Hydraulic performance indicators optimization for sprinkler irrigation systems: Interactive study for optimal distribution efficiency by sprinkler type and operating pressure

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Abstract

Water is one of the most important resources for sustainable agricultural production specifically in arid and semi-arid areas. This study was done to evaluate the effect of two types of sprinkler irrigation systems: rotary sprinklers and double-nozzle impact sprinklers, at two levels of operating pressure (2 and 3 bar). Various key performance indicators, such as the coefficient of uniformity (Cu) .Field-scale measurements of wettability radius, spray intensity and irrigation efficiency. Results indicated that both sprinkler type and operating pressure respectively had a significant effect on all characteristics examined. This difference compared to the other results indicates that the rotary sprinkler was a suitable option for obtaining greater uniformity in water distribution and irrigation efficiency. In contrast, the impact sprinkler yielded better results for wettability radius and spray intensity. All the studied increased with the operating pressure from 2 to 3 bar characteristics, because of better dispersion of droplets and less variation in water distribution. Results of the interactions between sprinkler type and pressure also indicated that the best performance was obtained with the rotary sprinkler at 3 bar pressures, recording the highest distribution uniformity coefficient (90%) while the impact sprinkler at 2 bar pressure recorded the lowest value (78%). These results confirm the importance of selecting the appropriate sprinkler type and operating pressure to achieve optimal irrigation system performance.

The study concludes that adopting rotary sprinklers within optimal operating pressures contributes significantly to improving water use efficiency and enhancing the sustainability of modern irrigation systems, which positively impacts agricultural productivity and reduces water loss.

Keywords: Sprinkler irrigation, rotary sprinkler, double-nozzle impact sprinkler, operating pressure, irrigation efficiency.

Introduction

Demands are increasing for the use of modern irrigation technologies

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such as sprinkler and drip irrigation systems and other technologies that save irrigation water. This comes as a result of the decline in the rates of water suitable for agriculture in Iraq, due to the low levels of the Tigris and Euphrates rivers, in addition to the drying up and decline of water in most rivers and tributaries. These calls are made because these methods save a lot of water and make it possible to expand cultivated areas horizontally to meet the growing need for food caused by the large population growth. Due to the scarcity of irrigation water sources, it was necessary to move from traditional irrigation systems to economical and sustainable irrigation systems.[2]

Sprinkler irrigation is one of the main methods used in farms and fields, where water is delivered to the soil surface in the form of raindrops. This is achieved by using a nozzle to convert pressure inside pipes into kinetic energy as the water flows at high speed from the nozzle.[4] The water then disperses and falls onto the soil or plants at a specific rate and consistency. Several factors influence water distribution when using sprinkler irrigation, and uniformity of water distribution is the primary objective of the process. This was confirmed by [7], where it was stated that the water distribution uniformity coefficient generally increases with increasing pressure. Additionally, explained that evaluating [12,6] the performance of a sprinkler irrigation system depends on measuring the uniformity of water distribution, operating pressures, and losses due to evaporation as indicated by [9] the efficiency of irrigation uniformity can be determined in terms of water distribution over the irrigated area.

It was indicated in [17] that evaluating the performance of sprinkler irrigation systems relies primarily on analyzing the uniformity of the applied water depth distribution using coefficients such as CU and DU. However, these indicators may not adequately reflect spatial variability. It was also explained that using water depth distribution maps provides a more accurate representation of distribution patterns and helps improve the design and operation of irrigation systems [10].

It was further explained that the uniform distribution of water in a sprinkler irrigation system depends on several factors, including the type of sprinkler, the number and size of sprinkler nozzles, the arrangement of sprinklers, and the operating pressure [11].

Designing and investing in sprinkler networks requires knowing the appropriate pressure in the sprinkler nozzle. The appropriate pressure is the pressure that ensures the largest possible spray radius with the least energy consumption [5] It must also ensure the spread and distribution of water well over the designated area. Previous studies show that the spray radius increases with increasing pressure until it reaches a limiting

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value, after which it decreases as a result of the decrease in the kinetic energy of the water droplets, since increasing the pressure leads to the dispersal of water droplets into small spray droplets [13].

