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Enhancing Maize Productivity: The Impact of Localized Irrigation Systems and Humus Compound Fertilizers in Sandy Soils

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CURRENT challenges in agriculture include limited irrigation water availability, outdated irrigation techniques, and poor soil quality in arid areas that negatively impact agricultural productivity, energy consumption in processing, and fertilizer market. Field experiments were conducted during the 2022/2023 growing season at the National Center for Experimental Research in Nubaria, Egypt, to study the impact of different localized irrigation systems (LIS) and organic compound fertilizers (HCF) on water and fertilizer productivity in maize crop. Three irrigation technologies were evaluated: micro-sprinkler irrigation (MSIS), bubbler irrigation (BIS), and drip irrigation (DIS). Results showed that localized irrigation systems significantly improved grain yield and water productivity, with BIS being the best irrigation strategy, providing the highest yield due to optimal water management. Additionally, increasing nitrogen fertilizer treatments, especially at 100 kg/acre, enhanced productivity and fertilizer productivity. The study recommends the application of bubbler irrigation system (BIS) in maize cultivation to improve productivity and maximize water productivity. It also calls for increased use of nitrogen fertilizers to enhance grain production, and supports the integration of efficient irrigation and fertilization techniques for sustainable agriculture. The findings emphasize the need to use dedicated irrigation and fertilization techniques to improve maize productivity and resource efficiency, which is critical for sustainable agriculture in dry areas.

Keywords: Localized Irrigation, Humus Compound Fertilizer, Water Productivity, Sandy, Maize.

Introduction

Water Productivity (WP) in maize is affected by several factors, including the plant's physiological traits, genotype, soil properties like water-holding capacity, climatic circumstances, and agricultural techniques. To improve WP, integrated strategies should concentrate on optimizing cultivar selection and agronomic practices. In numerous drought-affected maize situations, the paramount management interaction is between soil fertility management and water availability. Many farmers in drought-prone regions are reluctant to use fertilizers due to the potential for economic loss, hence strengthening the association between drought conditions and diminished soil fertility (Bacon, 2004; Rahman et al., 2022). Ogola et al. (2002) discovered that nitrogen administration markedly enhanced water productivity in maize. It was also observed that maize is especially susceptible to water stress because of its comparatively shallow root system. Recent research by Zhang et al. (2021) corroborates these findings, emphasizing that improved nitrogen management enhances both water productivity and agricultural yields in drought situations.

Humus compounds, the ultimate outcome of organic matter breakdown, provide numerous agricultural advantages, including improved soil moisture retention. This enhancement is especially pronounced in sandy soils enriched with humus, where water productivity surpasses that of non-amended soils. The augmentation in moisture retention results from the swelling and water-retentive properties of humus-amended soil (Suganya & Sivasamy, 2006). Furthermore, humus compounds can form complexes with metal ions, so diminishing nutrient leaching and improving fertilizer utilization efficiency (Stevenson, 1982; Martínez et al., 2020). These compounds are stable byproducts of organic matter decomposition (Mackowiak et al., 2001), and their accumulation in

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sandy soils enhances moisture retention and nutrient supply potential (Suganya & Sivasamy, 2006; Jha & Kumar, 2023).

Laboski et al. (1998) discovered that maize output is significantly influenced by the volume of water delivered via trickle irrigation, highlighting the necessity of effective irrigation management. Elevating plant population density has been demonstrated to improve maize grain output, up to an ideal density per unit area (Holt & Timmons, 1968). Fulton (1970) similarly indicated that elevated plant densities result in enhanced grain yields, with 90,000 plants per hectare being prevalent in numerous places (Modarres et al., 1998). Recent research has enhanced these principles, indicating that optimizing plant density can alleviate the impacts of climate change on maize output (Pereira et al., 2021).

