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Evaluation of Different Irrigation Settings to Maximize Water Productivity

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Abstract: This study evaluates the impact of different irrigation systems on maize crop performance, focusing on plant height, stem diameter, grain yield, and water productivity. The results demonstrate that drip irrigation is the most effective system, producing the tallest plants (254.6 cm), the largest stem diameter (17.9 mm), and the highest grain yield (6,728.3 kg/ha). It also achieved the greatest water use efficiency at 15.62 kg/ha-mm, with minimal water wastage. The sprinkler irrigation system also performed well but with slightly lower metrics compared to drip irrigation. Conversely, furrow and flood irrigation systems resulted in shorter plants, smaller stem diameters, and lower yields, with significantly lower water productivity due to higher water usage and wastage. The study underscores the advantages of drip irrigation in enhancing maize growth and yield while conserving water, highlighting its potential as a sustainable agricultural practice.

Keywords: Water Resource Management; Sustainable Irrigation System; Water Use Efficiency; Crop Water Use; Maize; Water Productivity

1. Introduction

The severe consequences of climate change have become increasingly evident throughout this century, marked by a rise in extreme weather events and greater variability in weather patterns. Global warming is manifested through an increase in the Earth's average surface temperature, with all models indicating ongoing climate change. Temperature records show that the Northern Hemisphere is experiencing a more pronounced increase in temperatures compared to the Southern Hemisphere [1]. While predicting short-term changes in Earth's climate is relatively straightforward, it is projected that the global mean temperature could rise by 1.5 to 2°C by 2050. In the coming decades, shifts in atmospheric conditions are expected to impact various aspects of life. Current trends indicate rising sea levels, increasing air and ocean temperatures, and higher ocean acidity. The effects of global warming include temperature fluctuations, more severe droughts, accelerated glacier melting, and greater frequency and intensity of floods [2].These changes have contributed to a decline in biological diversity. The variability in rainfall has heightened the risk of desertification, floods, droughts, and inconsistent crop production. Additionally, there is growing concern over the impact of climate change on food security, as it annually degrades millions of hectares of land. Climate changes in the future present a serious danger mostly to fragile environmental zones while agriculture remains most vulnerable to these threats.

Water crisis along with the requirement to achieve a sustainable and nutritious diet for the expanding population rank as the primary worldwide difficulties. Inadequate water resource management has made existing water scarcity worse due to climate changes [3]. Traditional irrigation techniques will generate future water scarcity problems for agricultural crop supplies. An integrated method that unites technology with decision-making and sustainable farming represents an effective solution to handle these problems. The framework executes smart irrigation alongside virtual plant surveillance together with systemized crop-to-water management systems as well as remote operational monitoring. Research data from this method gives both farmers and water managers the tools to determine effective irrigation methods which increase crop productivity and protect water supplies [4]. The approach provides various important advantages but organizations need to consider both implementation costs and technological complexity when adopting this methodology. Such approaches serve to transform agricultural practices by creating more efficient and environmentally friendly and safer production methods particularly in areas with water scarcity.

The biggest user of water worldwide is agriculture and its irrigation method inefficiently consumes large volumes of water. Traditional flood irrigation controls most water usage patterns throughout Punjab despite its known inefficiency which creates massive water waste problems [5]. Excessive leakage in lowlands and untimely water application in raised areas causes both soil nutrient loss and production declines. Because Pakistan's water distribution system falls short of meeting optimal crop requirements the irrigation timing impacts crop yield productivity negatively. Groundwater alongside surface water resources in Pakistan are experiencing decreasing availability even though demand keeps increasing which generates harmful contamination of groundwater sources by arsenic and fluoride substances that cause health risks. The Khanewal district of South Punjab shows dangerous water conditions in many samples due to geological reasons combined with human activities thus demanding fresh management strategies.

