Improving Water Use Efficiency of Maize Under A Laser Spray Irrigation System.

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ABSTRACT: The research highlights the urgent need for Egypt to enhance its agricultural productivity to meet the demands of its rapidly growing population. While widely used, the current prevalent method of surface irrigation suffers from inefficiencies primarily due to inadequate design and management. Consequently, there is a compelling demand for innovative field irrigation systems that can enable efficient water management. The Laser Spray Irrigation System (LSIS) is introduced as a groundbreaking alternative, characterized by its operation at low pressure, simulating gentle rainfall. This research aims to assess the performance of LSIS under varying pressure and spacing conditions and to evaluate its effectiveness as a replacement for Surface Furrow Irrigation (SFI) in terms of water use efficiency and maize yield under deficit irrigation scenarios. Laboratory experiments were conducted to evaluate LSIS performance. These experiments revealed that an operating pressure of 0.71 bar and a spacing of 4.0 meters between laser spray pipelines yielded optimal results. These results included a mean application rate of 11.23 mm/h, a coefficient of variation of 8.9%, a uniformity coefficient of 92.4%, and a distribution uniformity of 90.34%. These findings recommend the utilization of LSIS with a spacing of 4.0 meters and an operating pressure of 0.7 bar. Field trials demonstrated significant differences between LSIS and SFI. While SFI applied the highest volume of water (908.7 mm at 100% ET_c), LSIS utilized substantially less water (409.3 mm at 60% ET_c) yet achieved a superior grain yield (10.02 t/ha compared to 6.81 t/ha with SFI). Water use efficiency values were notably higher for LSIS, ranging from 1.907 to 1.436 kg/m3 across different water stress coefficients. Additionally, LSIS exhibited superior grain water production, surpassing SFI by 32.04% while using 12.94% less water. These results confirm LSIS as an advanced and efficient irrigation method, particularly effective under deficit conditions. Furthermore, LSIS demonstrated superiority over SFI across all levels of deficit irrigation, with the highest maize growth and yield recorded at 80% ETc, followed by 100% ET_c. This underscores the potential of LSIS in enhancing maize productivity and water use efficiency. In conclusion, LSIS represents a cutting-edge approach for optimizing irrigation water utilization, clearly demonstrating its superiority over conventional methods under deficit irrigation conditions.

***Keywords**: Laser spray irrigation system, deficit irrigation, water use efficiency, maize, productivity*

1. INTRODUCTION

About 40% of the world's food is produced on irrigated land, while 70% of freshwater is used in agriculture. To increase food production as the global water crisis deepens, agricultural water supplies must be improved **(Wani and Karuku, 2022).** The Nile is Egypt's principal renewable supply of water, and a large portion of its summer supplies are imported from Ethiopia. Egypt's water supply will be affected by the Ethiopian High Dam. Additionally, in order to satisfy the needs of Egypt's rapidly expanding population, we must save every last drop of water for the traditional patterns of surface irrigation that are present on the majority of the country's irrigated land. So, it is necessary to regulate and improve irrigation management. Food insecurity is being threatened by water shortage, a global issue that is becoming more acute, especially in arid and semi-arid countries **(Abdelaal and Thilmany, 2019; Ouda *et al.*, 2020; Ahmed *et al.*, 2022).** Egypt is one of the arid countries with severe water scarcity according to **Wahba *et al.* (2018) Hussein *et al.* (2022)**. Similar to other regions worldwide, Egypt's agriculture faces several challenges, including water scarcity and the impacts of climate change **(Abdelghany *et al.*, 2021; Abd-Elaty *et al.*, 2022)**. Additionally, for Egypt's worrisome population growth, an effective use of the irrigation water that is available is crucial to boosting agricultural output. The burden on Egypt's agriculture is growing along with the country's population as a whole **(Amer *et al.*, 2017)**.

Water supplies for irrigation are decreasing worldwide, especially in Egypt. Long drought stretches, poor precipitation distribution, and groundwater declines contribute to this deterioration **(McGuire, 2004)**. Due to a scarcity of surface water in Egypt, many regions now rely heavily on groundwater for agriculture. According to **Tan *et al.* (2015)** and **Zhao *et al.* (2014)**, groundwater levels are steadily declining, and overuse of these scarce water resources has necessitated the development of water-saving techniques to increase agricultural productivity and Irrigation water use efficiency (IWUE). Therefore, increasing the irrigation water productivity (IWP) of crops produced in these areas, such as maize, is required to enhance the management and consumption of soil water **(Li *et al.,* 2001; Gao *et al.,* 2014)**.

Traditional irrigation wastes too much water and causes water logging and salinity in many regions **(Bhattacharya, 2007)** Under situations of restricted water supply, it is necessary to increase irrigation efficiency through water optimization. Under these conditions, pressured irrigation is the only method that can achieve high application efficiency. To increase water consumption efficiency, pressurised irrigation systems including drip, trickle, and sprinkler irrigation have recently replaced open channel irrigation systems. To address the issue of irrigation development and management, irrigation research places a high importance on the evaluation of irrigation system performance. Many irrigation systems are not operating to their full potential. Water may not be distributed consistently and uniformly because of this circumstance. It is essential to have a pressured irrigation system that is well-designed if you want to meet irrigation plan objectives like efficiency and cost-effectiveness **(El-Agha *et al.*, 2011)**. The irrigation system must also fulfil a minimum pressure requirement while satisfying a variety of needs. Pressurized irrigation systems powered by solar photovoltaic pumps are challenging to implement, yet cost-effective alternatives that meet hydraulic limits are constantly needed. In these circumstances, a novel irrigation method known as Laser Spray irrigation is excellent for producing tightly spaced crops like groundnut, onion, and garlic, as well as vegetable crops. It functions on practically all types of soil **(Kathiriya *et al.*, 2021)**.

Laser Spray Irrigation System (**LSIS**) simulates light rainfall with low pressure. The lateral pipes have tiny laser-punched holes for water discharge in the form of sprays. Using LSIS instead of drip and sprinkler watering methods is innovative. Laser Spray and laser drip irrigation use laser holes at specific intervals to discharge small drops of water crop. With a life expectancy of roughly 3-5 years depending on usage and maintenance, Laser Spray accessories are relatively economical compared to other irrigation systems and are accessible to all farmers. Laser irrigation increases humidity and modifies the microclimate, improving yields, especially in the summer,

on a wide range of crops, especially leafy vegetables and onions. The Laser Spray modifies the microenvironment to reduce air temperature. Field crops of many types can benefit from laser irrigation. Laser irrigation prevents watering techniques that harm crops' fruit set, pollination, and blooming. Additionally, greenhouses and horticultural crops can benefit **(Yerasi *et al.*, 2022)**. A thin-walled, flat hose pipe called Laser Spray uses nano-punching technology that creates tiny holes in a zigzag pattern. On one side of the Laser Spray, there are microholes that are consistently spaced apart enough to maintain a consistent flow of water. The mistiest irrigation system is Laser Spray because of its tiny water spray. Compared to conventional sprinklers, it is softer and mistier. Sprinkler irrigation performance is influenced by variables such as the Christiansen uniformity coefficient and distribution uniformity operating pressure **(Aboamera and Sourell, 2003)**. In this trend, reported that each laser punch has a 12 m wetting diameter; however, the best results can be obtained at a 10m distance with 100 % overlapping. The Wall thickness of the lateral line is 0.3 mm. It can drizzle up to 5-6 feet (1.5 to 1.8m) in height depending on the operating pressure.

In the Poaceae family, maize (*Zea mays* L.) is a significant cereal crop that serves several functions in food and feed industries. Its products include maize oil, flakes, starch, dextrose, glucose, and animal and poultry feed **(Gul *et al.*, 2021)**. After rice and wheat, maize, or corn, is regarded as Egypt's third-most important fundamental food crop. In Egypt, maize is produced on 1.03 million hectares, or 25.2% of the total area used for agriculture. The average output is 8.3 tons per hectare **(FAOSTAT, 2023)**. By boosting grain output per unit of water and agricultural land, the Egyptian government intends to close the gap between demand and production.

A typical field crop called maize frequently employs flood irrigation, a traditional irrigation method that can cause salinization and water saturation. Basins, borders, or furrows are widely used in irrigation techniques to achieve this **(Ishfaq, 2002)**. Ineffective practises result in significant water loss, which raises salinization and water saturation levels and reduces irrigation effectiveness by creating barriers that keep tiny amounts of water from entering the system. Productivity must be improved and raised to meet the growing demand for agricultural goods and to offset yield decrease brought on by inadequate or erratic rainfall distribution. Irrigation, however, confronts several difficulties, including the need to produce more food of higher quality while using less water overall. The time and interval of irrigation affect soil water distribution, which influences the growth and distribution of plant roots, which influences above- and below-ground plant growth **(Hussain *et al.*, 2021; Neupane *et al.*, 2022)**. When there is a lack of water, irrigation is crucial for maintaining crop productivity, especially during droughts. As a result, water quotas for irrigated agriculture may be reduced to better assist other water resource stakeholders **(Ajaz *et al.*, 2019)**. As temperatures are predicted to climb due to climate change, soil evaporation increases, decreasing the amount of water available to crops. Soil evaporation in semi-arid regions can reduce the soil water balance by up to 50% of the total rainfall **(Kinama *et al.*, 2005)**. Climate change-related unpredictable regional and temporal patterns of precipitation are impeding the timely availability of irrigation water to meet agricultural water demands for the region's maize output **(Xiao *et al.*, 2020)**.