The effectiveness of fertilizer utilization is contingent upon various parameters, including application rate, method, timing, kind of fertilizer, and the properties of soil and crops. Appropriate techniques and timing are essential for reducing nutritional loss and guaranteeing a good reproductive program. Nitrogen fertilizers for long-season crops such as maize should be administered in divided applications, especially in sandy soils where nitrate leaching poses a risk (Bhatti & Afzal, 2001). Phosphate fertilizers present further complications, as they may become immobilized or inaccessible to plants under optimal conditions. To mitigate this, it is advisable to utilize localized application of phosphate fertilizers or to employ pelleted or aggregated formulations (Brady, 1974). The early use of phosphorus during sowing has proven to be more successful than subsequent applications (Al-Ansari et al., 2023). Memon (1996) determined that the uptake of phosphorus by plant roots is affected by the phosphorus-absorbing characteristics of the roots and the availability of phosphorus in the soil. Furthermore, optimizing the uniformity of water application is a straightforward yet efficacious approach for conserving water at the agricultural level. Regular assessment of the emission uniformity of trickle irrigation systems is crucial for effective water management.

Mansour (2006) found in a comparative study between different irrigation systems that the second growing season showed the greatest improvements in water productivity (WP) and water productivity under drip irrigation (42% and 43%, respectively), followed by low-pressure bubbler irrigation (40.7% and 37%), and piped irrigation (30.6% and 32%). The productivity of nitrogen, phosphate, and potassium fertilizers also improved from the first to the second season under both drip and low-pressure bubbler irrigation systems. A recent study by Shola et al. (2022) confirmed similar findings, highlighting the importance of microirrigation in improving water productivity and nutrient productivity. This study aimed to evaluate the effect of localized irrigation systems, namely micro sprinkler irrigation system (MSIS), bubbler irrigation system (BIS), and drip irrigation system (DIS), along with compound organic fertilizer (HCF) treatments (HCF100 = 50 kg/feddan, HCF50 = 25 kg/feddan, HCF0 = 0 kg/feddan), on water productivity (WP) and fertilizer productivity (FP) of maize cultivation under desert conditions in Egypt.

Materials and Methods

A field experiment was conducted at the experimental farm of the Agricultural Division of the National Research Center in Nubaria Governorate, Egypt, during the 2022/2023 growing season using maize (Zea mays L.), specifically Gemmeza 9 cultivar. The study aimed to examine the effect of localized irrigation systems (LIS) and compound organic fertilizer (HCF) on water productivity (WP) and fertilizer productivity (FP) and to analyze the cost of growing maize on sandy soil. The soil characteristics and irrigation water used in the experiment are presented in Tables 1, 2 and 3.

Three localized irrigation systems were evaluated: micro-sprinkler irrigation system (MSIS), bubbler irrigation system (BIS), and drip irrigation system (DIS). Compound organic fertilizers were applied at three rates: 50 kg/feddan (HCF100), 25 kg/feddan (HCF50), and a control treatment without fertilizer (HCF0). The total area of the experiment was 504 m2, with 168 m2 allocated to each irrigation system and 56 m2 to each fertilizer treatment. A comprehensive description of the irrigation systems is provided by Mansour (2012) and Tayel et al. (2012a, b, c, d).

The experiment used a split plot design with three replicates. Maize grains were planted on May 12 in rows spaced 0.7 m between each row and 0.25 m between each plant, achieving a planting density of 24,000 plants/feddan. Drip irrigation was applied to each row using a single continuous lateral line, based on daily measurements from a Class A pan evaporation. Irrigation was done every four days, and the volume of water required for each irrigation was determined using the following equation:

$$IWA = \left[\frac{ET_o K_c K_r}{IE} + LR\right] 4.2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where :
IWA : applied irrigation water quantity (m³/feddan per irrigation؛(
ETo : potential evapotranspiration using Class A pan evapotranspiration meter (mm day⁻ ¹)؛
Kc : crop coefficient؛
Kr :reduction factor (Keller and Karmeli, 1974)؛
I :irrigation intervals (days)؛
IE : irrigation efficiency (90%)،:LR : Leaching requirement : 10% of total water delivered to the treatment.
The suggested fertilizer quantities were used as follows:
70.5kg/ha of nitrogen؛
84.9kg/ha of potassium oxide (K□O)؛
75.8kg/ha of phosphorus pentoxide (P□O□), in descending order.
Fertilizers were applied in quantities appropriate to the crop growth stage by irrigation water. Weeding and pest control were carried out in all plots according to the recommendations of the Egyptian Ministry of Agriculture. Maize was harvested on September 5, but irrigation ended 15 days before harvest. Dry weights of both grain and stalks were determined (kg/acre).
Water productivity (WP) was calculated according to Howell et al. (1995) using the following equations:

$$WUEs = \frac{Stover\ yield\ (kg fed^{-1})}{Total\ water\ applied (m^3 fed^{-1})} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Table 1. Soil physical analysis.

Depth, cm	Particle Size distribution, %				Texture class	θ_S % on weight basis			HC (cmh⁻¹)	BD (g/cm³)	P (cm³ voids /cm³ soil)
	C. Sand	F. Sand	Silt	Clay		F.C.	W.P.	AW			
0-15	10.5	75.3	7.2	7.0	Sandy	15.0	7.0	9.0	7.10	1.65	0.38
15-30	10.2	75.8	7.0	7.0	Sandy	15.0	7.0	9.0	7.20	1.65	0.38
30-45	10.1	76.1	7.1	6.7	Sandy	15.0	7.0	9.0	7.05	0.66	0.38
45-60	9.9	75.9	7.3	6.9	Sandy	15.0	7.0	9.0	7.30	1.64	0.39

Table2. Chemical characteristics of the investigated soil.

Depth, cm	pH 1:2.5	EC dS/m	Soluble Cations, meq/L				Soluble Anions, meq/L			
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{--}	Cl^{-}
0-15	8.1	0.40	0.55	0.42	1.10	0.25	0	0.15	0.90	1.35
15-30	8.2	0.42	0.58	0.47	1.12	0.26	0	0.16	0.92	1.31
30-45	8.3	0.39	0.60	0.45	1.15	0.24	0	0.14	0.88	1.30
45-60	8.4	0.75	0.70	1.50	1.18	0.28	0	0.18	0.94	1.28

Table 3. Some chemical properties of irrigation water used.

pH	EC dS/m	Soluble cations, meq/L				Soluble anions, meq/l				SAR
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{--}	Cl^{--}	
7.4	0.45	0.80	0.28	2.8	0.15	0	1.0	0.35	2.60	4.75

The means of treatments were compared utilizing analysis of variance (ANOVA) and the least significant difference (L.S.D) at a significance level of 1%. Steel and Torrie (1980.(

Results and Discussion

Effect of Localized Irrigation Systems (LIS) on Grain Yield, Stover Yield, and Water Productivity (WP):

The data indicates that the bubbler irrigation system (BIS) produced the highest grain and stover yields compared to the mini-sprinkler irrigation system (MSIS) and the drip irrigation system (DIS). For example, the grain yield under BIS was 5009.73 kg/fed, which is higher than MSIS (4835.60 kg/fed) and DIS (4374.15 kg/fed). In terms of water productivity, the BIS system showed the highest efficiency in both grain yield (WPg = 1.64 kg/m³) and stover yield (WPs = 1.72 kg/m³) compared to other systems. This suggests that the bubbler irrigation system provides more yield per cubic meter of water applied, making it the most water-efficient system among those tested.
Conversely, the drip irrigation system (DIS) was the least efficient in terms of water use and yield, showing the lowest values for both WPg and WPs.

Table 4. Localized Irrigation Systems (LIS) and Humus Compound Fertilizer (HCF) Effects on Maize Yield and Water Productivity (WP).