A recent study demonstrated that operating pressure plays a crucial role in determining the uniformity of water distribution in sprinkler irrigation systems. The results showed that low pressure leads to a significant deterioration in distribution uniformity, while optimizing sprinkler design can improve the uniformity coefficient even under low pressure conditions. The study also revealed clear differences between sprinkler types and irrigation system design methods [16].

A modern study also showed that the uniformity of water distribution in sprinkler irrigation systems is directly affected by hydraulic factors, particularly operating pressure and sprinkler characteristics. The results confirmed that operating pressure and nozzle diameter are among the most influential factors in the distribution uniformity coefficient. The study also indicated that improving these factors leads to increased water management efficiency and reduced variability in distribution, which positively impacts overall irrigation efficiency, especially in solid-set systems and under arid conditions [7].

Water hydraulics in the sprinkler irrigation system depend on the diameter and height of the sprinkler opening, the operating pressure, and the spacing between the sprinklers to achieve a state of harmony and control in the distribution of water [15]. also pointed out [19] that knowing the uniformity of the distribution of sprinkler water is important because it reflects the extent to which water reaches most plants throughout the field and thus predicts the expected benefit of the water used. He emphasized that one of the reasons for the decrease in the uniformity of distribution of the sprinkler irrigation system is due to fluctuations in the operating pressure.

Sun and his research partners described that the operating characteristics of sprinkler irrigation systems, such as application intensity and droplet size (which are related to operating pressure), directly affect the surface soil pore structure [18]. Higher intensity or larger droplet size leads to a decrease in overall porosity due to the deterioration of larger pores. It was further explained that the operating pressure and spray parameters need to be adjusted for the maintenance of soil structure and to have a balanced distribution of water. Despite previous studies on sprinkler irrigation systems, limited information is available regarding the combined effects of sprinkler type and operating pressure on hydraulic performance indicators under local field conditions.

Therefore, the present study aimed to evaluate the effects of rotary and double-nozzle impact sprinklers under different operating pressures and to determine their influence on water distribution uniformity, wetted radius, spray intensity, and irrigation efficiency.

Material and Methods

The experiment was conducted in one of the fields of College of Agriculture in University of Karbala, which relies on well water for irrigation. The experiment was carried out in February 2026 when the wind was calm to reduce the influence of external environmental factors, especially wind, on the spray radius. This was to obtain standard conditions which could be compared between different treatments. Performance of the fixed sprinkler irrigation system was evaluated by recording the readings of the coefficient of uniformity, irrigation efficiency, wettability radius and spray intensity.

The sprinkler irrigation was of solid-set type, with sprinklers mounted on supports 90 cm above the soil surface, which ensured stable operating conditions and uniform water distribution. The present research was concentrated on two main factors; sprinkler type and operating pressure. Two sprinkler types were used in this study: a double-nozzle impact sprinkler and a single-nozzle rotary sprinkler. The double-nozzle impact sprinkler is made of environmentally resistant plastic and metal materials. It operates on the principle of the pulse mechanism based on intermittent impact motion and is characterized by the ability to work under various operating conditions. The single-nozzle rotary sprinkler is made of high-quality engineering plastic. It operates on the principle of continuous rotation mechanism and is characterized by a higher uniformity of water distribution Table (1).

The second factor was the operating pressure, for which two pressure levels were adopted: 2.0 bar (200 kPa) representing the lower pressure, and 3.0 bar (300 kPa) representing the higher operating pressure. The operating pressure of the system was monitored by a pressure gauge installed on the return line of the irrigation system. To control the required pressure levels (2 bar and 3 bar), a control valve installed on the return line was based on the principle of 'throttling' the flow. When it was desired to raise the pressure, the valve was partially closed to increase the hydraulic resistance to the flow, while to lower the pressure, the valve was opened wider to reduce that resistance.

Thus, four experimental treatments resulted from the interaction between sprinkler type and operating pressure, as shown in Table 2. The performance of each treatment was evaluated separately for comparison between them.

