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INTEGRATED EFFECTS OF IRRIGATION METHOD, FERTILIZATION, AND TILLAGE ON GRAIN YIELD AND WATER PRODUCTIVITY OF WHEAT TRITICUM AESTIVUM L. UNDER ARID CONDITIONS OF IRAQ

(Interactions of irrigation method, fertilization, and tillage on bread wheat yield and water-use efficiency under field conditions in Iraq)

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Abstract:
A field study was conducted over two growing seasons (2022–2023 and 2023–2024) in an agricultural field in Asdira Al-Sufla area, Al-Shirqat District, northern Iraq, on bread wheat (Triticum aestivum L.). The experiment included three factors: The first factor was irrigation method at three levels (center pivot sprinkler irrigation, solid-set sprinkler irrigation, and surface irrigation). The

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second factor was fertilization at two levels (with fertilization and without fertilization). The third factor was tillage at two levels (conventional tillage and no-tillage). The experiment was arranged according to a Randomized Complete Block Design (RCBD) using a Split-Split Plot Design. Data were collected on grains yield and water productivity efficiency. The results were as follows: For total grain yield, center pivot irrigation significantly outperformed the other irrigation methods, producing 4528.68 kg/ha, whereas surface irrigation recorded the lowest yield (2933.32 kg/ha). The highest yield (5188 kg/ha) was obtained under the triple interaction (I1 × T1 × F1). In terms of water productivity, center pivot irrigation achieved the highest water productivity at 1.29 kg/m³, considerably exceeding surface irrigation, which recorded 0.31 kg/m³.

Keyword: Irrigation Systems, Fertilization, Tillage, Grain yield, water productivity.

1. Introduction

Water is a fundamental resource for life, but urban, agricultural, and industrial development have diversified and increased human water needs, while agricultural use remains loosely regulated in many regions (Ingrao et al., 2023). Although rich in resources, Iraq faces droughts and climate-change impacts that reduce the Tigris and Euphrates, making modern irrigation technologies essential to cut irrigation water use. Effective water management is crucial in semi-arid and arid areas, with rising demand for fresh water for agriculture and domestic use (Rizzi and Mollinga, 2024).

Irrigation success depends on suitability to local conditions, including climate, crop type, water availability, soil quality and texture, and economic factors. Sprinkler irrigation offers flexibility to control water application over time, with systems ranging from pivot to other configurations (Chauhdary et al., 2023).

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Fertilizer use generally promotes root and vegetative growth and yields, but excess application causes environmental problems such as water pollution, field gas emissions, and soil degradation. Repeated overuse can lead to nutrient deficiencies in soils. To sustain higher productivity, nutrients (P, N, K, and others) should be added in varying ratios according to soil quality, crop type, regional conditions, irrigation methods, and other factors (Krasilnikov et al., 2022; Pahalvi et al., 2021).

Wheat (Triticum aestivum L.) is globally vital for food security, supplying a primary food source for more than one-third of the world's population and used in bread, pastries, pasta, and other products (FAO, 2024).

Tillage is the mechanical soil preparation process to create a suitable seedbed and enhance production, influencing soil moisture and properties that affect yield at different depths (Ashraf et al., 2022). Deep and traditional tillage can improve porosity, moisture, aeration, and nitrate levels while reducing weeds and compaction; no-till farming preserves soil quality compared with deep or traditional tillage (Saleem et al., 2020; Basir et al., 2017).

The study aims to evaluate the performance of three irrigation systems and two levels of both fertilization and tillage to identify the combination that most effectively achieves the highest wheat yields and water productivity.

2. MATERIALS AND METHODS

2.1 The study Area: Experiments for this study were conducted in the 2022–2023 season on 120 dunams in Asdira Sofla, Al-Shirqat District, south of Nineveh Governorate, Iraq. The field is north of Salah al-Din Governorate, about 127 km north of Tikrit, along the Tigris River. Al-Shirqat District covers 685,789 dunams, with over 77% arable, and actual land use is 42% of the area. The study area has 111 center-pivot irrigation systems of varying sizes and over 900 fixed systems (Salah al-Din Agriculture Directorate Annual Report, 2024). Al-Shirqat is among

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the world's oldest agricultural regions and a center of the ancient Assyrian Empire.