LIS	Applied HCF (kg/fed)	Applied Water (m³/fed)	Grain Yield (kg/fed)	Stover Yield (kg/fed)	WPg (kg/m³)	WPs (kg/m³)
BIS	50	3372.82	5315.86a	5437.85a	1.74a	1.77a
	25		4905.78c	5266.14c	1.60c	1.72c
	0		4807.55e	5101.25e	1.57e	1.66e
MSIS	50	3359.28	5086.07b	5299.14b	1.66b	1.74b
	25		4793.03f	5020.62f	1.57fe	1.64f
	0		4627.59g	4973.99g	1.52g	1.63h
DIS	50	3338.94	4802.41d	5165.82d	1.58d	1.71d
	25		4240.61h	4977.50h	1.40h	1.64gf
	0		4071.43i	4856.83i	1.34i	1.60i
Effect of HCF Levels		50	5067.78a	1.66a	5295.10a	1.74a
		25	4646.51b	1.52b	5087.05b	1.67b
		0	4502.19c	1.47c	4976.95c	1.63c
Interaction: LIS X HCF Levels			5009.73a	1.64a	5268.45a	1.72a
			4835.60b	1.58b	5097.62b	1.67b
			4374.15c	1.44c	5000.05c	1.65cb

LIS: Localized Irrigation System; HCF: Humus Compound Fertilizer applied; (HCF50): Humus Compound quantity applied = 50 kg/fed; (HCF0): Humus Compound quantity applied = 0 kg/fed. BIS: Bubbler Irrigation System, MSIS: Mini-Sprinkler Irrigation System, DIS: Drip Irrigation System, WPg: Grain Water Efficiency Water Productivity of Stover.

Table 5. Effect of different localized irrigation systems and humus compound fertilizer treatments on fertilizer productivity(FP).

		Applied fertilizers (kgfed^{-1})				FP (kg yield kg fertilizer^{-1})		
LIS	**HCF (kg/fed)**	**N**	**P2O5**	**K2O**	**Grain yield (kg fed^{-1})**	**FP (kg yield kg fertilizer^{-1})**	**FPN**	**FPP2O5**
BIS	50	77.55	93.39	83.38	5315.86	75.46	62.59	70.4
	25				4905.78	69.63	57.75	65.01
	0				4807.55	68.20	56.65	63.69
MSIS	50				5086.07	72.16	59.95	67.32
	25				4793.03	67.98	56.43	63.47
	0				4627.59	65.67	54.56	61.27
DIS	50				4810.41	68.20	56.65	63.69
	25				4240.61	60.17	49.94	56.21
	0				4071.43	57.75	47.96	53.9
LSD 0.01						0.01		
Means	50				5009.73	71.06	58.96	66.33
Means	25				4835.6	68.64	56.98	64.02
Means	0				4374.15	62.04	51.48	57.97
LSD 0.01					7.04	2.42	1.65	0.01

LIS, Localized Irrigation System; HCF, Humus Compound Fertilizer applied; FP, Fertilizer efficiency; (FP)N, Nitrogen efficiency; (FP)P2O5, Phosphorus efficiency; (FP)K2O, Potassium efficiency; (HCF100), Humus compound amount applied: 50 kg/fed; (HCF50), Humus compound amount applied: 25 kg/fed; (HCF0), Humus compound amount applied: 0 kg/fed; BIS, Bubbler Irrigation System; MSIS, Mini-Sprinkler Irrigation System; DIS, Drip Irrigation System.

Effect of Humus Compound Fertilizer (HCF) Levels on Grain Yield and Water Productivity:

Applying 50 kg/fed of humus compound fertilizer (HCF50) resulted in the highest grain yield (5067.78 kg/fed) and stover yield (5295.10 kg/fed), along with the best water productivity values (WPg = 1.66 kg/m³, WPs = 1.74 kg/m³). Reducing the fertilizer amount to 50 kg/fed (HCF50) significantly decreased these values.

When no fertilizer was applied (HCF0), the grain and stover yields dropped considerably, reflecting the critical role of fertilizer in improving both productivity and water-productivity.

Correlation between factors:

Irrigation Systems and Fertilizer Application: There is a positive correlation between more efficient irrigation systems (such as BIS) and higher fertilizer application rates. For instance, the combination of BIS and 50 kg/fed fertilizer produced the highest yields and water-productivity. Conversely, lower fertilizer amounts or less efficient irrigation systems resulted in reduced productivity.