One of the management strategies that has been effectively used in a number of crops is deficit irrigation **(Zhang *et al.*, 2016)**. Deficit irrigation systems withhold or limit watering during specific development phases during the growing season, exposing crops to programmed drought stress. To enhance water usage efficiency (WUE), deficit irrigation systems offer crops less water than they need **(Chen *et al.*, 2018)**. In return, an acceptable yield penalty is incurred. When contrasted to the price or value of water maintained in locations with limited water resources, this yield penalty may be economically acceptable. According to **Chuanjie *et al.* (2015),** deficit irrigation has been effectively applied to enhance yield/unit water consumed and improve WUE in a variety of crops, including maize **(Jahansouz *et al.*, 2014)**. Due to the inaccurate operation of the traits such as water deficit stress during the pre-flowering and grain filling stages has a significant negative impact on the plant's performance as growth and yield **(Li *et al.*, 2018; Sah *et al.*, 2020; Gomaa *et al.*, 2021)**. Deficit irrigation is a significant factor in reducing plant growth, development, productivity, and quality **(Hussain *et al.*, 2019)**. Water deficit conditions affect plants at all periods of growth, especially at the vegetative stage **(El-Gedwy, 2020)**. Deficit irrigation is one potential adaptation technique that enables farmers to reduce irrigation quantity in accordance with irrigation quota and water availability **(Ouda *et al.*, 2020)**. All wheat cultivars' growth characteristics and productivity were significantly reduced by deficit irrigations, particularly when employing 50% IR. Additionally, it reduced NPK levels in plant shoots while increasing proline, peroxidase, and catalase levels. The quantity of water utilized to produce tons of wheat grains, or virtual water content, dropped as a result of this form of irrigation **(Saad *et al.*, 2023)**. On the other hand, **Abu-Grab *et al.* (2019); Kandil *et al.* (2023); Ramos-Fuentes *et al.* (2023)** revealed that irrigation deficit reduced growth, yield, its components, and water characteristics of maize.

Providing resources and opportunity for rural populations to live a healthy and productive life, applying climate-smart technology to ensure environmental sustainability, and contributing to the local and national economy are all problems that need to be overcome. Improving irrigation water management for agricultural production may increase output while reducing water usage. Only when agricultural water consumption is optimized is this feasible. boost water productivity by effectively managing water use **(Ishfaq, 2002)**.

A small sprinkler, drip irrigation, or surface irrigation alternative is the **Laser Spray Irrigation System (LSIS)**. To determine if LSIS is a viable alternative to **Surface Furrow Irrigation (SFI)** in terms of water consumption efficiency and yield of maize under deficit irrigation regimes, the research will assess the hydraulic performance of LSIS under variable pressure and spacing.

2. MATERIALS AND METHODS

2.1.Lab Experiment

2.1.1.Laser Spray Performance

The experiment was conducted within the Irrigation Laboratory of the Department of Agricultural and Biosystems Engineering, Faculty of Agriculture, Alexandria University, located in Egypt. The experimental setup comprised a 2 hp direct current (DC) electrical pump. A Laser Spray pipeline with an inner diameter of 32 mm and a length of 30 meters was positioned on the laboratory floor. The primary objective of the experiment was to assess the performance of a single Laser Spray pipeline and three Laser Spray pipelines, with varying distances between each pair set at 3.0, 3.5, 4.0, or 4.5 meters, as illustrated in **Figure 1**.

To facilitate data collection, a grid measuring 0.5 meters by 0.5 meters was employed to place a matrix of catch cans across the experimental area between each pair of Laser Spray pipelines. The experiment followed to a predetermined protocol to evaluate important performance indicators like Christiansen's Uniformity Coefficient (CU), Distribution Uniformity (DU), Coefficient of Variation (CV), and Mean Application Rate (MAR).

Initially, only one Laser Spray pipeline was operated for a duration of half an hour at four distinct pressure levels: 0.32, 0.53, 0.71, and 1 bar. Subsequently, three Laser Spray pipelines, with the same spacing of either 3.0, 3.5, or 4.5 meters, were operated for half an hour at the same four pressure settings: 0.32, 0.53, 0.71, and 1 bar.

The operating pressure was determined by the utilization of a manometer, while the regulation of said pressure was achieved by employing an aby-pass valve. The water discharged by the Laser Spray was collected in catch cans placed at the two sides laser spray pipeline and between each laser spray at four different pressures of 0.32, 0.53, 0.71 and 1 bar. The water depth in catch cans was measured and then converted into the depth of water in accordance with the cross-sectional area of the catch can.

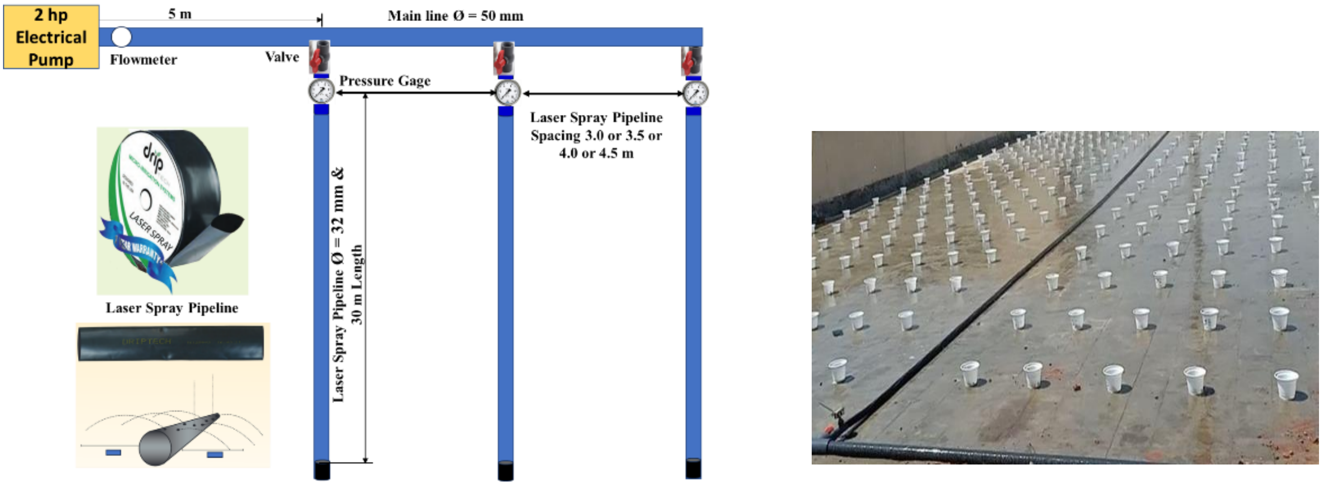

Fig. (1): Layout of the laser spray lab experiments

- **Uniformity Coefficient, U_c**

A quantifiable indicator of the level of uniformity achieved by any sprinkler of varying size operating within specific conditions is referred to as the uniformity coefficient. The formula used to calculate the uniformity coefficient is as follows, as proposed by **Christiansen (1942)**.

It is expressed by the equation:

$$U_c = \left(1 - \frac{\sum X}{\bar{X}\, N}\right) * 100 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where:

U_c is the uniformity coefficient established by {Christiansen, 1942 #102@@author-year}, %

X is the absolute deviation of the individual catch cans from the mean, mm

$\bar{x}$ is the average value of all catch-cans, mm

N is the number of catch-cans

- **Distribution Uniformity, D_u**

Distribution uniformity is a term that may be used to quantify the uniformity of application for irrigation systems (D_u). D_u is also known as pattern efficiency (Pe). It indicates the uniformity of water application throughout the field and is computed by,

$$D_u = \frac{\text{Minimum depth}}{\text{Average depth}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The determination of the minimum depth involves calculating the mean value of the lowest 25% of the cans utilized in a specific test.

- **Coefficient of Variation, CV**

Coefficient of variation (CV) is the quotient between the standard deviation of the applied water depths (SD) and the average water depth collected according to **Chaves and Nearing (1991)**.

$$CV = \frac{SD}{\dot{m}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where:

SD is the standard deviation of the water depth of catch-cans.

$\dot{m}$ is the mean of all water depth of catch-cans.

- **Mean Application Rate, I**

The mean application rate refers to the amount of water deposited onto the soil surface per unit of time by the Laser Spray system. This was computed using the subsequent formula:

$$\text{the } I = \frac{\sum X}{n * t} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where:

I = application rate, mm/h

Σx = total depth of water collected in the catch cans (volume/area of the can), mm

n = number of catch cans
t = time of operation, *h*

- **Discharge and Width Coverage**

The discharge rate of the Laser Spray system was ascertained by collecting the water discharged by the Laser Spray over a one-meter length during a specific time interval. This discharge observation was recorded twice for each operating pressure along a 30-meter length of the Laser Spray system. Additionally, the maximum width of the wetted area produced by a single Laser Spray system at various operating pressures was manually measured using a measuring tape.

2.2.Field Experiments

2.2.1.Location of Experiment

Two filed experiments were carried out at old Delta lands, Itay El-Baroud, El- Behira Governorate, Egypt (N 30° 53' 11.7564", E 30° 39' 56.3976") during 2022 and 2023 to evaluate the effectiveness of Laser Spray Irrigation System (LSIS) as alternate to Surface Furrow Irrigation (SFI) on water use efficiency and productivity of maize *cv* SC 3084 under deficit irrigation regimes (WSC =1.0, 0.8 and 0.6 of ET_c) in clay soil conditions.

2.2.2.Soil analysis

Before sowing, soil samples were collected from various locations at a depth ranging from 0 to 60 centimeters. These soil samples were then subjected to a series of physio-chemical assessments at the Faculty of Agriculture, Alexandria University. The determination of soil texture was accomplished using the hydrometer technique, as detailed by **Topp *et al.* (1993)**. Organic matter content was assessed utilizing the modified Walkey-Black method, as recommended by **Nelson and Sommers (1996)**. Available phosphorus (P) and potassium (K) levels were determined using the **Olsen and Sommers (1965)** method, while nitrogen content was estimated following the procedure of **Jackson (1958)**.

An overview of the physical and chemical analyses conducted at the experimental site is presented in **Table 1**, which represents the average data from two seasons.

Table (1): Some physical and chemical properties of the experimental site.