Maize functions as a vital cereal crop worldwide while securing global food security by supplying large quantities of dietary calories to the human population. Maize holds the third position among Pakistani common crops while making substantial contributions to agricultural value creation according to research. Water scarcity that affects key growth periods including vegetative development and reproductive period through grain filling produces major yield reductions [6]. Reduced kernel production along with lower biomass and decreased yields are all consequences of water stress that occurs during key growth stages [7]. Various factors including the duration of the growing season and the characteristics of the soil as well as climatic elements determine the amount of water needed for maize plants [8]. Water availability plays a fundamental role in optimizing maize yield output because restricted water supply specifically during growth periods results in reduced plant size and delayed maturity as well as reduced harvest yields.[9]

The management of water stress requires reliable irrigation systems as a key solution [10]. Drip irrigation systems and sprinklers show better performance than flood irrigation methods according to research [11]. Drip irrigation provides targeted root water delivery which both saves water resources and escalates crop production levels [12]. Water scarcity remains a barrier for maize production in Pakistan even though the country has strong potential for cultivating this crop [13]. Strategies for water conservation and contemporary irrigation system adoption must be implemented to enhance crop quantity and satisfy Pakistan's maize requirements [14]. The results of research studying irrigation effects on crop production and its influencing factors will give important guidance for upcoming agricultural procedures.

2. Material and methodology

The experiment took place on a farm in Muzaffargarh, with coordinates at N2956.292 latitude and E7069.395 longitude. The study focused on maize cultivation from January to May 2024. The experimental area covered one acre, which was divided into four zones, each occupying 0.25 acres, as illustrated in Figure 1. The field's width was 67 feet, with each zone measuring 60 feet in length and 17 feet in width. The main irrigation line had a diameter of 2.0 inches, while the sub-main line was 1.5 inches. Prior to the experiment, the soil was prepared by first tilling with a chisel plough, followed by a cultivator to achieve a fine soil texture. A bed planter was then used to create beds for planting the crops. Maize was sown on January 20, 2024, using the appropriate seed rate. The crop was planted on beds 75 cm wide, with manual dibbling employed as the planting method. Plants were spaced 20 cm apart, and the distance between rows was four feet [15]. The plot, replicated in world space and volume net, measured 60.35 m by 67.06 m. Zone 1, which utilized drip irrigation, had the following parameters: a line length of 30 cm, a flow spacing of 4 feet, a flow rate of 6.639 m^3/hr, and an irrigation duration of approximately 58 minutes. Zone 2, which employed a sprinkler system, featured inter-sprinkler and flow spacing of 4 feet, a total flow rate of 6.300 m^3/hr, and an irrigation time of 1 hour and 10 minutes.

In Zone 3, where furrow irrigation was used, the watering duration was 7 hours, with a flow rate of 956.871 m^3/hr. In Zone 4, utilizing flood irrigation, the watering also took 7 hours, with a total flow rate of 1194.367 m^3/hr.

Groundwater was used for irrigation throughout the experiment. Water samples were collected at the outlet of the submersible pump. These samples were analyzed at the Soil and Water Testing Lab in Muzaffargarh, resulting in a water quality report, identified as report no. 299, as shown in Table 1.