Relationship Between Grain Yield and Water Productivity: A strong correlation exists between grain yield and water productivity, with more efficient irrigation systems (BIS) and higher fertilizer levels resulting in the best water productivity values. This indicates the significant impact of organic fertilizers on enhancing water use in sandy soils and improving crop yield.

Impact of Irrigation Systems on Water Productivity: The table shows that higher-flow irrigation systems like BIS and MSIS achieved better water productivity compared to the drip irrigation system (DIS), which had the lowest efficiency. This highlights the influence of irrigation systems on the effective use of water resources. Fertilizers productivity (FP):

Table (5) illustrated the impact of LIS and HCF treatments on the efficiency of fertilizer utilization for N, P2O5, and K2O (FPN, FPP2O5, FPK2O).

Based on the fertilizer productivity (FP) values for the three fertilizers applied, the treatments involving the localized irrigation system (LIS) and the organic compound fertilizer (HCF) can be ranked in the following ascending order: DIS < MSIS < BIS and (HCF0) < (HCF50) < (HCF100). Significant differences in fertilizer productivity (FP) were detected between the LIS and HCF treatments at the 1% significance level, with the exception of the comparison between (BIS; MSIS) and (HCF50; HCF0) concerning nitrogen productivity (FP)N. The interactions between the LIS and HCF treatments exhibited significant effects at the 1% level for certain interactions, while others lacked statistical significance. The maximum recorded values for nitrogen productivity (FPN), phosphate productivity (FPP2O5), and potassium productivity (FPK2O) were 68.6, 56.9, and 64.0 kg/kg of fertilizer, respectively, while the minimum values were 52.5, 43.6, and 49.0 kg/kg of fertilizer. These results stemmed from the interactions: BIS X (HCF50) and DIS X (HCF0), respectively. These findings were corroborated by Balliger and Bennett (1986).The collected data showed that fertilizer productivity (FP) followed a similar pattern in vegetative growth, yield, and water productivity (WP) indicators. This observation can be explained by the direct linear relationship between water productivity (WP) and fertilizer productivity (FP) reported by Tile et al. (2006).

Increased Nutrient Application; The data indicates that the application of nitrogen (N), phosphorus (P2O5), and potassium (K2O) fertilizers has a significant impact on grain yield. An increase in nitrogen levels is associated with improved grain yield, with the highest yield achieved at the maximum nitrogen application of 50 kg/fed in the Bubbler Irrigation System (BIS) treatment.

Yield Response to Fertilizers; The yield per unit of fertilizer applied (FP) illustrates that higher fertilizer applications typically result in increased grain yields. For example, at an application rate of 50 kg/fed of nitrogen, the grain yield is elevated, reflecting an effective conversion of fertilizer into yield.

Comparison of Treatments; The BIS treatment consistently yields the highest grain output across all fertilizer levels. In contrast, the Drip Irrigation System (DIS) treatment displays the lowest grain yields, particularly with lower fertilizer applications. This variation implies that the effectiveness of fertilizer application may depend on the type of treatment used.

Fertilizer Efficiency; The FP values reflect the efficiency of each fertilizer type in contributing to grain yield. These values exhibit different efficiency levels across treatments, indicating that both the fertilizer type and its interaction with the treatment significantly affect crop performance.

Statistical Significance; The Least Significant Difference (LSD) values highlight the level of statistical significance among the means. A lower LSD value indicates a higher likelihood that the differences in means are statistically significant. This is essential for assessing the reliability of the results and drawing conclusions regarding the effects of various treatments and fertilizer applications.

Discussion

The data presented in the two tables reflects the significant impact of different treatments and fertilizer applications on crop yields and water productivity (WP). The first table highlights the relationship between the applied water, grain yield, and stover yield across different irrigation strategies

(BIS, MSIS, DIS). The second table provides insights into how varying fertilizer applications of nitrogen (N), phosphorus (P2O5), and potassium (K2O) affect grain yields and fertilizer productivity.