Physical Properties

Particle size distribution (%)			Soil texture class	BD (g cm^{-3})	F.C (% vol.)	PWP % vol.	TAW % vol.	Basic infiltration rate, f_o
Clay	**Silt**	**Sand**						
46.6	22.50	30.90	clay	1.32	37.90	17.40	20.60	5 mm h^{-1}

Chemical Properties

pH	OM	Total $CaCO_3$ %	EC_e dS/m	Soluble Cations (meq/l)				Soluble Anions (meq/l)				Total N %	Available (ppm)	
				Mg^{++}	Ca^{++}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}		P	K
8.25	1. 75	15.27	2.18	2.88	5.65	12.50	0.77	-	3.50	13.90	4.40	0.50	5.3	260.2

Water Irrigation Analysis

A subsidiary canal sourced from the Nile River, known as the Mahmoudiyah canal, provides the irrigation water supply for the field experiments. **Table 2** presents the outcomes of specific chemical analyses performed on this irrigation water.

Table (2): The chemical profile of irrigation water.

EC_e dS/m	pH	Soluble cations (meq/l)				Soluble anions (meq/l)			
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}
1.095	**7.70**	**3.39**	**1.66**	**2.67**	**0.65**	**-**	**0.577**	**0.225**	**1.60**

2.2.3.Soil Preparation and Sowing

Land preparation involved the utilization of a tractor for ploughing and harrowing, following which it was subdivided into plots measuring 30 meters by 4 meters, with a border spacing of 1 meter.

Yellow maize hybrid (Single Cross Pioneer 3084 = SC P3084) produced by Pioneer Company, Egypt, and grains were planted on the 6th and 4th of May 2022 and 2023, respectively. Each hill had two kernels planted by hand method. The furrow's length from the hill was 25 cm, and the distance between each furrow was 66 cm. Before the initial irrigation, plants were reduced to only one plant per hill. The first irrigation was applied two weeks after sowing; under LSIS, irrigation intervals for the initial, development, midseason, and late season stages were 15, 6, 4, and 4 days respectively; while, under SFI, the intervals were 15, 13, 12, and 12 days.

2.2.4.Field Experimental Design and Treatments

The experiment was structured using a Randomized Complete Block Design (RCBD) and involved two irrigation systems: the Laser Spray Irrigation System (LSIS) and Surface Furrow

Irrigation (SFI) used as a control. Each treatment was replicated three times. Three distinct soil water deficit irrigation regimes were applied consistently throughout the crop's growth period, all corresponding to a fraction of the crop's Evapotranspiration (ET_c), specifically at rates of 1.0, 0.8, and 0.6 of ET_c.

The experimental layout is depicted in Figure 2, illustrating the segregation of the two irrigation systems into separate plots. One plot was designated for the Laser Spray Irrigation System (LSIS), while the other was allocated for Surface Furrow Irrigation (SFI). Thorough field preparation included ploughing, harrowing, the removal of various plant residues, leveling of the field, and the creation of 66 cm wide furrows.

The total experimental area covered 2280 square meters, divided into six plots. Three of these plots were assigned to the Laser Spray Irrigation System (LSIS), each occupying 600 square meters (20 meters in width by 30 meters in length), with buffer zones between them (20 meters in width by 2.5 meters in length). Each LSIS plot contained three replicates without border areas (4 meters in width by 30 meters in length). The remaining three plots were designated for Surface Furrow Irrigation (SFI), with each SFI plot covering 120 square meters (4 meters in width by 30 meters in length), separated by a border area (4 meters in width by 2.5 meters in length). Each LSIS and SFI plot consisted of six furrows, each 30 meters long and 66 cm wide, with sealed ends.

The field slope was meticulously graded to maintain a precise slope of approximately 1 mm per meter. For irrigation, a portable agricultural gasoline engine water pump was employed, possessing the following technical specifications: Model (WP30), Outlet size (80 mm), Inlet size (80 mm), Speed (3600 rpm), Maximum discharge (60 m^3/h), Maximum static suction head (7 m), Maximum total dynamic head (30 m), and Maximum output power (6.5 HP).

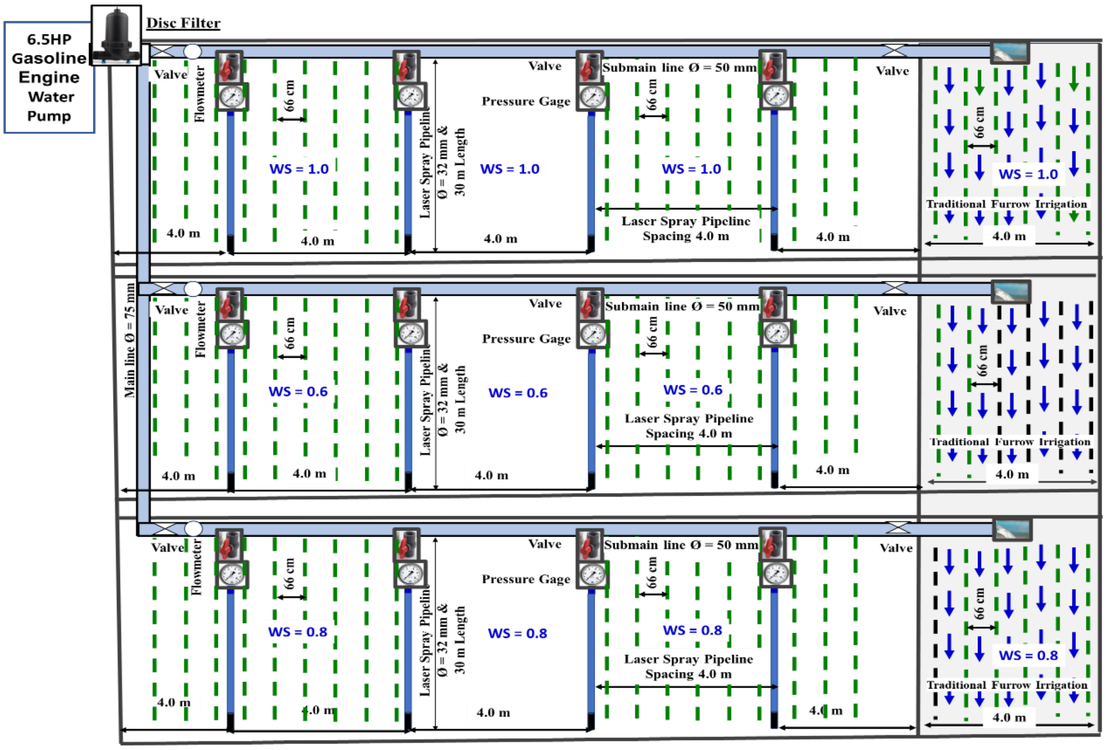

Fig. (2): Field Layout of Laser spray irrigation system and surface furrow irrigation experimental treatments and replicates.

2.2.5.Maize Fertilization

During both seasons, the potassium sulphate (K_2SO_4) form was treated at a rate of 120 kg/ha during sowing time. Before planting, a phosphorus fertilizer of '60 kg P2O5/ha' was added in the form of calcium super phosphate (15.5% P_2O_5). During the two seasons, ammonium nitrate (NH4NO3 - 33.50 N%) at a rate of '288 kg N/ha was utilized as the N source' and administered in four equal doses in LSIS during the four irrigations after sowing, while SFI was applied in three equal doses during the three irrigations after sowing.

Except for those being studied, all other agronomic techniques were kept regular and constant throughout all treatments as advised by the Ministry of Agriculture and Land Reclamation.

2.2.6.Field Irrigation Systems

A field experiment was conducted involving maize to make a comparative assessment between Surface Furrow Irrigation (SFI) and Laser Spray Irrigation Systems (LSIS). The irrigation systems employed a control head assembly, consisting of a disc filter, a non-return valve, a pressure regulator, a control valve, pressure gauges, and a gasoline-driven centrifugal pump.

For the LSIS setup, two laser spray lines of the ***Driptech type*** were utilized. These lines had a diameter of 32 mm, a wall thickness of 300 microns, operated at a pressure of 0.7 kg/cm2, and delivered a discharge of 89.9 liters per hour per meter at the specified pressure, with an effective wetting diameter of 8 meters. Each LSIS plot within the initial sub-plots of the maize crop during the growing season was irrigated using these two laser spray lines.

In contrast, the Surface Furrow Irrigation (SFI) system employed one pipeline equipped with a valve with a diameter of 50 mm. This pipeline supplied 180 liters per minute at a pressure of 1 bar and was equipped with one pressure gauge and one flowmeter. Each of the six furrows in every sub-plot of the maize crop, as depicted in **Figure 2**, was irrigated using this SFI setup.

2.2.7.Crop Water Requirement and Irrigation Management

The daily net water requirements of the crop were computed in accordance with Equation (5) as outlined by **Doorenbos (1975)**, and it is expressed as follows:

$$\mathbf{dn = ET_c = ET_o * Kc * WSC} \quad \dots\dots\dots\dots \quad (5)$$

Where: dn is the net irrigation water requirement (mm)

ET_c is the crop water requirement (mm),

ET_o is the reference crop evapotranspiration (mm),

Kc is the crop coefficient that varies by crop development stage, and

WSC is the water stress coefficient.

The maize crop coefficients (Kc) were determined as follows: 0.3 for the initial stage, 0.68 for the development stage, 1.17 for the mid-season stage, and 0.77 for the late stage, as specified by **Allen *et al.* (1998)**. The corresponding stage durations were 18 days for the initial stage, 32 days for the development stage, 40 days for the mid-season stage, and 30 days for the late stage. These values, in conjunction with the water stress coefficient (WSC) associated with each irrigation treatment level in the experiment, were used to calculate the crop water requirement (ET_c) for the growing months of May through August. The ET_c values were determined as 4.71 mm/day, 5.37 mm/day, 5.38 mm/day, and 5.06 mm/day, respectively, employing the FAO Penman-Monteith method as detailed by **Allen *et al.* (1998)**.

To establish irrigation schedules, historical weather data spanning a 15-year period (2005-2020) was sourced from the Egyptian Meteorological Data of GEMMEIZA, situated at an elevation of 20 meters above sea level, located at coordinates 30.71° N and 31.11° E.