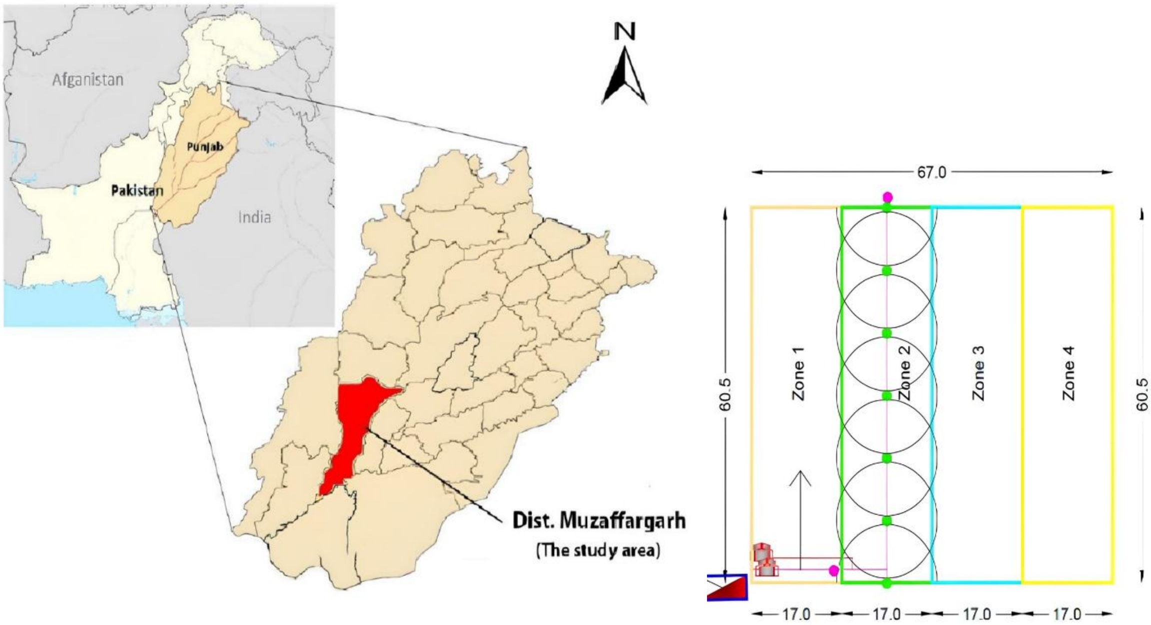

Figure 1. Study Area and Design Layout of Experimental Site

Table 1. Water Quality Analysis

Parameters	Degree of Presence / Problem				Lab Result
	Unit	Normal	Higher	Extreme	
pH		7	<7 Acidic	>7 A	7.41
Electrical Conductivity	uS/cm	<1500	1500- 3000	>3000	425
Total dissolved solids	ppm	<500	500 - 600	>600	380
Hardness	ppm	<200	200 - 300	>300	106
Calcium	ppm	<60	60 - 100	>100	34.2
SAR	-	<3	3-9	>9	6.4
Iron	ppm	<0.1	0.1 - 0.4	>0.4	0.005

The measurements of the plants were conducted at the maturity stage. For each plot, the height of 10 plants was measured from the ground level to the top using a meter rod, and the average height was then calculated. Collection of experimental data is shown in figure 2.

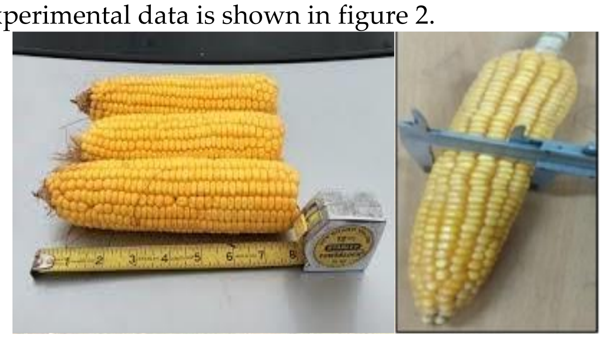

Figure 2. Collection of experimental Data

This process was repeated across all replications. The stem diameter was measured using a Vernier caliper, taking readings from three positions on the stem upper, middle, and lower for each plant, and then calculating the average diameter [16].After harvesting, the cobs were detached from the plants and sun-dried. The yield was recorded in kilograms per hectare (kg/ha) after the threshing process. Water productivity was calculated using the following formula.

$$\text{Water Productivity (kg ha}^{-1}\text{ mm}^{-1}) = \frac{\text{crop yield (kg } ha^{-1})}{water\ used\ (mm)}$$

3. Result and Discussion

The drip irrigation system resulted in the tallest plants, with an average height of 254.6 cm. This height was statistically similar to the 244.2 cm achieved with the sprinkler irrigation system. The study indicated that drip irrigation outperformed sprinkler irrigation due to its consistent water delivery directly to the root zone throughout the growth period, which reduced water stress and led to taller plants with longer internodes [17]. Conversely, the furrow irrigation system produced the shortest plants, with a height of 243 cm, although in one instance, it allowed the plants to grow to 248.1 cm. It is shown in figure 3.