2.2 Irrigation Systems and Components: The present study evaluated three irrigation methods: center-pivot sprinkler irrigation, fixed sprinkler irrigation, and seepage irrigation. Center-pivot irrigation was implemented using a center-pivot sprinkler with 60-dunam coverage, manufactured by Valley, Austria; fixed sprinkler irrigation was implemented using a locally manufactured system made from Turkish-origin raw materials; seepage irrigation was implemented using an Iranian-made EM 100-400 pump mounted on a Korean-made Daewoo engine.

2.3 The Crop Used and Agricultural Practices: The study was conducted on soft wheat (Triticum aestivum) of the Cihan variety, an introduced Turkish-origin cultivar purchased in 20-kg bags with high purity and germination. Seed treatment was applied to protect against fungal diseases. Sowing used a seed rate of 40 kg per dunam, in rows with a Turkish-made planter (Ozduman) model 2018, featuring a 3 m working width, 20 units, and two separate hoppers (one for seeds and one for fertilizer), Seeds were planted in rows with 15 cm row spacing.

2.4. Experiments

2.4.1. Experimental Design and Replication: The experimental field was arranged in a Randomized Complete Block Design (RCBD) and analyzed using a Split-Split Plot Design (SSPD) (Al-Zubaidi and Al-Jabouri, 2022). Main plots corresponded to irrigation methods, each main plot subdividing into two secondary plots for fertilization, with each secondary plot further split into sub-sub plots for tillage. Three factors were tested: (1) irrigation method with three levels (center-pivot, fixed sprinkler, seepage), (2) fertilization (with vs without fertilizer), and (3) tillage (with vs without tillage). The design comprises (3 × 2 × 2) × 3 replicates, resulting 36 treatments, each 30 meters in length.

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2.4.2 Stage of Seed Sowing and Germination Irrigation: In this stage, grains were sown in the field on 15/11/2022 at a rate of 40 kg per dunum, with rows spaced 15 cm apart. DAP fertilizer was applied in the fertilized treatments at a rate of 50 kg per dunum, followed by irrigation across the entire field to provide moisture for germination and to speed up germination and ensure a high germination rate. The number of irrigation events per treatment varied according to the irrigation method used, based on the crop's actual water requirements.

2.4.3 Stage of Growth Monitoring and Crop Maintenance: Growth monitoring began with regular visits and systematic tracking of growth stages (germination, booting, flowering, grain filling, and maturity) and the performance of crop maintenance operations such as pest control and additional fertilization. Growth indicators were recorded for each stage as needed indicators reflecting the plant's condition.

2.4.4 Stage of Crop Maturation and Harvest: In this stage, the final plant height was recorded, and samples were collected randomly using a sampling frame. The plants were then harvested and collected in bags and transported to the work area.

2.4.5 Field Indicators Studied: The grains yield and water productivity efficiency.

3.5 Statistical Analysis: Data for the studied traits were entered into a computer, organized and categorized in Microsoft Excel, and statistically analyzed using SAS (Version 9.4). Means of the main effects and their interactions were compared using Duncan's multiple range test at the 0.05 probability level to identify significant differences. Alphabetical letters were assigned to the means according to significance: means sharing the same letters are not significantly

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different, while means with different letters are significantly different (Al-Zubaidi and Al-Jabouri, 2022).

3 RESULTS AND DISCUSSION

3.1 Total Grain Yield (Kg/ha)

3.1.1 Effect of Irrigation Method, Fertilization and Tillage on Total Grain Yield (Kg/ha): The results presented in Table (1) demonstrate that irrigation method, fertilization, and tillage each had a significant effect on total grain yield (kg/ha). Among irrigation treatments, pivot irrigation (I_1) produced the highest yield (4528.68 kg/ha), followed by fixed irrigation (I_2) (3823.00 kg/ha), while flood irrigation (I_3) resulted in the lowest yield (2933.32 kg/ha). The superior performance of pivot irrigation is likely due to its ability to provide uniform and timely water application, reducing water stress and enhancing photosynthesis, assimilate partitioning, and overall crop growth (Farooq et al., 2012; Howell, 2001). These findings are consistent with earlier results in this study showing higher yield components—such as grain number per spike and 1000-grain weight—under pivot irrigation.

Fertilization had a pronounced positive impact on yield, with fertilized plots (F_1) producing significantly higher yields (4514.44 kg/ha) than unfertilized plots (F_2) (3008.88 kg/ha). This reflects the essential role of adequate nutrient availability, particularly nitrogen, in supporting vegetative growth, grain formation, and final yield accumulation (Fageria, 2014). The yield advantage associated with fertilization aligns with the observed increases in spike number, grain number, and grain weight reported in earlier tables, indicating a cumulative effect of improved nutrient supply on yield formation.