Each irrigation treatment was characterized by a specific WSC value, with WSC (1) representing 100% of ET_c with no water stress, WSC (0.8) corresponding to 80% of ET_c, and WSC (0.6) equivalent to 60% of ET_c. Irrigation was administered using the **Laser Spray Irrigation System (LSIS)** on the same day for all treatments, achieving a water application efficiency of 85%. However, **Surface Furrow Irrigation (SFI)** followed the irrigation schedule with identical WSC treatment levels but with a water application efficiency of 60%.

Using the following equation, which **Allen *et al.* (1998)** described, the gross daily crop water requirements—also known as gross irrigation depth—were calculated:

The gross daily crop water requirements, also known as gross irrigation depth, were computed using the following equation described by:

$$\mathbf{dg = \frac{dn}{E_a(1-LR)}} \quad \dots\dots\dots(6)$$

dg represents the gross irrigation depth in mm,

E_a represents the water application efficiency,

LR represents the leaching coefficient, it was calculated according to **Ayers and Westcot (1985)** as follows:

$$\mathbf{LR = \frac{EC_i}{5EC_e - EC_i}} \quad \dots\dots\dots (7)$$

Where the electrical conductivity of irrigation water (EC_i) and saturated soil extract (EC_e) is given in dS/m.

To simulate the irrigation practices relevant to the Itay El-Baroud region, the LSIS treatments were allocated average irrigation intervals of 15 days during the initial stage, 6 days for the development stage, and 4 days for the mid and late seasons. Conversely, the surface furrow irrigation treatment was assigned irrigation intervals of 15 days during the initial stage, 13 days during the development stage, and 12 days for both the mid and late seasons. For each irrigation interval, the volume of applied irrigation water (Wm) in cubic meters per period was determined using the following equation **(Cuenca, 1989):**

$$\mathbf{W_m = \frac{\sum_1^n A * ET_o * K_c * \mathit{WSC}}{E_a(1-LR) * 1000}} \quad \dots\dots (8)$$

where: A is an irrigated area in m^2

n is the irrigation period in days

The water application efficiency of LSIS and SFI, (E_a) was calculated according to the following equation **(Doorenbos and Pruitt, 1977)**:

$$\mathbf{E_a = \frac{WCU}{W_m}} \text{ ....}\mathbf{(9)}$$

where:
WCU stands for seasonal water consumption utilization.

The total water consumed during each irrigation time period, expressed in millimeters (*WCU_m*), was used to determine *WCU*. According to **Israelson and Hanson (1962)**, *WCU_m* was determined using soil samples from various soil depths before and after 24 hours of each irrigation session.

$$\textbf{the } \mathbf{WCU_m = \sum_{i=1}^{ns} \frac{M_{ai} - \rightleftarrows M_{bi}}{100} \times \gamma_{si} \times z_i} \text{ ....}\mathbf{(10)}$$

where:
m symbolizes the irrigation (Nr.),
i symbolizes the soil-layer (Nr.),
ns symbolizes the soil-layer numbers,
M_{ai} and M_{bi} correspond to the soil-moisture content by (weight %) after 24 hours of irrigation. and before the next irrigation immediately for layer i,
γ_{si} symbolizes the specific bulk density of the soil layer, and
z_i symbolizes the thickness of the soil layer.
The root zone's three levels (0-20, 20-40, and 40-60 cm) were chosen to depict it. According to the experimental findings, the E_a was determined to be 0.85 for LSIS but 0.6 for surface furrow irrigation.

2.2.8.Irrigation Treatments

The Laser Spray Irrigation System and Surface Furrow Irrigation were applied at three distinct irrigation levels, corresponding to 100%, 80%, and 60% of the crop water requirement (ETc). These irrigation treatments were replicated three times for each treatment, as illustrated in **Figure 2**. Water application was synchronized with the prescribed irrigation schedule for each respective irrigation system. The maize cultivation's irrigation season concluded nine days before the commencement of the harvest.

2.2.9.CROPWAT-model

The CROPWAT version 8.0 model, as developed by **Swennenhuis (2006)**, was employed for the computation of crop water requirements and the formulation of irrigation schedules to assess various water management strategies. The input parameters for the CROPWAT model encompassed climatic, crop, and soil data:

- Daily rainfall data and reference crop evapotranspiration (ET_o) data were obtained from the Egyptian Meteorological Data of GEMMEIZA.
- A cropping pattern was established, comprising information regarding the crop type, planting date, and crop coefficient data files containing K_c values and depletion fraction (*p*). The depletion fraction values were determined as 0.65 for the initial and mid-season stages and 0.57 for the late-season stage, following the methodology outlined by **Allen *et al.* (1998)**, employing the subsequent equation:

$$\mathbf{p = p_{ET5} + 0.04(5 - ET_c)} \text{ ... ... } \mathbf{(11)}$$

where: p is the cropping pattern (average percentage of the total amount of soil water), and p_{ET5} is the percentage of soil water depletion under no stress (for maize 0.55)

- The following measurements for each soil type were made: total soil moisture that is now accessible, maximum rain penetration rate, maximum rooting depth, and initial soil moisture depletion.
- Scheduling criteria: The options of user-defined net application depth (calculated from Eq. 5) and irrigate at user-defined irrigation intervals by days for LSIS and SFI were used to develop the irrigation schedule for all treatments. This was done after the completion of both seasons in 2022 and 2023. The scheduling criteria for the three irrigation treatments were entered into the CROPWAT model along with the climatic data for LSIS and SFI, and the results of deep percolation (DP), irrigation schedule efficiency (EIS), irrigation schedule deficiency (DIS), and yield reduction (Y_R) were gathered and examined.
- The efficiency irrigation schedule (EIS) assesses how well the crop utilises the net irrigation (I) contributions over the growing season. The EIS is calculated as the ratio between net irrigation (I), which is the difference between net irrigation and irrigation losses, and net irrigation, which is given as a percentage **(Swennenhuis, 2006)**. Net irrigation, or irrigation water that reaches the root zone, is not always effectively utilized by the crop. Consequently, the following equation might be used to determine the EIS.

$$\text{the the EIS} = \frac{\sum(I_i - DP_i)}{\sum I_i} \times 100 \quad \text{... ... ...} \mathbf{(12)}$$

The deficiency in the irrigation schedule (DIS) is quantified as a percentage and is determined by comparing the deficit in irrigation water, which is the variance between the crop's reference water consumption (seasonal ET_c) and the actual water consumption by the crop (seasonal $ET_{c\ adj}$), relative to the crop's reference water consumption, as outlined by **Swennenhuis (2006)**.

Consequently, the calculation of DIS is expressed as follows:

$$Seasonal\ \mathrm{ET_c} = \sum (\mathrm{ET_o} \cdot \mathrm{K_c}) \ \ldots\ldots\ldots\ldots\ \ldots(\mathbf{13})$$

$$\mathrm{Seasonal\ ET_{c\,adj}} = \sum (\mathrm{ET_o} \cdot \mathrm{K_c} \cdot \mathrm{daily\ WSC_i}) \ldots\ldots(\mathbf{14})$$

$$\mathrm{DIS} = \frac{\mathrm{Seasonal\ ET_c} - \mathrm{Seasonal\ ET_{c\,adj}}}{\mathrm{Seasonal\ ET_c}} \times 100 \ldots(\mathbf{15})$$

The reduction in crop yield resulting from soil moisture stress is represented as a percentage of the maximum attainable production under ideal conditions within the given region. This reduction can be calculated with respect to either a specific stage of the crop's growth cycle or the entirety of the growing season. To express yield reduction, the following equation is applied:

$$an\mathrm{Y_R} = \left(1 - \frac{\mathrm{GY_a}}{\mathrm{GY_{max}}}\right) = \mathrm{K_y}\left(1 - \frac{\mathrm{ET_{c\,adj}}}{\mathrm{ET_c}}\right) \ldots\ldots\ldots\ldots(\mathbf{16})$$

GY_a is the grain yield that can be produced under current conditions, GY_{max} is the crop yield that can be produced if all of the crop's water needs are met, and K_y is the yield response factor, which is chosen to be 0.4, 0.4, 1.3, 0.5, and 1.25 for the initial, development, mid-season, and late-season stages, respectively, of the growing season **(Doorenbos and Kassam, 1979)**.

2.2.10.Maize Parameters

Growth Parameters were studied as follows; Plant height (cm) at harvest was taken from the soil surface to the leave base of the highest fully expanded leaf. Measurements were taken from five tagged plants per treatment using a meter ruler, Leaf area index (LAI) was calculated by the following formula LA = L ×W×0.75 where; LA= leaf area, 0.75 = constant), where leaf area (LA) divided by land area per plant (p), where the leaf length (L) and width (W) **(Radford, 1967)**, and Total chlorophyll content (SPAD) was determined by chlorophyll meter apparatus using 5 random leaves taken from each plot at (90 DAS), according to the method that described by **Minolta (1989)**.

The yield and its component characteristics were determined at 120 days after sowing (DAS) as follows; Ear height (cm), Ear length (cm), Number of rows/ear, and Number of grains/row were determined from ten plants which were taken from each plot. While 100- grains weight (g) was recorded from five randomly, and an average for the treatments. This measurement was done using a weighing machine. Meanwhile, Biological yield (t/ha) was calculated from the weight of all plants (grain + straw) from the middle rows in each plot, also Grain yield (t/ha) was recorded from air-dried cob, separated, and cleaned before drying it to 14% moisture content. The grains were weighed and recorded in kilograms (kg) before it was converted to t/ha and Straw yield (t/ha): was calculated as follows: Straw yield (t/ha) = Biological yield – Grain yield. 9- Harvest index (HI%): this refers to the crop's economic yield divided by total dry weight, as described as follows by **Donald and Hamblin (1976)**; **Harvest index**

$$\mathbf{(\%)} = \frac{\textbf{Grain yield}}{\textbf{Biological yield}}\mathbf{x100} \ \ldots\ldots\ldots\ldots(\mathbf{17})$$

2.2.11.Crop Water Productivity, CWP

The ratio of grain yield (GY) to volume of applied water (W), as evaluated by **Kijne *et al.* (2003)**, is the measure of agricultural water productivity:

$$\mathbf{CWP} = \frac{\mathbf{GY}}{\mathbf{W}} \quad \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\mathbf{18})$$

In general, the connection between GY (grain yield) and W (applied water) is referred to as the grain-water production function (GWPF). The GWPF takes on a curvilinear shape because a portion of the surplus applied water is lost through drainage or other means. It essentially illustrates the advantage of applying water in terms of producing grain yield or biological yield. The quadratic polynomial function, as proposed by **Helweg (1991)**, is articulated as follows:

$$\mathbf{GY = b_0 + b_1W + b_2W^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(\mathbf{19})$$

where GY is grain yield (ton ha^{-1}), W is applied irrigation water (m^{3}ha^{-1}), and b_0, b_1, and b_2 are fitting coefficients.