The hydraulic performance indicators of the system were measured using water collection containers (Catch Cans) distributed regularly within the coverage area of each sprinkler, with all other operational factors such as sprinkler height and operating conditions kept as constant as possible to ensure accurate comparison.

The data were analyzed by a fully factorial experimental design (2×2) with three replications, in order to evaluate the influence of the type of sprinkler, the operating pressure and their interaction on the characteristics studied. Differences between treatments were considered statistically significant at probability level of 0.05 using analysis of variance (ANOVA). Means were compared by the least significant difference (LSD) test to detect statistically significant differences among the different treatments.

The studied characteristics:

Water Distribution Uniformity Coefficient (UC)

The water distribution efficiency of the sprinklers used in the experiment was evaluated by measuring the distribution uniformity coefficient (CU) using the Catch Can Method.

Water collection boxes (measuring containers) were positioned in a regular pattern around the sprinklers under test, covering the entire wetted area. The distances between the containers were guaranteed in longitudinal and transverse directions to guarantee a good distribution of water. These containers were maintained at a constant height above the soil surface, and their level and stability were checked throughout the measurement period.

The irrigation system was run at the recommended pressure for each treatment (2 and 3 bar) and the sprinkler was run for a fixed period (40 minutes) so that enough water was collected in the containers. Water collected at the end of the operating period was measured with a graduated cylinder and converted to water depths (mm) where needed.

To calculate the water distribution uniformity coefficient, the following equation was used: [3]

$$CU = \left[1 - \frac{\sum_{0}^{1}(xi - x^{-})}{nx-}\right] \times 100$$

(1)

where:

CU = Water distribution uniformity coefficient (%)

xi = Water height in the different measuring vessels (mm)

$\bar{x}$ = Average height of water collected in the vessels (mm)

n = Number of measuring vessels in the studied area.

The Irrigation Efficiency.

Irrigation efficiency is defined based on the uniformity of water distribution and the amount of water available to the plant, and can be expressed using the Distribution Efficiency formula [8]:

ED = Dmin/($\bar{D}$) (2)

where:

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ED = Distribution Efficiency (%)
Dmin = Minimum water depth in the containers (mm)
D¯ = average water depth in the containers (mm)

Wetted Radius Measurement

The wettability radius refers to the extent of water dispersion around a sprinkler. The wettability radius for each sprinkler was determined by operating the sprinkler at its specified operating pressure and then observing the maximum effective distance the water reaches around the sprinkler.

Catch cans were placed on radial lines radiating from the center of the sprinkler, and the distance at which water collection decreased significantly (or became almost nonexistent) was recorded. This distance was then used as the wettability radius .

Spray Intensity calculation

Spray intensity was calculated using the average depth of water collected in the containers during a fixed operating period.

Spray intensity was calculated using the following formula:

$$I = \frac{\bar{x}}{t} \qquad (3)$$

Where:

- I = Spray intensity (mm/hr)

- x̄ = Average depth of water in the containers (mm)

- t = Operating time (hr)

Spray intensity reflects the speed at which water is applied and is an important factor in:

- Preventing surface runoff

- Improving soil permeability

Results and Discussion

Distribution Uniformity Coefficient CU%

The results shown in Table (3) indicate that the uniformity coefficient CU% was affected by the type of sprinkler and the operating pressure. The rotary sprinkler recorded the highest value of 90% at a pressure of 3 bar, while the impact sprinkler recorded the lowest value of 78% at a pressure of 2 bar. The differences between the treatments exceeded the value of the least significant difference (LSD) at the level of (0.05), which was 3.2%, indicating that there were significant differences between them ،except between the impact sprinkler at 2 bar and the rotary sprinkler at 2 bar.

Contingent upon the design of the rotary sprinkler, it could turn 360 degrees regularly which implies focal and radial sprinkling upgrades spread consistency across taken readings along lines. The effects of sprinkler type and operating pressure on the interaction between sprinklers and further, results of variance analysis revealed one significant interaction ($P \leq 0.05$) effect: Sprinkler type and operating pressure resulted in increased benefiting rotary irrigation than impact sprinkler irrigation at higher speeds for more uniformly water distribution. This is in agreement with previous studies [14,16] that confirmed the dependence of water distribution uniformity on design parameters and irrigation system components (including water discharge characteristics) revealing positive relations between increase in sprinkler performance and pressures for rotary sprinklers.