Similarly, tillage significantly increased total yield, with tilled plots (T_1) (3983.76 kg/ha) outperforming non-tilled plots (T_2) (3539.56 kg/ha). Tillage likely enhanced soil physical properties such as aeration, water infiltration, and root development, thereby improving nutrient and water uptake efficiency (Lal, 2004).

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The positive effect of tillage on yield corroborates its influence on plant height and yield components observed earlier in this study.

Overall, these results emphasize that total yield is the integrated outcome of improved water management, nutrient availability, and soil conditions. The consistency between yield and its contributing components supports the importance of adopting integrated irrigation, fertilization, and tillage practices to maximize crop productivity, particularly under semi-arid conditions similar to those of the study area.

Table (1): Effect of irrigation methods, fertilization and tillage on Total Grain Yield (kg/ha).

Treatments	Treatment levels	Total Grain Yield (kg/ ha)
Irrigation methods	I_1	4528.68[a]
	I_2	3823.00[b]
	I_3	2933.32[c]
Fertilization	F_1	4514.44[a]
	F_2	3008.88[b]
Tillage	T_1	3983.76[a]
	T_2	3539.56[b]

Means in columns having the same letter(s) are not significantly different at $P \leq 0.05$ according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization

3.1.2 Interaction between Irrigation Method and Fertilization and Tillage on Total Grain Yield (kg/ha): The interaction between irrigation methods and both fertilization and tillage had a significant influence on the achieved yield (kg/ha) (Table 2). Across all irrigation systems, fertilized treatments (F_1) consistently produced higher yields than unfertilized treatments (F_2), with the greatest yield recorded under pivot irrigation combined with fertilization ($I_1 \times F_1$) (5012.00 kg/ha). This highlights the strong dependence of yield formation on adequate

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nutrient supply when sufficient soil moisture is available, as efficient irrigation enhances nutrient uptake and utilization (Fageria, 2014).

Yield declined progressively from pivot (I_1) to fixed (I_2) and flood irrigation (I_3), regardless of fertilization status. The lowest yield was observed under flood irrigation without fertilization ($I_3 \times F_2$) (2116.00 kg/ha), reflecting the combined negative effects of uneven water distribution and nutrient limitation on crop growth and grain filling. Similar trends have been reported in previous studies where controlled irrigation systems improved water use efficiency and yield compared with traditional surface irrigation (Howell, 2001; Farooq et al., 2012).

Tillage also interacted positively with irrigation method, as tilled plots (T_1) consistently outperformed non-tilled plots (T2) under all irrigation systems. The yield advantage under $I_1 \times T_1$ (4808.68 kg/ha) suggests that improved soil structure and root development under tillage enhance the benefits of precise irrigation management (Lal, 2004). Conversely, the yield reduction under no-tillage was more pronounced under flood irrigation, indicating that suboptimal soil physical conditions exacerbate water-related stresses.

Table (2): Interaction between Irrigation Methods versus Fertilization and tillage on Total Grain Yield (kg/ha).

Treatments		Total Grain Yield (kg/ ha)
I_1	F_1	5012.00^a
	F_2	3955.32^c
I_2	F_1	4690.68^b
	F_2	2955.32^e
I_3	F_1	3750.68^d
	F_2	2116.00^f
I_1	T_1	4808.68^a
	T_2	4248.68^b
I_2	T_1	4072.00^b
	T_2	3574.00^c
I_3	T_1	3070.68^d
	T_2	2796.00^e

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Means in columns having the same letter(s) are not significantly different at P ≤ 0.05 according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization

Overall, these findings confirm that maximum yield is achieved when efficient irrigation is integrated with proper fertilization and tillage, supporting the results of earlier tables showing parallel improvements in yield components. This reinforces the need for integrated water, nutrient, and soil management strategies to optimize crop productivity under semi-arid conditions.

3.1.3 Interaction between Fertilization and Tillage at fixed Irrigation Method on Total Grain Yield (kg/ha): The interaction between fertilization and tillage significantly influenced the achieved yield (kg/ha) (Table 3). The highest yield was recorded under fertilization combined with tillage ($F_1 \times T_1$) (4589.76 kg/ha), while the lowest yield occurred under no fertilization and no tillage ($F_2 \times T_2$) (2640.00 kg/ha). This clear gradient highlights the synergistic effect of nutrient availability and improved soil physical conditions on crop productivity.