As the yield nears its maximum attainable value, the gradient of the water productivity function in relation to applied water diminishes to zero. Consequently, the maximum amount of applied water (W_{max}) was determined by setting the derivative of GY (as per Equation 20) to zero. Subsequently, the maximum predicted yield (GY_{max}) was computed by inserting the value of W_{max} into the final equation **(Ismail, 1993a; Ismail, 1993b; Aly and Benaabidate, 2010)**.

$$\mathbf{\frac{dGY}{dW} = b_1 + 2b_2W = 0} \quad \ldots\ldots\ \ldots\ldots\ldots\ldots(\mathbf{20})$$

$$\mathbf{W_{max} = \frac{-b_1}{2b_2}} \quad \ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots(\mathbf{21})$$

$$\mathbf{GY_{max} = b_0 + b_1W_{max} + b_2W_{mas}^2} \ \ldots\ldots\ldots(\mathbf{22})$$

2.2.12.Yield Water Relation

The ultimate crop yield was assessed at the conclusion of the growing season, following the harvest of the crop. A precise electronic balance with a sensitivity of 0.001 grams was employed to measure the weight of the maize grain yield across different treatment groups. To calculate the water use efficiency for each treatment within each irrigation system, the harvested grain yield was divided by the total seasonal water usage.

$$\mathbf{CWUE} = \frac{\mathbf{Ya}}{\mathbf{CWU}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; \mathbf{(23)}$$

where: CWUE is crop water use efficiency (kg/m^3),

Y$_a$ is the actual yield (kg ha^{-1}), and

CWU is crop water use (m^3 ha^{-1}).

Stewart *et al.* (1977) fitted the crop production response data from deficit irrigation to the following linear equation.

$$\textbf{the } 1 - \frac{Y_a}{Y_m} = K_y\left[1 - \frac{ET_a}{ET_m}\right] \ldots\ldots\ldots \mathbf{(24)}$$

Y_m **is** th maximum yield (ton ha^{-1}) from 100% water requirement,

Y_a **is** the actual yield (ton ha^{-1}) from different levels of water requirement,

ET_m and ET_a **are** maximum and actual evapotranspiration (mm), and

K_y **is** a yield response factor that indicates the response of maize grain production to deficit irrigation.

2.2.13.Statistical Analysis

Three replications of the randomized complete block design (RCBD) experiments were employed. Statistical analysis of the recorded data was performed using the statistical program **CoStat (2005)**. To test for significant differences between the means values of each treatment, Least Significant Differences (LSD) with 0.05 percent probability was used **(Steel and Torrie, 1960)**.

3. RESULTS AND DISCUSSION

3.1.Lab Experiment

3.1.1.Laser Spray Performance

The analysis of the data obtained from the laboratory tests occurred:

First: a single laser spray pipeline (30 m length) was operated to calculate Christiansen's uniformity coefficient (U_c), distribution uniformity (D_u), coefficient of variation (CV), mean application rate (I), Discharge per meter of laser spray (Q_m) and width coverage (WC) by a single laser spray pipeline, The results are shown in **Table (3).** The results show that at high or low operating pressure there was a decrease in the value of the uniformity coefficient, 72.72%, and an increase in the coefficient of variation, 31.36%. **Fig. (3)** shows the mean application rate of the laser spray pipeline under different pressure (single line). Additionally, at an operating pressure of 1 bar, the maximum width coverage was 9m (4.5 m radius). A single laser spray pipeline should not be used for irrigation since it was discovered during the execution of the experiments in the laboratory that the material could not withstand operating pressure of more than 1 bar.

Table (3): Effects of different operating pressures on the performance of laser spray pipeline

Operating pressure (bar)	Uniformity coefficient, Uc (%)	Distribution uniformity, Du (%)	coefficient of variation, CV (%)	Mean application rate, I (mm/h)	Discharge per meter, Q_m (LPH)	Width Coverage, WC (m)
0.32	76.59	72.44	29.27	9.84	59.09	6
0.53	79.31	80.71	25.49	10.52	73.66	7
0.71	78.27	65.58	25.67	11.24	89.91	8
1.0	72.72	73.51	31.36	12.02	108.14	9

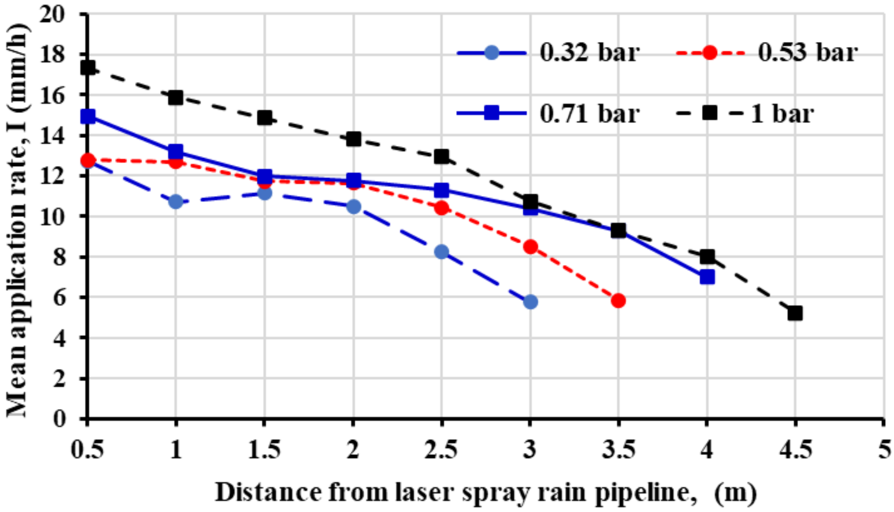

Fig. (3): Mean application rate of the laser spray pipeline under different pressure (single line)

Second: four different pressures of 0.32, 0.53, 0.71, and 1 bar were applied to three laser spray pipes (30 m in length) with the same spacing of 3.0, 3.5, 4.0 or 4.5 m for a half-hour before the determination of Uc, Du, CV, I, and Q_m in each instance (pressure & space), as indicated in **Table (4). Fig. (4)** shows mean application rate of the laser spray pipeline under various operating pressures for each of the two pipelines (100% Overlap); in addition, the results demonstrate that at operating pressure 0.71 bar and a distance of 4 m between the laser spray pipelines, the coefficient of variation, CV (%) was 8.9% (less than 10%), the uniformity coefficient (Uc) was 92.4% and the distribution uniformity (Du) was 90.34%. therefore, it is recommended to use laser spray pipelines for irrigation with a 4 m (100% Overlap) distance between pipelines and 0.71 bar operating pressure.

Table (4): Effects of different operating pressures on the performance of laser spray pipelines at different distances between laser spray pipelines (100% Overlap)

Operating pressure (bar)	Uniformity coefficient, Uc (%)	Distribution uniformity, Du (%)	coefficient of variation, CV (%)	Mean application rate, I (mm/h)	Discharge per meter, Q_m (LPH)	Distance between Laser Spray (m)
0.32	87.13	74.82	15.96	9.84	59.09	3
0.53	89.9	83.13	12.54	10.52	73.66	3.5
071	92.4	90.34	8.9	11.23	89.91	4.0
1.0	96.45	94.05	4.48	12.15	108.14	4.5

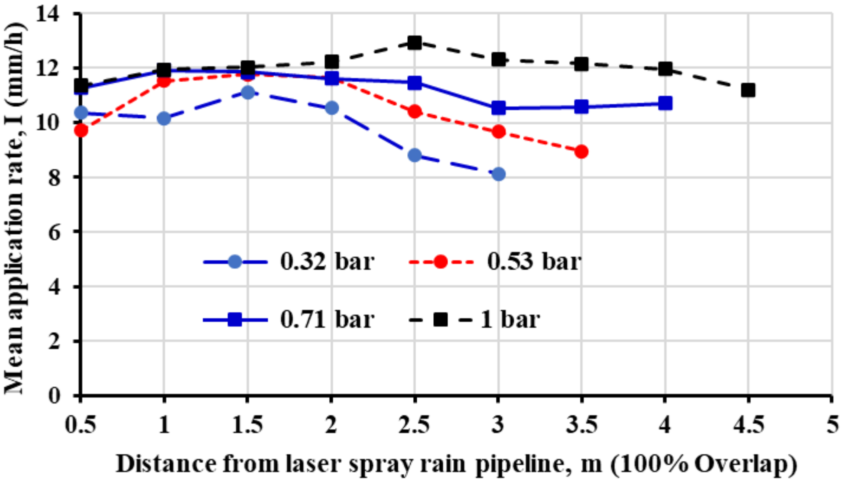

Fig. (4): Mean application rate of the laser spray pipeline under different pressures and different laser spray pipeline spacing (100% Overlap

3.2.Field Results

3.2.1.Irrigation Water Amount

LSIS was operated on the field at 0.71 bar operating pressure for a half-hour before the determination of Uc, Du, CV, I, and Q_m, as indicated in **Table (5)**.