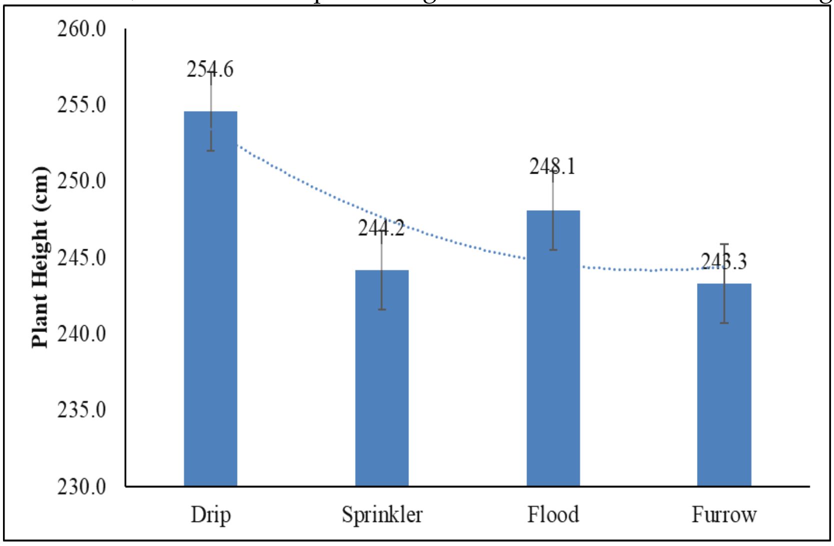

Figure 3. Effect of different irrigation systems on Plant Height

It was observed that the drip irrigation system produced the largest stem diameter, reaching up to 17.9 mm shown in figure 4. In comparison, furrow irrigation resulted in a maximum stem diameter of 16.4 mm, while the sprinkler irrigation system recorded a stem diameter of 15.4 mm. The thickest stem, measuring 12.3 mm, was found in the drip irrigation system.

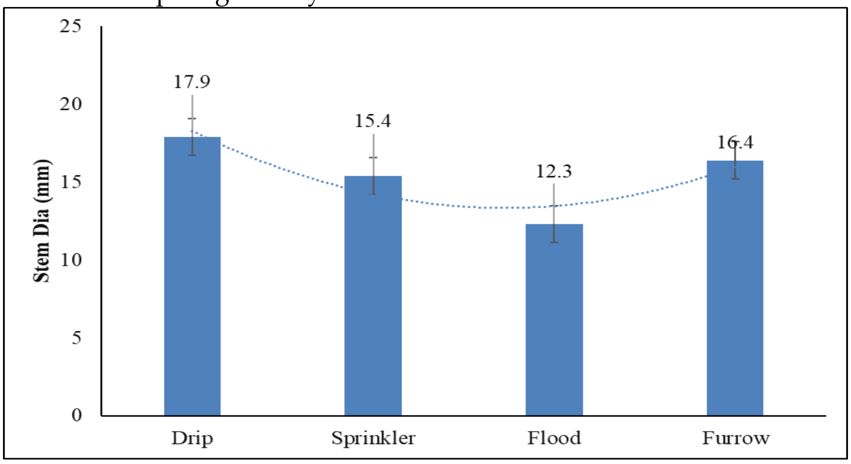

Figure 4. Influence of various types of irrigation methods on Stem Diameter

The study revealed that the drip irrigation system produced the highest grain yield, averaging 6,728.3 kg/ha. The sprinkler irrigation system followed with an average yield of 6,296.6 kg/ha. The furrow irrigation method resulted in the lowest grain yield, at just 5,563.2 kg/ha, while flood irrigation produced a yield of 6,135.2 kg/ha. The findings shown in figure 5 and suggest that different irrigation methods can significantly impact maize crop growth and grain yield.

The first reason might be the decrease in crop water supply when water was sprayed using the furrow irrigation method at prearranged intervals. Thus, it is possible to draw the conclusion that this research demonstrates that drip irrigation may be used to provide crops with enough and timely watering, which will maximize plant development and, ultimately, agricultural output [18]. Figure 6 illustrates the water productivity of maize under different irrigation methods. Drip irrigation was the most efficient with the lowest water wastage at 15 percent and the highest water use efficiency, reaching 15.62 kg/ha-mm. Sprinkler irrigation was the second most efficient, with a water use efficiency of 12.12 kg/ha-mm. In contrast, flood irrigation had the lowest water use efficiency at 5.13 kg/ha-mm, although in another study furrow irrigation showed a slightly higher efficiency of 6.12 kg/ha-mm. A similar study was conducted to evaluate water productivity and yield for drip, flood and furrow irrigation systems during the years 2020-21[19].