Fertilization markedly increased yield under both tillage systems, confirming the central role of adequate nutrient supply—particularly nitrogen—in enhancing biomass accumulation, grain formation, and final yield (Fageria, 2014). The additional yield advantage observed under tillage suggests that soil disturbance improved root proliferation, water infiltration, and nutrient uptake efficiency, thereby maximizing the response to fertilization (Lal, 2004). In contrast, the pronounced yield reduction under unfertilized and non-tilled conditions reflects compounded nutrient stress and suboptimal soil structure, which limit crop growth and yield potential. These findings are consistent with earlier tables in this study, where fertilization and tillage similarly enhanced yield components, and agree with previous research emphasizing the importance of integrating nutrient and soil management practices to sustain high yields (Khan et al., 2017).

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Table (3): Interaction Effect of Fertilization and Tillage on Total Grain Yield (kg/ha)

Treatments		Total Grain Yield (kg/ ha)
F_1	T_1	4589.76[a]
	T_2	4439.12[b]
F_2	T_1	3377.76[c]
	T_2	2640.00[d]

Means in columns having the same letter(s) are not significantly different at $P \leq 0.05$ according to Duncan Multiple Range test. $\mathbf{T_1}$ = tillage, $\mathbf{T_2}$ = without tillage. $\mathbf{F_1}$= fertilization, $\mathbf{F_2}$= without fertilization

3.1.4 Effect of Triple Interaction between Irrigation Methods, Fertilization, and Tillage on Total Grain Yield (kg/ha): The three-way interaction between irrigation method, fertilization, and tillage had a highly significant effect on total grain yield (kg/ha) (Table 4), indicating that yield response was strongly dependent on the combined management of water, nutrients, and soil. The highest grain yield was obtained under pivot irrigation with tillage and fertilization ($I_1 \times T_1 \times F_1$) (5188.00 kg/ha), whereas the lowest yield occurred under flood irrigation without tillage and fertilization ($I_3 \times T_2 \times F_2$) (1893.32 kg/ha). This wide yield gap reflects the cumulative and synergistic influence of optimal agronomic practices.

Pivot irrigation consistently outperformed fixed and flood irrigation across all tillage and fertilization levels. This superiority can be attributed to improved water use efficiency, uniform moisture distribution, and reduced water stress during critical growth stages, which enhance biomass production and grain filling (Howell, 2001; Farooq et al., 2012). These results agree with earlier findings in this study showing higher spike number, grain number, and 1000-grain weight under pivot irrigation.

Fertilization significantly enhanced yield under all irrigation and tillage combinations, highlighting the essential role of adequate nutrient supply in

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maximizing crop productivity. The positive response to fertilization was most pronounced under efficient irrigation and tillage conditions, indicating that nutrient uptake and utilization are optimized when soil moisture and structure are favorable (Fageria, 2014). Conversely, the lowest yields under unfertilized treatments, particularly under flood irrigation, reflect nutrient limitations and reduced physiological efficiency.

Tillage further amplified yield response, especially when combined with pivot or fixed irrigation. Improved soil structure, aeration, and root development under tillage likely enhanced water infiltration and nutrient availability, resulting in superior yield performance (Lal, 2004). In contrast, no-tillage treatments exhibited sharp yield reductions under flood irrigation, suggesting that poor soil physical conditions exacerbated water and nutrient stresses.

Table (4): Interaction between Irrigation methods, Fertilization and Tillage on Total Grain Yield (kg/ha)

Treatments			Total Grain Yield (kg/ ha)
I_1	T_1	F_1	5188.00[a]
		F_2	5016.00[ab]
	T_2	F_1	4429.32[d]
		F_2	3481.32[fg]
I_2	T_1	F_1	4778.68[bc]
		F_2	4602.68[cd]
	T_2	F_1	3365.32[g]
		F_2	2545.32[h]
I_3	T_1	F_1	3802.68[e]
		F_2	3698.68[ef]
	T_2	F_1	2338.68[h]
		F_2	1893.32[i]

Means in columns having the same letter(s) are not significantly different at $P \leq 0.05$ according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization.

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Overall, the results of Table (4) confirm that maximum grain yield is achieved only when efficient irrigation is integrated with fertilization and proper soil management. These findings align closely with earlier tables in this study and reinforce previous agronomic research emphasizing the importance of integrated water, nutrient, and tillage management strategies to optimize crop yield under semi-arid conditions (Khan et al., 2017).