Table (5): LSIS performance on the field at 0.71 bar operating pressure (100% Overlap)

Operating pressure (bar)	Uniformity coefficient, Uc (%)	Distribution uniformity, Du (%)	coefficient of variation, CV (%)	Mean application rate, I (mm/h)	Discharge per meter, Q_m (LPH)	Distance between Laser Spray (m)
0.71	90.7	88.03	9.7	10.02	84.73	4.0

The results demonstrate that at operating pressure 0.71 bar and a distance of 4 m between the laser spray pipelines (100% Overlap), the uniformity coefficient (U_c), the distribution uniformity (D_u), mean application rate (I) and discharge per each meter length (Q_m) were decreased by 1.8%, 2.6%, 1.2% and 6.1 respectively, in the same time, the coefficient of variation, CV (%) was increased to 9.7% (less than 10%). This effect is due to the difference in operating conditions between the laboratory and field experiments, especially the quality of the water used, as the water in the laboratory experiments was from the tap, but in the field from open channels.

Figure 5 illustrates how much water was applied for maize throughout the growing season by the two irrigation technologies, surface furrow irrigation and laser spray irrigation **(Table 6)**. For the three measured amounts of water input, the two irrigation systems exhibit a similar pattern. From the second irrigation event until the last irrigation event under LSIS or SFI, the shortage in applied water quantities from 100% of ET_c to 80% and 60% during the growing season was distributed equally. The maximum amount of applied irrigation water was achieved at mid-season growing stages in all irrigation treatment in LSIS and SFI, but the minimum value of applied water was achieved at late-season growing stages, 10 days before harvest. The SFI furrow irrigation technique produced the maximum gross water irrigation depth (920.6 mm at 100% of ET_c), whereas the LSIS approach produced the lowest value (403.72 mm at 60 percent of ET_c).

As a result of the surface LSIS's greater water application efficiency compared to SFI, it is advised when insufficient water is available. SFI application efficiencies were 60% and surface LSIS application efficiencies were 85%. **Yerasi *et al.* (2022)** reported that LSIS was more effective than conventional irrigation techniques in this trend.

Table (6): For LSIS and SFI, the total depth of irrigation during the maize growing seasons.

Days from planting	Growing stage	Kc	ET_o mm/day	Gross Irrigation Depth dg (mm)					
				LSIS			SFI		
				WSC = 1.0	WSC = 0.8	WSC = 0.6	WSC = 1.0	WSC = 0.8	WSC = 0.6
1-18	Initial	0.3	4.41	61	61	61	110	110	110
19-50	Development	0.75	5.37	151.6	121.3	91	214.8	171.8	128.9
51-90	Mid-season	1.2	5.38	303.8	243.0	182.28	430.4	344.3	258.2
91-120	Late	0.7	5.06	125.0	100.0	75.01	177.1	141.7	106.3
Total Irrigation depth (mm)				**641.41**	**525.31**	**409.29**	**908.7**	**767.8**	**603.4**

Kc = crop coefficient --- WSC = water stress coefficient.

The irrigation depths corresponding to various water stress coefficients (WSC = 0.6, 0.8, and 1.0), calculated using Eq. 9 and implemented in the field during both the 2022 and 2023 seasons, are depicted in **Figure 5**. These depths are presented for the following stages: the initial stage, development stage, mid-season, and late season, with average time intervals of 15, 6, 4, and 4 days for LSIS treatments, and 15, 13, 12, and 12 days for SFI treatments.

However, the starting irrigation depth for surface furrow irrigation was 110 mm. This adjustment was made due to the necessity of soil particle aggregation, reconfiguration of the soil surface, and facilitation of water movement to reach the furrow's end. In order to enhance seed germination, a higher initial watering depth, amounting to 61 mm, was used in the laser spray irrigation system, as calculated by Eq. 7.

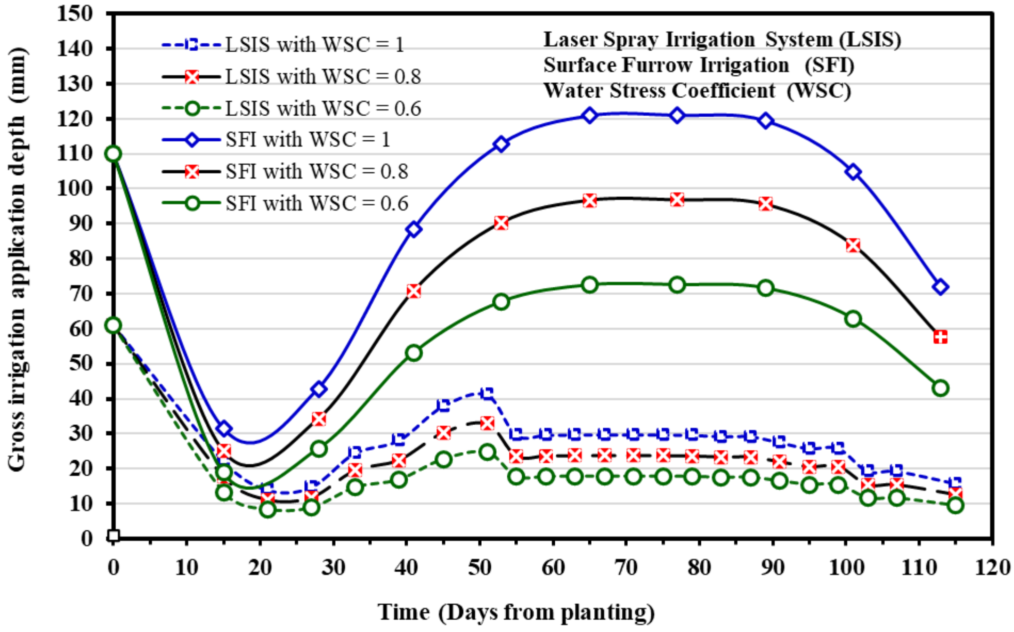

Fig. (5): Gross irrigation application depth along growing season under LSIS and SFI.

3.2.2.Scheduling Irrigation utilizing CROPWAT software.

The gross irrigation application depths (dg) for all irrigation treatments at the required time intervals, as shown in **Figure 5** above, were incorporated into the CROPWAT model as scheduling criteria. Additionally, daily reference crop evapotranspiration (ET_o) data, calculated for the location of GEMMEIZA (situated at 20 meters above sea level, coordinates 30.71° N and 31.11° E), were employed in conjunction with these criteria.

As a result, the CROPWAT model generated various outputs, including daily root zone depletion (daily $D_{r,i}$), deep percolation (DP), the daily water stress coefficient ($WSC_{,i}$), crop actual water use ($ET_{c\ adj}$), and irrigation schedule efficiency (EIS). These outputs collectively provided insights into the crop's water requirements, as delineated in **Table 7**.

Table (7): Crop water usage in total and in actuality, irrigation losses, and the effectiveness of the irrigation schedule for various irrigation treatments.

Irrigation Treatments (WSC)	Gross Irrigation depth dg (mm)	Total Rain (mm)	Crop Reference water use ET_c (mm)	Deep percolation loss DP (mm)	Crop actual water use $ET_{c\ adj}$ (mm)	Moisture deficit at harvest (mm)	EIS (%)
			Laser Spray Irrigation System, LSIS				
1.0	641.4	2.5	519.9	124	517.3	0.4	100
0.8	525.31	2.5	519.9	7.91	517.3	31.8	100
0.6	409.29	2.5	519.9	0	448.2	76.7	100
			Surface Farrow Irrigation, SFI				
1.0	908.7	2.5	519.9	391.3	506.9	15.7	100
0.8	767.8	2.5	519.9	250.4	506.9	15.7	74.9
0.6	603.4	2.5	519.9	86.0	506.8	16.0	99.6

The soil water balance over the course of the growing season was assessed for three water stress coefficients (WSC = 1.0, 0.8, and 0.6) under both LSIS and SFI irrigation systems, and the results are presented in **Figures 6 and 7**. The soil moisture content in the root zone can be quantified by a parameter known as root zone depletion (D_r), which represents the deficit in water relative to field capacity. At field capacity, the root zone depletion is zero ($D_r = 0$).

In instances where the net irrigation contribution leads to soil moisture content surpassing field capacity (F.C), any excess water above F.C is considered lost to deep percolation (DP). When the irrigation depth exceeds F.C., it is categorized as irrigation losses, as outlined by **Swennenhuis (2006)**. Figure 6 illustrates that, except for cases with a WSC of 1.0, LSIS treatments did not exhibit significant water losses. Specifically, in the case of WSC = 1.0, deep percolation (DP) losses amounted to 124 mm, representing 0.314 times the highest DP losses recorded in SFI treatment (WSC = 1.0).

Regarding the data presented in **Figure 7**, SFI treatments (WSC = 1.0 and 0.8) experienced measurable water losses due to deep percolation (DP) at all stages of maize growth. Consequently, the results indicate that the percentage of deep percolation (DP) when utilizing a water stress coefficient of WSC = 100% and 80% of ET_c under SFI was 3.16 and 31.66 times higher, respectively, in comparison to LSIS under the same WSC conditions. However, at WSC = 60% of ET_c, DP reached 860 m3/ha under SFI, while it remained at zero under LSIS.