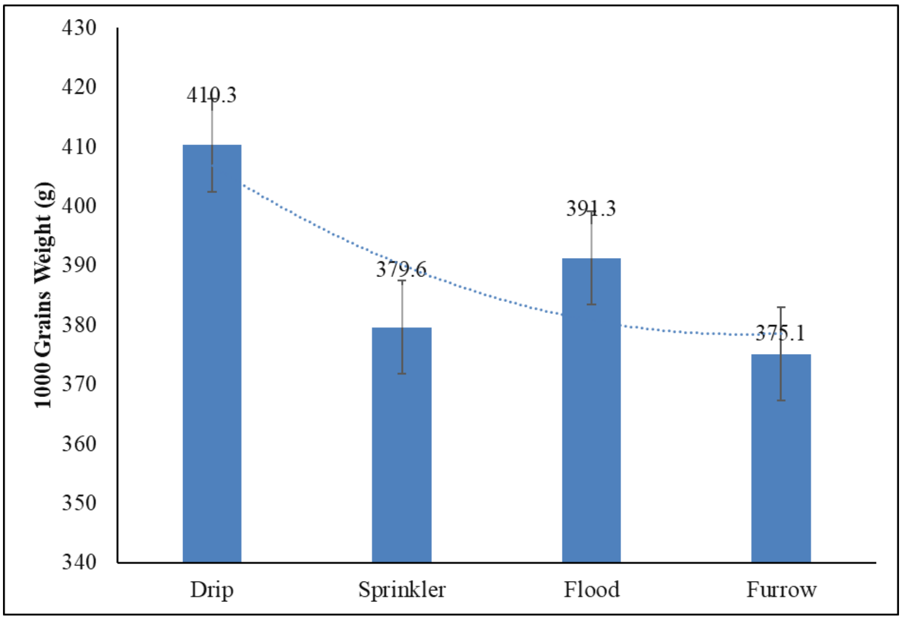

Figure 5. Effect of different irrigation systems on grain Yield

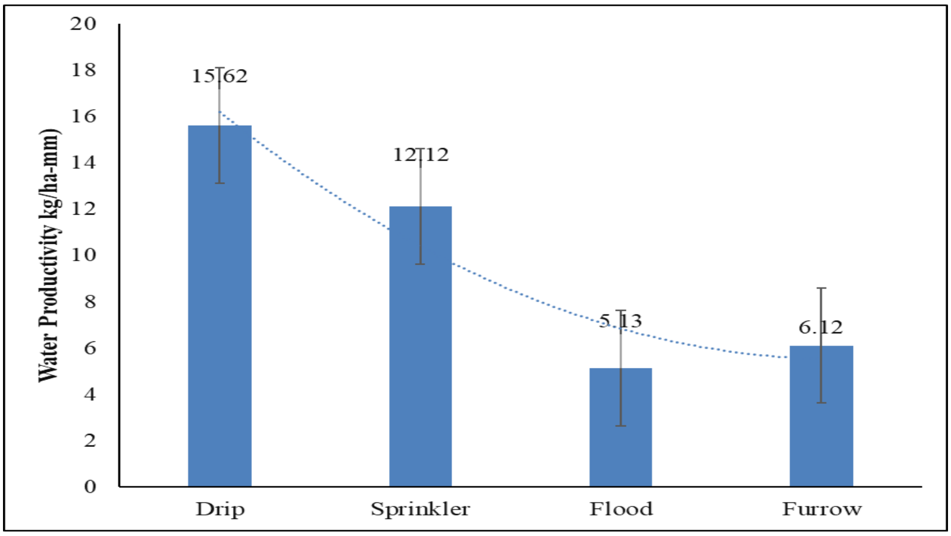

Figure 6. Effect of different irrigation systems on water productivity.