3.2 Water Productivity (kg/m^3)

3.2.1 Effect of Irrigation Method, Fertilization and Tillage on Water Productivity (kg/m^3): Water productivity is a key indicator of irrigation efficiency and sustainability, representing the amount of crop yield produced per unit of water consumed (kg/m^3). It reflects how effectively available water resources are converted into economic yield and is particularly critical in arid and semi-arid regions, where improving water use efficiency is essential for sustainable agricultural production (Howell, 2001; Pereira et al., 2012).

The results presented in Table (5) demonstrate that irrigation method, fertilization, and tillage significantly influenced water productivity. Pivot irrigation (I_1) achieved the highest water productivity (1.29 kg/m^3), followed by fixed irrigation (I_2) (0.88 kg/m^3), whereas flood irrigation (I_3) recorded the lowest values (0.31 kg/m^3). This pattern highlights the superior efficiency of controlled irrigation systems in reducing water losses and enhancing yield per unit of water applied, in contrast to traditional surface irrigation methods (Howell, 2001).

Fertilization significantly improved water productivity, indicating that adequate nutrient supply enhances plant physiological efficiency and enables greater biomass and grain production per unit of water consumed (Fageria, 2014). Similarly, tilled plots exhibited higher water productivity than non-tilled plots, likely due to improved soil structure, infiltration, and root development, which enhance water uptake and utilization (Lal, 2004).

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Overall, these findings confirm that water productivity is not determined by irrigation practices alone, but by the combined effects of efficient irrigation, proper fertilization, and appropriate soil management. This integrated approach is essential for maximizing water use efficiency and crop productivity under water-limited conditions, in agreement with previous agronomic studies emphasizing holistic resource management strategies (Khan et al., 2017).

Table (5): Effect of Irrigation Methods, Fertilization and Tillage on Water Productivity (kg/m^3)

Treatments	Treatment levels	Water Productivity (kg/m^3)
Irrigation methods	I_1	1.29[a]
	I_2	0.88[a]
	I_3	0.31[c]
Fertilization	F_1	0.98[a]
	F_2	0.68[b]
Tillage	T_1	0.88[a]
	T_2	0.78[b]

Means in columns having the same letter(s) are not significantly different at $P \leq 0.05$ according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization

3.2.2 Interaction between Irrigation Method and Fertilization and Tillage on Water Productivity (kg/m^3): The interaction between irrigation methods and both fertilization and tillage significantly influenced water productivity (kg/m^3) (Table 6). Across all irrigation systems, fertilized treatments (F_1) consistently

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produced higher water productivity than unfertilized treatments (F_2), with the highest value recorded under pivot irrigation combined with fertilization ($I_1 \times F_1$), (1.45 kg/m³). This indicates that the efficient use of irrigation water is strongly enhanced when adequate nutrient supply supports crop growth, allowing greater yield per unit of water consumed (Fageria, 2014).

Water productivity declined progressively from pivot (I_1) to fixed (I_2) and flood irrigation (I_3), regardless of fertilization or tillage. The extremely low values observed under flood irrigation without fertilization ($I_3 \times F_2$), (0.23 kg/m³) reflect substantial water losses and poor physiological efficiency, which limit yield formation relative to water use (Howell, 2001; Pereira et al., 2012). These findings are consistent with earlier results (Table 5), confirming the superiority of controlled irrigation systems in maximizing water use efficiency.

Tillage further improved water productivity across irrigation methods, with tilled plots (T_1) outperforming non-tilled plots (T_2). The advantage of I1 × T1 suggests that improved soil structure and root development under tillage enhance water uptake and reduce unproductive water losses, thereby increasing water productivity (Lal, 2004). In contrast, the minimal differences between tillage treatments under flood irrigation indicate that poor irrigation efficiency may override the benefits of soil management.

Overall, the results demonstrate that maximum water productivity is achieved only when efficient irrigation is combined with fertilization and proper soil management, reinforcing the concept that water productivity is an integrated outcome of agronomic practices rather than irrigation alone (Khan et al., 2017).