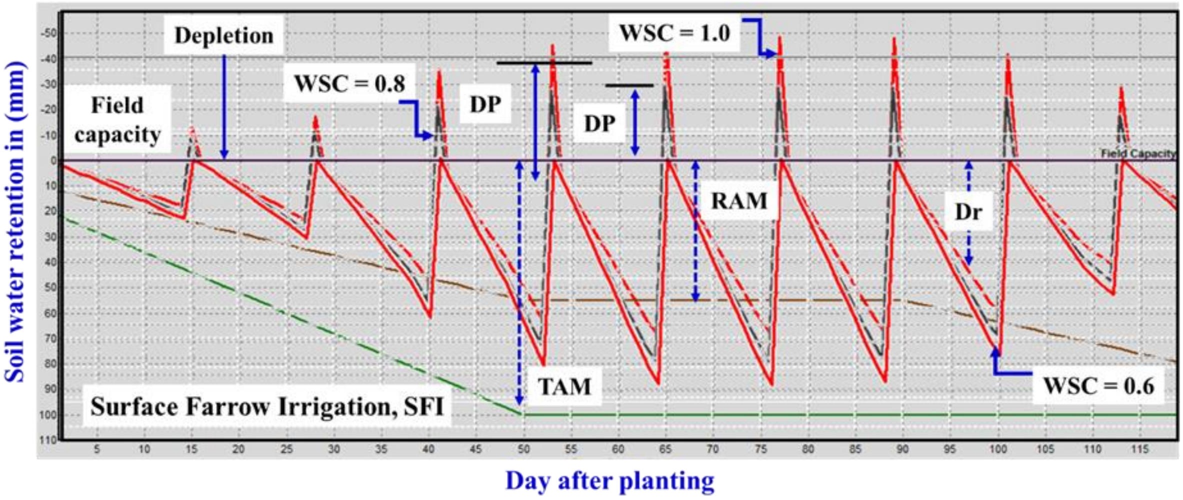

Fig. (6): Soil water balance during the growth season at WSC = 0.6, 0.8 and 1 under LSIS.

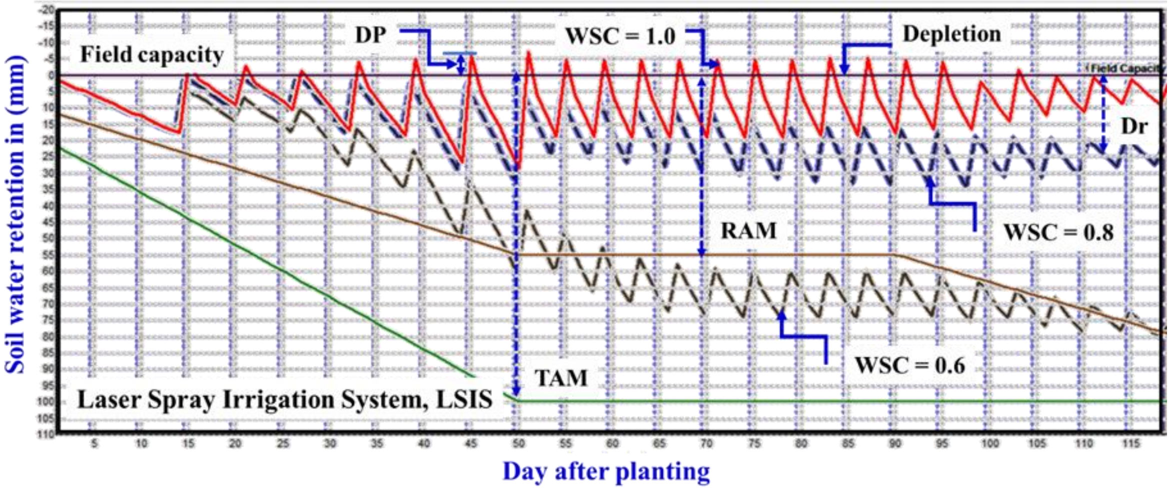

Fig. (7): Soil water balance during the growth season at WSC = 0.6, 0.8 and 1 under SFI.

3.2.3.Crop Water Use Efficiency

For the employed irrigation systems, the correlation between irrigation levels and maize grain output was quite similar. Except for the irrigation level decreasing from WSC = 1.0 to 0.8 utilising LSIS, where the yield improved by 8.08 percent, the maize grain yield dropped as the irrigation level decreased. However, the yield decline between LSIS and SFI was different. According to the results presented in **Table (8)**, the maximum maize grain yield at 80 and 100 percent of ET_c was 10.02 ton/ha and 9.21 ton/ha, respectively, with LSIS. At 100 percent of ET_c, the yield with SFI was 8.66 ton/ha.

The calculations of crop water consumption efficiency in relation to LSIS, SFI, and all three irrigation levels are shown in **Table (8)**. They show that the highest values of irrigation water use efficiency (1.907, 1.803 and 1.436 kg/m^3) were obtained with LSIS at WSC= 0.8, 0.6 and 1.0, respectively, followed by (1.129 kg/m^3) at WSC = 0.6 with SFI. The least water use efficiency value was 0.953 kg/m^3 registered with SFI at WSC = 1.0.

It is also evident that, at LSIS and SFI, the crop water use efficiency decreased when the application rate of water increased above 80% of ET_c. On the other side, at both LSIS and SFI, the crop water use efficiency increased with a decrease in the application rate of water except at 80% of ET_c with LSIS.

When comparing LSIS with SFI for the documented crop water usage efficiency, it is evident that LSIS has an edge in terms of water application efficiency. This is as a result of its greater agricultural water usage efficiency ratings compared to SFI data. This is as a result of the consistent moisture distribution in the maize effective root zone under LSIS.

Table (8): Crop Water Use Efficiency under LSIS and SFI.

Parameters	Irrigation Type					
	LSIS			SFI		
	WSC 1.0	WSC 0.8	WSC 0.6	WSC 1.0	WSC 0.8	WSC 0.6
Irrigation amount (m^3/ha)	6414	5253	4093	9087	7678	6034
Yield (t/ha)	9.21	10.02	7.38	8.66	8.24	6.81
Crop water use efficiency (CWUE) (kg/m^3)	1.436	1.907	1.803	0.953	1.073	1.129
Decreasing percent in yield due to water application (%)	8.08	0	26.35	0	5.1	27.17
Decreasing percent in yield due to irrigation system (%)	0	0	0	5.97	17.77	7.72
Decreasing percent in yield due to the interaction between water application and irrigation system (%)	8.08	0	26.35	13.57	17.77	32.04

A polynomial function was employed to establish a relationship between the seasonal irrigation water applied at various water stress coefficients and maize yield within the context of LSIS and SFI, as depicted in **Figure 8**. Through mathematical analysis of the grain-water production function (GWPF), it was determined that the projected maximum maize grain yield (GY) reached 20.93 and 8.145 tons per hectare (t/ha) for LSIS and SFI, respectively. This corresponded to calculated water irrigation amounts of 7100 m3/ha for LSIS and 8750 m3/ha for SFI.

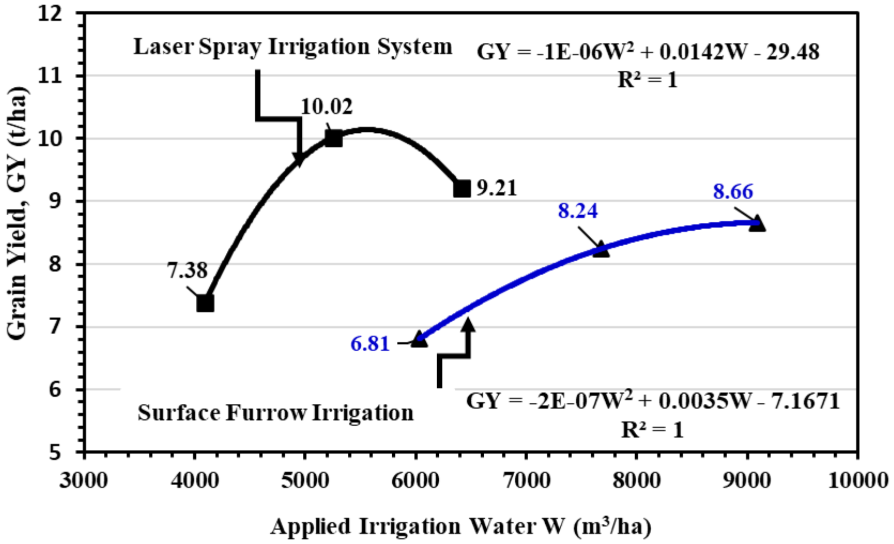

Fig. (8): Maize grain yield vs. applied irrigation water under LSIS and SFI.

The findings from **Table (7)** and **Fig. (8)** are in contrast to those reported by **Shehata (2009)**, who claimed that the irrigation system with the highest water usage efficiency (1.907 kg/m3) at WSC = 100% of ET_c and the LSIS with the lowest (1.803 kg/m3) at 60% of ET_c. **Abubaker *et al.* (2006)** and **Adeboye *et al.* (2015)** were nevertheless in agreement.

3.2.4Field Results Statistical Analysis

The results presented in **Table (9)** showed the effect of irrigation deficit on maize characters i.e., plant height (cm), leaf area index (LAI), chlorophyll reading (SPAD unit), days to 50% tasseling (days), 50% of silking (days), ear height (cm), grain number/row, grain number/ear, 100-grain weight (g), biological yield (t/fed), straw yield (t/fed), grain yield (t/fed), harvest index (HI %), and grain: stover ratio under laser irrigation system and surface irrigation during 2022 and 2023 seasons.

Concern to the effect of irrigation deficit of laser system and surface irrigation on growth, yield and its components characters, the results in **Table (9)** showed the significant effect of irrigation deficit on all the studied characteristics where irrigation deficit treatment WSC (80 %) under the modern system (LSIS) achieved the maximum values of plant height (303.6 and 300.8 cm), leaf area index (5.42 and 5.40), chlorophyll reading (58.92 and 58.28 SPAD), ear height (147.3 and 145.3 cm), ear length (26.50 and 25.33 cm), grain number/row (47.00 and 46.00 grains/row), grain number/ear (752.0 and 720.0 grains/row), 100- grain weight (40.27 and 40.67 g), biological yield (24.48 and 24.31 t/ha), stover yield (14.48 and 14.27 t/ha), grain yield (10.0 and 10.02 t/ha), harvest index (40.88 and 41.26 %), and grain: stover ratio (69.69 and 70.25), respectively in the first and second seasons.In addition to WSC (100 %) of ET_c with LSIS (modern system) and WSC (80%) with SFI (old system) came in the second order after WSC (80%) LSIS in comparison with the other treatment under the studied conditions in both seasons.