Drip irrigation proved to be the most effective management practice, as it achieved the highest yield with the least water usage, resulting in the greatest water use efficiency. Consequently, water productivity in flood and furrow irrigation systems is lower compared to sprinkler and drip irrigation systems, primarily due to the larger amounts of water applied in the former methods. Impact of different irrigation systems are given in the table 2 below.

Table 2. Impact of different irrigation systems

Parameter	Drip	Sprinkler	Flood	Furrow	Remarks
Stem Diameter (mm)	17.89	15.4	12.3	16.39	Drip irrigation results in the largest stem diameter.

Plant Height (cm)	254.6	244.2	248.1	243.3	Drip irrigation had the tallest plant growth.
1000 Grains Weight (g)	410.3	379.6	391.3	375.1	Drip irrigation had the more grain weight.
Water Productivity (kg/ha-mm)	15.62	12.12	5.13	6.12	Drip irrigation shows the highest water productivity.

The comparative analysis of different irrigation systems revealed significant variations in various maize crop parameters. Drip irrigation proved to be the most efficient among the irrigation systems due to its best rates of water productivity which reached 15.62 kg/ha-mm. The drip irrigation system permitted ideal plant growth that yielded the biggest stem diameter of 17.89 mm.

4. Discussion

The study demonstrates strong evidence that irrigation systems extensively impact maize crop metrics such as plant height and stem diameter together with grain output and water productiveness. Among the evaluated systems, drip irrigation emerged as the most effective in enhancing crop growth and yield. A study by de Almeida, A.M., et al. (2022) similarly found that drip irrigation maximized maize yield and water use efficiency compared to furrow and sprinkler irrigation with drip irrigation systems optimizing water distribution and minimizing wastage through evaporation and runoff [20].Maize plants under drip irrigation reached a height of 254.6 cm, had a stem diameter of 17.9 mm, and achieved the highest grain yield of 6,728.3 kg/ha. Research findings indicate that drip irrigation optimizes water distribution because it enables efficient root zone targeting and improves nutrient uptake and root development (Cannavo, P et al. 2016).

The system achieved remarkable water use efficiency of 15.62 kg/ha-mm because it optimized yields while requiring minimal water. Under conditions of restricted water availability this system demonstrates its suitability because it generates minimal water waste while accomplishing effective irrigation results. Research results showed favorable plant characteristics in sprinkler irrigation but lower values than drip irrigation for plant height and stem diameter alongside grain yield measurements. The imprecise water distribution of sprinkler systems leads to higher declines in water use efficiency by causing both evaporation losses and wind-driven waste. Sprinkler irrigation used 12.12 kg/ha-mm of water effectively yet required greater water consumption than drip irrigation to achieve similar yields. Furrow along with flood irrigation demonstrated the lowest efficiency rate. These management systems demonstrate lower water productivity because they use high water application levels and lose water through both runoff and deep seepage. Since water distribution under these methods proves inefficient, more water becomes necessary to maintain crop growth thus decreasing productivity and making water resources unsustainable.

5. Conclusion

The study establishes that drip irrigation produces the best results for maize farming because it results in the highest plant heights and stem diameters and the best yield of grains. The best water productivity emerged from drip irrigation because it used water with an efficiency rate of 15.62 kg/ha-mm while being the most environmentally friendly method for water-stressed areas. Drip irrigation systems supply water directly to the root area which maximizes nutrient retention rates and minimizes waste resulting in better crop health and superior production outcomes. This irrigation technique proved efficient yet less effective than drip irrigation and reached a water use efficiency level of 12.12 kg/ha-mm. Very moderate water areas can persist ably use this technique but need to improve their water-saving methods. Crop performance together with water usage was suboptimal under flood and furrow irrigation practices since these irrigation methods proved the least efficient. Drip irrigation stands as the most advantageous system for maize cultivation because it provides high yields and protects water resources in arid regions although it is applied only in specific water-scarce areas. Modern irrigation systems require adoption because they enhance both crop productivity as well as ensure sustainable water consumption.

Supplementary Materials

No supplementary materials were provided or required for this study.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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