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Table (6): Interaction between Irrigation Methods versus Fertilization and Tillage on Water Productivity (kg/m^3)

Treatments		Water Productivity (kg/m^3)
I_1	F_1	1.45^a
	F_2	1.13^b
I_2	F_1	1.08^c
	F_2	0.68^d
I_3	F_1	0.39^e
	F_2	0.23^f
I_1	T_1	1.37^a
	T_2	1.21^b
I_2	T_1	0.94^c
	T_2	0.83^d
I_3	T_1	0.33^e
	T_2	0.29^e

Means in columns having the same letter(s) are not significantly different at $P \leq 0.05$ according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization

3.2.3 Interaction between Fertilization and Tillage treatments at fixed Irrigation Method Water Productivity (kg/m^3): The interaction between fertilization and tillage at fixed irrigation method significantly affected water productivity (Table 7). Fertilized treatments (F_1) recorded the highest water productivity values, with no significant difference between tilled and non-tilled conditions, indicating that adequate nutrient supply plays a dominant role in enhancing yield per unit of water used. In contrast, unfertilized treatments (F_2) showed a clear decline in water productivity, particularly under non-tillage (T_2), where the lowest value was observed.

The improved performance under fertilization reflects enhanced crop growth and physiological efficiency, allowing better conversion of water into biomass and yield (Fageria, 2014). The positive effect of tillage under unfertilized conditions

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suggests that improved soil physical properties can partially compensate for nutrient limitations by facilitating root growth and water uptake (Lal, 2004). These findings complement earlier results (Tables 5 and 26), emphasizing that fertilization is essential for maximizing water productivity, while tillage plays a supportive but secondary role.

Table (7): Interaction Effect of Fertilization and Tillage at fixed Irrigation Method on Water Productivity (kg/m^3)

Treatments		Water Productivity (kg/m^3)
F_1	T_1	0.99[a]
	T_2	0.96[a]
F_2	T_1	0.76[b]
	T_2	0.59[c]

Means in columns having the same letter(s) are not significantly different at P ≤ 0.05 according to Duncan Multiple Range test. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization

3.2.4 Effect of the Triple Interaction between Irrigation Methods, Fertilization, and Tillage on Water Productivity (kg/m^3): The three-way interaction among irrigation methods, fertilization, and tillage had a pronounced effect on water productivity (Table 8). Under pivot irrigation (I_1), the highest water productivity values were recorded, particularly when combined with tillage and fertilization (T_1F_1) (1.48 kg/m^3), though fertilized and unfertilized plots under tillage did not differ significantly. This indicates that efficient irrigation can partly offset nutrient limitations by improving water use efficiency. However, the absence of tillage (T_2) under I_1 led to a marked reduction in water productivity, especially without fertilization, highlighting the combined importance of soil management and nutrient availability.

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Under fixed irrigation (I_2), water productivity declined compared with I_1, but fertilization and tillage still exerted significant positive effects. Tilled and fertilized plots (T_1F_1) maintained relatively higher productivity (1.10 kg/m^3) whereas non-tilled and unfertilized treatments (T_2F_2) showed a sharp decrease (0.59 kg/m^3), reflecting restricted root development and reduced water uptake efficiency.

Flood irrigation (I_3) consistently resulted in the lowest water productivity across all management combinations, with minimal differences between fertilized and unfertilized treatments under tillage. This suggests substantial water losses and poor conversion of applied water into yield under flood irrigation. Overall, the results confirm that the integration of efficient irrigation systems, fertilization, and appropriate tillage is essential for maximizing water productivity, in agreement with earlier findings (Tables 5–7) and previous studies emphasizing the superiority of pressurized irrigation systems in improving water use efficiency (Howell, 2001; Fereres and Soriano, 2007).

Table (8): Interaction between Irrigation Methods, Fertilization and Tillage on Water Productivity (kg/m^3)

Treatments			Water Productivity (kg/m^3)
I_1	T_1	F_1	1.48^a
		F_2	1.43^a
	T_2	F_1	1.26^b
		F_2	0.99^d
I_2	T_1	F_1	1.10^c
		F_2	1.06^c
	T_2	F_1	0.78^e
		F_2	0.59^f
I_3	T_1	F_1	0.40^g
		F_2	0.39^g
	T_2	F_1	0.25^h
		F_2	0.20^h

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Means in columns having the same letter(s) are not significantly different at P ≤ 0.05 according to Duncan Multiple Range test. **I_1** = pivot, **I_2**= fixed, **I_3**= flood. **T_1** = tillage, **T_2** = without tillage. **F_1**= fertilization, **F_2**= without fertilization.

Conclusion

Center pivot irrigation is the most influential factor for wheat yield and water productivity, yielding 4528.68 kg/ha and 1.29 kg/m^3, respectively. The maximum grain yield (5188 kg/ha) occurred with center pivot irrigation plus conventional tillage and fertilization (I1 × T1 × F1). Overall, center pivot irrigation with proper tillage and fertilization greatly enhances yield and water-use efficiency.

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