu, Y.F.; Fu, S.W.; Zhang, B.R. Effects of straw returning with chemical fertilizer on soil enzyme activities and microbial community structure in rice-rape rotation. *Environ. Sci.* **2021**, *42*, 3985–3996.
45. Ni, G.R.; Tu, G.Q.; Wei, S.J.; Wu, J.F.; Shi, Q.H.; Zhou, C.H.; Pan, X.H. Effects of combination of straw returning and a microbial agent on microorganisms and enzyme activity in rhizosphere soil and yield of late rice. *Meteorol. Environ. Res.* **2017**, *8*, 78–82.
46. Zhang, L.G.; Chen, X.; Xu, Y.J.; Jin, M.C.; Ye, X.X.; Gao, H.J.; Chu, W.Y.; Mao, J.D.; Thompson, M.L. Soil labile organic carbon fractions and soil enzyme activities after 10 years of continuous fertilization and wheat residue incorporation. *Sci. Rep.* **2020**, *10*, 11318. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Huang, W.; Wu, J.F.; Pan, X.H.; Tan, X.M.; Zeng, Y.J.; Shi, Q.H.; Liu, T.J.; Zeng, Y.H. Effects of long-term straw return on soil organic carbon fractions and enzyme activities in a double-cropped rice paddy in South China. *J. Integr. Agric.* **2021**, *20*, 236–247. [\[CrossRef\]](#)

48. Qian, H.Y.; Yang, B.J.; Huang, G.Q.; Yan, Y.P.; Fan, Z.W.; Fang, Y. Effects of returning rice straw to fields with fertilizers and microorganism liquids on soil enzyme activities and microorganisms in paddy fields. *Ecol. Environ. Sci.* **2012**, *21*, 440–445.
49. Navarro-Noya, Y.E.; Gómez-Acata, S.; Montoya-Ciriaco, N.; Rojas-Valdez, A.; Suárez-Arriaga, M.C.; Valenzuela-Encinas, C.; Jiménez-Bueno, N.; Verhulst, N.; Govaerts, B.; Dendooven, L. Relative impacts of tillage, residue management and crop-rotation on soil bacterial communities in a semi-arid agroecosystem. *Soil Biol. Biochem.* **2013**, *65*, 86–95. [[CrossRef](#)]
50. Wang, E.Z.; Lin, X.L.; Tian, L.; Wang, X.G.; Ji, L.; Jin, F.; Tian, C.J. Effects of short-term rice straw return on the soil microbial community. *Agriculture* **2021**, *11*, 561. [[CrossRef](#)]
51. Zheng, W.; Wan, Y.; Li, Y.; Liu, Z.; Chen, J.; Zhou, H.; Gao, Y.; Chen, B.; Zhang, M. Developing water and nitrogen budgets of a wheat-maize rotation system using auto-weighing lysimeters: Effects of blended application of controlled-release and un-coated urea. *Environ. Pollut.* **2020**, *263*, 114383. [[CrossRef](#)] [[PubMed](#)]
52. Zhang, F.; Cui, Z.; Chen, X.; Ju, X.; Shen, J.; Chen, Q.; Liu, X.; Zhang, W.; Mi, G.; Fan, M.; et al. Chapter one—Integrated nutrient management for food security and environmental quality in China. *Adv. Agron.* **2012**, *116*, 1–40.
53. Zhao, B.; Dong, S.; Zhang, J.; Liu, P. Effects of controlled-release fertilizer on yield and nitrogen accumulation and distribution in summer maize. *Acta Agronom. Sin.* **2010**, *10*, 301–304.
54. Grassini, P.; Yang, H.; Cassman, K.G. Limits to maize productivity in Western corn-belt: A simulation analysis for fully irrigated and rainfed conditions. *Agric. For. Meteorol.* **2009**, *149*, 1254–1265. [[CrossRef](#)]
55. Jia, Q.; Shi, H.; Li, R.; Miao, Q.; Feng, Y.; Wang, N.; Li, J. Evaporation of maize crop under mulch film and soil covered drip irrigation: Field assessment and modelling on West liaohe plain, China. *Agric. Water Manag.* **2021**, *253*, 106894. [[CrossRef](#)]
56. Li, Y.; Song, H.; Zhou, L.; Xu, Z.; Zhou, G. Vertical distributions of chlorophyll and nitrogen and their associations with photosynthesis under drought and rewetting regimes in a maize field. *Agric. For. Meteorol.* **2019**, *272–273*, 40–54. [[CrossRef](#)]

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