Irrigation Efficiency (%)

In table (4), sprinkler type and operating pressure were the main factors influencing irrigation efficiency. For the rotary sprinkler, it had the highest value (87.5%) at 3 bar and for impact sprinkler, the lowest value (77.5%) at 2 bar The differences between among most treatments were larger than the least significant difference (LSD) at the 0.05 level, which was 3.1%.

The improved irrigation efficiency of the rotary sprinkler is due to its continuous plot rotating mechanism, which enables even water distribution in every corner of the central coverage area. It reduces volume distribution in the irrigated areas (area of excess and deficit), minimizes losses due to evaporation reaching a low range, and improves irrigation efficiency. The impact sprinkler, on the other hand, causes a rather constant, or even further uneven distribution of water; therefore more losses and lower efficiency compared to the pulsating pattern.

However, an increase in operating pressure improved the irrigation efficiency by improving water jet characteristics and droplet breakup which resulted in increased uniformity of distribution and reduced losses due to surface runoff and erosion These results agree with previous studies [1], reporting that higher operating pressures for rotary sprinklers are associated with irrigation efficiency greater than 60% due to the improved distribution and water loss under these conditions.

Wetting radius (m)

The results shown in Table (5) indicate that the wetting radius was affected by the type of sprinkler and the operating pressure, as the impact sprinkler recorded the largest radius of (15.2 m) at a pressure of 3 bar, while the rotary sprinkler recorded the smallest radius of (10 m) at a pressure of 2 bar. **Differences between treatments exceeded LSD** value (1.6 m) at ($p \leq 0.05$), indicating that most of the extracted means are sufficient to state a statistical difference between treatments. The jet thrust produced by the design nozzle and pulsating spray mechanism leads to the increased wettability radius in impact sprinkler compared with that of rotary sprinkler affected by continuous rotation, for it realizes more uniform distribution over a shorter range. The results also showed that the wettability radius increased with increasing operating pressure for both sprinklers because of the increase in water discharge velocity and droplet kinetic energy, which mean increased water coverage of the irrigated area. These findings are in accordance with the previous literature which showed that droplets carry more energy and momentum with the increase of sprinkler operating pressures and increased nozzle sizes, thus contributing positively to water dispersion process; however at higher operating pressure, the reduction in droplet size will impact negatively on distribution uniformity [15].

Spray intensity (mm/hr)

The results shown in Table (6) that the spray intensity was clearly affected by the type of sprayer and the operating pressure, as the rotary sprayer recorded the highest spray intensity of 7.75 mm/hour at a pressure of 3 bar, while the impact sprayer recorded the lowest intensity of 6 mm/hour at a pressure of 2 bar. The outcomes also indicated that most of the treatments were significantly different from each other beyond LSD estimated during (0.4 mm/hour).

While the rotary sprinkler provides a better spray intensity due to its continuous rotational movement, allowing for a more consistent droplet distribution, the impact sprinkler creates larger, less uniform droplets in a pulsed pattern. Results also indicated that the operating pressure, when increased to a certain extent, is more appropriate and helps improve the spray intensity of the sprinklers used in this experiment (due to increase in jet velocity, improvement of droplet fragmentation and therefore their kinetic energy and decrease in non-uniform distribution of water). A two-way analysis of variance identified a significant interaction between sprinkler type and pressure.

Showing in a greater degree that using higher pressure was more beneficial to rotary than impact at $P \leq 0.05$, resulting from the fact that the improved spray intensity and coverage uniformity of rotary has higher dependence on kinetic energy generated by pressure. The results provide a good agreement with [16], which reported that droplet size and uniformity of distribution are dependent on the nozzle type, pressure in sprinkler irrigation systems.