Irrigation Strategies and Their Effects on Yield

From the first table, it is evident that the BIS (Best Irrigation Strategy) consistently produced higher yields compared to MSIS (Moderate Irrigation Strategy) and DIS (Deficit Irrigation Strategy). This finding aligns with previous research emphasizing that adequate water supply is crucial for maximizing crop yield. For instance, studies have shown that optimal irrigation practices significantly enhance grain production, leading to better water productivity (Zhang et al., 2023).

The data also indicates a clear trend: as the applied water increases, both grain and stover yields improve, illustrating the relationship between water availability and crop productivity. This is consistent with the findings of Farahani et al. (2020), who stated that sufficient water application directly correlates with increased biomass and grain yield, especially in drought-prone areas.

Fertilizer Application and Yield Response

The second table demonstrates that increasing fertilizer applications significantly enhances grain yields. The nitrogen application shows a particularly strong effect, with yields improving notably at higher rates. This is supported by recent literature suggesting that nitrogen plays a critical role in crop growth and yield enhancement due to its influence on physiological processes (Ali et al., 2022).

Moreover, the fertilizer productivity (FPN, FPP2O5, FPK2O) indicates that grain yield responses per kilogram of fertilizer applied vary by treatment. Higher FP values at increased N levels indicate a positive response of grain yields to nitrogen fertilization. This aligns with research by Zhang et al. (2023), who noted that optimizing nitrogen application rates can significantly improve fertilizer efficiency and overall crop performance.

Comparative Analysis of Treatments

A comparison of the treatments indicates that the BIS strategy, which integrates adequate irrigation with optimal fertilization, achieves the most favorable outcomes. This holistic approach to resource management is supported by research demonstrating that integrated crop management practices improve not only yield but also sustainability (Gupta et al., 2022; Mansour et al., 2015 a-e; Mansour et al., 2019a-e; Hu et al., 2019; Abdalla et al., 2019; Jiandong et al., 2019; Abd-Elmabod et al., 2019a-b; Tayel et al., 2012a,b; Tayel et al., 2016; Hellal et al., 2019; Mansour and Pibars, 2019; Attia et al., 2019; Hellal et al., 2021; Mansour et al., 2020a-d; Mansour and Aljughaiman, 2020; Eldariry et al., 2015; EL-Hagary et al., 2015). Additionally, the findings underscore the inefficiencies in water and fertilizer use observed in the DIS treatment, highlighting the necessity for precise irrigation and nutrient management strategies to maximize agricultural productivity in environments with limited water resources.

Conclusion

The results from both tables underscore the essential connection between irrigation and fertilization methods in maximizing grain yield and resource utilization efficiency. Ongoing study is essential to enhance these methods and adjust them to evolving environmental situations. Given the escalating pressures on agriculture from climate change and resource constraints, efficient management of water and nutrients will be crucial for sustainable crop production.

Currently, the world faces significant challenges related to food insecurity and widespread malnutrition, compounded by limited water resources, a continually increasing population, severe climate change, environmental pollution, and insufficient dependence on biofuel energy. Dehydration is a major factor leading to reduced crop yields. To combat drought and water stress in crops, it is crucial to implement modern irrigation techniques known as localized irrigation systems (LIS), especially for key crops like maize. This approach enables effective irrigation management, thereby alleviating drought conditions and positively impacting maize productivity and food security.

Moreover, the use of organic fertilizers, such as humus compound fertilizer (HCF), is essential, as it has recently been acknowledged for its beneficial effects on agricultural production, particularly in maize cultivation. From the results discussed, it can be concluded that applying the optimal amount of HCF (50 kg fed^{-1}) in conjunction with a bubbler irrigation system (BIS) significantly enhances water and fertilizer productivity (WP and FP) as well as maize crop productivity. The optimal outcomes were attained through the utilization of the bubbler irrigation system (BIS) in conjunction with 50 kg/fed of humus compound fertilizer, markedly enhancing both grain production and water productivity.

Decreasing fertilizer application or employing less effective irrigation systems diminished productivity and efficiency, underscoring the necessity of choosing suitable irrigation methods and fertilizer quantities to optimize yield and resource utilization.

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