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Table (1) Technical characteristics of the sprinklers used in the study

Sprinkler type	Operating pressure range	Discharge rate ($m^3\ h^{-1}$)	Wetting diameter (m)	Droplet size
Impact sprinkler	200–400 kPa	0.80–1.50 $m^3\ h^{-1}$	12–18 m	Medium to large
Rotary sprinkler	150–300 kPa	0.60–1.20 $m^3\ h^{-1}$	10–16 m	Small to medium

Table (2) **Experimental treatments and operating conditions**

Treatment	Sprinkler type	Operating pressure
T1	Impact sprinkler	2 bar
T2	Impact sprinkler	3 bar
T3	Rotary sprinkler	2 bar
T4	Rotary sprinkler	3 bar

Table 3: Effect of sprinkler type and operating pressure on the uniformity coefficient of distribution (CU%)

pressure/Sprinkler Type	2 Bar	3 Bar
Impact	78 ^{c}	85 ^{b}
Rotary	82 ^{b}	90 ^{a}
LSD (α = 0.05)	**3.2**	

- *Means followed by different letters are significantly different at P ≤ 0.05.*

Table 4: Effect of sprinkler type and operating pressure on irrigation efficiency (%)

pressure/Sprinkler Type	2 bar	3 bar
Impact	77.5 ^{c}	82.5 ^{b}
Rotary	81.5 ^{b}	87.5 ^{a}
LSD (α = 0.05)	3.1	

- *Means followed by different letters are significantly different at P ≤ 0.05.*

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Table 5: Effect of sprinkler type and operating pressure on wetted radius (m)

pressure/Sprinkler Type	2 Bar	3 Bar
Impact	13.5 [a]	15.2 [a]
Rotary	10 [b]	13.8 [a]
LSD (α = 0.05)	**1.6**	

- *Means followed by different letters are significantly different at $P \le 0.05$.*

Table 6: Effect of sprinkler type and operating pressure on spray intensity (mm/hr)

pressure/Sprinkler Type	2 Bar	3 Bar
Impact	6 [c]	7 [b]
Rotary	6.25 [c]	7.75 [a]
LSD (α = 0.05)	**0.4**	

- *Means followed by different letters are significantly different at $P \le 0.05$.*

Conclusion

These results indicated that the rotary sprinkler outperformed the impact sprinkler in terms of flow uniformity coefficient (CU) and irrigation efficiency. Water in the rotary sprinkler also demonstrated more intense spray, demonstrating uniformity when watering. On the other hand, the impact had a larger wetted radius because of its high jet propulsion.

The interaction between sprinkler type and pressure showed that the optimum performance of the distribution uniformity coefficient was recorded under a rotary sprinkler at 3 bar (90%) while, under impact sprinklers at 2 bar, it gave the weak performance on uniformity of lateral spacing.

It was found that the performance of sprinkler systems and their response to working pressure is largely dependent on type and hydraulic characteristics of sprinkler.

Recommendations

On the basis of results of this study, the following operations can be proposed to

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increase water use efficiency and sustainability of sprinkler irrigation systems:

1. Rotary sprinklers are recommended to be used, specially in water-stressed regions because they have relatively higher distribution efficiencies and lower losses relative to impact-type sprinklers.
2. The sprinkler irrigation system should work until the best conditions of pressure are reached, around 3 bar being preferable. Low pressure operation of impact sprinklers is undesirable due to reduced distribution uniformity and lower irrigation efficiency.
3. Matching irrigation system design with hydraulic performance between the sprinkler type and operating pressure, can reduce variability in water distribution.
4. The extent of use of up-to-date irrigation technologies, especially sensor based systems should be promoted. Furthermore, extension programs must be targeted to increase awareness for easy access to adequate sprinkler types or operating pressures amongst farmers with an aim of increasing productivity through efficient water resource conservation.
5. Likewise, the recommendation promoted includes the incorporation of renewable energies such as solar in irrigation systems. Further studies are still needed to evaluate the effects of environmental factors, such as wind and temperature, on sprinkler performance in order to guide future development and achieve more efficient and sustainable irrigation practices.

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