In the same **Table,** the results indicated that the lowest values of days to 50% of tasselling (53.27 and 52.83 days), and silking (56.00 and 56.00) were recorded with full irrigation of LSIS (100%), respectively in both seasons followed by irrigation deficit 80% under LSIS as comparing among the other treatments during the studied seasons. Meanwhile, irrigation deficit treatment such as WSC (60 %) under the two irrigation systems was given the lowest values of growth, yield, and yield components of maize in both seasons.

Our results which revealed that a deficit irrigation regime in arid regions with water limitations is one of the best methods for enhancing WUE. Irrigation water constraints under effective management showed significant savings with no effect on the yield's quality and quantity that cleared in **Table (9)** where this study examined the impact of irrigation deficit under modern system (LSIS) and traditional method (SFI) treatments on maize growth, yield and its component applied at different growth stages in an arid area. It was found that in comparison to full irrigation treatment WSC (100 %) during the two-irrigation systems, the application of WSC (80%) in the modern system (LSIS) provided overall better growth, yield and its components followed by WSC (100%) in the same irrigation system comparing with the other treatments in the two growing seasons, where WSC(100%) in LSIS or (80%) in SFI yield was also close to WSC (80%) in LSIS, on an average for the two seasons.

Our findings in **Table 9** show that the major objective for increasing maize yield under deficit irrigation is the creation of water-saving growing techniques. Many scientists have been working on improving irrigation techniques and scheduling for a very long time, and deficit irrigation has received a lot of attention. On the dry matter of the crop, irrigation time has a significant effect. For instance, timing irrigation in maize is crucial to reducing stress throughout the milk and dough development stages **(Payero *et al.*, 2009)**. Also, our findings indicated that irrigation deficit in the two systems up to WSC (60 %) reduced the growth and productivity of maize in compression with the other treatments in both seasons, these results are in harmony with those results recorded by **Singh *et al.* (2007)** who stated that deficit irrigation has an impact on emergence time, number of leaves per plant, and the commencement of tasseling and silking, all of which have a direct impact on maize plant height and vegetative development. In maize plants treated to full and deficit irrigations. **Kaman *et al.* (2011)** found comparable results, with varying grain yield dependent on management of irrigation and cultivars, and the maximum grain yield in treatments without water shortfall. On the other hand, in the same trend as our results, **Sokht-Abandani and Ramezani (2012)** showed that lengthening the watering interval did not result in a considerable decrease in the growth and yield of maize. In the other investigation, reduction of water depths or deficit irrigation management, according to **Gheysari *et al.* (2015); Gheysari *et al.* (2017),** can enhance WUE without reducing the grain yield of maize plants.

Finally, modern techniques, such as LSIS, which was employed in our study, together with sprinkler, drip, and protected cultivation, have greatly reduced runoff and evapotranspiration losses, which has enhanced WUE in agriculture **(Topak *et al.*, 2014)**. It is crucial to create innovative irrigation methods that make the most use of the water that is available, rather than necessarily basing them on the complete crop water need. Irrigation scheduling may be used, among other things, to increase the return on agricultural inputs and the environmental quality of irrigation **(Zhang *et al.*, 2002; Mansour *et al.*, 2016)**.

Table (9). Maize characteristics as affected by deficit irrigation under laser spray rain system (LSIS) and surface furrow irrigation (SFI) in both seasons.

Seasons														
2022							**2023**							
LSIS			**SFI**			**LSD at 0.05**	**LSIS**			**SFI**			**LSD at 0.05**
WSC 100 %	**WSC 80 %**	**WSC 60 %**	**WSC 100 %**	**WSC 80 %**	**WSC 60 %**		**WSC 100 %**	**WSC 80 %**	**WSC 60 %**	**WSC 100 %**	**WSC 80 %**	**WSC 60 %**	
Plant height (cm)														
296.3	303.6	246.0	285.5	296.2	260.0	**17.04**	297.0	300.8	249.9	290.7	295.5	257.2	**16.9**
Leaf area index (LAI)														
4.85	5.42	3.91	5.02	5.04	3.55	**0.39**	4.78	5.40	3.91	5.11	4.95	3.76	**0.31**
Chlorophyll (SPAD unit)														
51.92	58.92	50.30	53.32	54.61	48.07	**3.70**	52.28	58.28	49.86	54.12	53.99	47.53	**2.48**
Days to 50 % tasselling (days)														
53.27	57.00	60.30	52.30	60.00	61.63	**3.08**	52.83	59.00	60.97	52.00	60.23	62.20	**1.84**
Days to 50 % silking (days)														
56.00	61.17	63.17	56.97	62.87	64.97	**2.41**	56.00	62.33	64.30	56.67	63.00	64.33	**2.11**
Ear height (cm)														
141.8	147.3	122.6	138.5	143.1	126.6	**6.9**	144.4	145.3	123.0	141.0	143.2	125.4	**7.2**
Ear length (cm)														
24.33	26.50	21.83	23.00	24.33	21.00	**1.37**	25.00	25.53	23.00	23.33	24.33	21.00	**0.97**
Grain number/row														
44.67	47.00	40.00	43.67	46.00	40.00	**2.39**	42.67	46.00	39.67	42.67	45.00	38.00	**2.57**
Grain number/ear														
714.7	752.0	640.0	698.7	750.0	640.0	**38.2**	682.7	720.0	634.7	682.7	736.0	608.0	**41.2**
100- grain weight (g)														
38.63	40.27	33.27	36.37	38.43	31.60	**2.27**	38.33	40.67	32.83	37.57	38.93	31.50	**1.57**
Biological yield (t/ha)														
22.71	24.48	18.92	21.62	20.36	18.13	**1.46**	22.82	24.31	19.24	21.72	21.25	17.58	**1.57**
Stover yield (t/ha)														
13.52	14.48	11.56	12.94	12.28	11.12	**0.73**	13.60	14.27	11.84	13.08	12.85	10.97	**0.73**
Grain yield (t/ha)														
9.19	10.00	7.36	8.68	8.08	7.01	**0.81**	9.22	10.04	7.40	8.64	8.40	6.61	**0.87**
Harvest index (HI %)														
40.74	40.88	38.91	40.18	39.69	38.68	**1.40**	40.38	41.26	38.45	39.78	39.55	37.65	**1.27**
Grain: stover ratio														
68.74	69.15	63.69	67.16	65.82	63.07	**3.86**	67.72	70.25	62.47	66.06	65.42	60.39	**3.49**

Least Significant Difference (LSD): This enables making a direct comparison between two means from two individual groups. Any difference larger than the LSD is considered a significant result.

4. SUMMARY AND CONCLUSIONS

The study emphasizes the critical need for Egypt to address its growing population and the increasing demands on its agriculture sector. Conventional irrigation methods have proven inefficient, leading to significant water wastage, as well as issues like salinity buildup and waterlogging. Consequently, optimizing water usage through the adoption of pressurized irrigation systems is of utmost importance.

One such innovative irrigation technology is the Laser Spray Irrigation System (LSIS), which is being considered as a potential replacement for traditional surface irrigation methods. LSIS operates at lower pressure, mimicking a gentle rain pattern. While still in its early stages of implementation in Egypt, this system deserves comprehensive evaluation across different crop types. If LSIS is introduced on a larger scale, it may necessitate increased regulation of existing micro-irrigation techniques such as drip and sprinkler systems. It's crucial for farmers to transition to more advanced micro-irrigation methods, particularly LSIS, for a wide range of crops. This transition holds the promise of improving crop yields and the economic viability of agricultural practices, especially in situations of water scarcity, notably during the summer months.

Deficit irrigation systems, designed to enhance water usage efficiency and crop yields per unit of irrigation water applied, are a central focus of this research. The study aims to assess the hydraulic performance of LSIS under varying pressure and spacing configurations, while also evaluating its effectiveness as an alternative to Surface Furrow Irrigation (SFI) concerning water efficiency and maize (cv SC 3084) productivity under deficit irrigation conditions (water stress coefficient, WSC = 1, 0.8, and 0.6 of ET_c) in clayey soil profiles.

Laboratory experiments conducted at the Agricultural and Biosystems Engineering Department, Faculty of Agriculture, Alexandria University, Egypt, were pivotal in identifying the optimal operational parameters for LSIS. The findings indicated that at a pressure of 0.71 bar and a 4-meter spacing between laser spray pipelines (100% overlap), LSIS exhibited superior application efficiency and uniformity.

Field trials, carried out in the old Delta lands of Itay El-Baroud, El-Behira Governorate, Egypt, during 2022 and 2023, revealed significant differences between LSIS and SFI. The results demonstrated that the percentage of deep percolation (DP) with water stress coefficient WSC = 100% and 80% of ET_c under SFI was 3.16 and 31.66 times higher, respectively, compared to LSIS at the same WSC. However, at WSC = 60% of ET_c, DP was 860 m3/ha under SFI, while it was negligible under LSIS. Despite LSIS applying significantly less water (409.3 mm compared to 908.7 mm with SFI), it yielded substantially higher grain output (10.02 t/ha compared to 6.81 t/ha with SFI). Correspondingly, water use efficiency metrics favored LSIS. Additionally, the study revealed that the minimum reduction in yield due to the interaction between water application and irrigation system was zero and 8.08% at WSC = 80% and 100%, respectively, under LSIS. In contrast, under SFI at the same WSC, the maximum reduction in yield reached 13.57% and 17.77%.

In conclusion, LSIS presents an innovative and effective irrigation method, particularly beneficial under conditions of water scarcity. Its widespread adoption, especially at a WSC of 80%, holds great promise for increasing maize productivity in El-Behira Governorate, Egypt. This research underscores the crucial role of deficit irrigation systems in optimizing water efficiency and enhancing crop yields per unit of applied irrigation water.

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الملخص العربي

تحسين كفاءة استخدام المياه لمحصول الذرة تحت نظام الري بالرش الرذاذي

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تسلط هذه الدراسة الضوء على الضرورة القصوى لمصر في التعامل مع النمو السكاني المتسارع بالتزامن مع الطلب المتنامي على القطاع الزراعي. أظهرت ممارسات الري التقليدية عجزاً في الكفاءة، مما أسفر عن هدر كبير للمياه ونتائج سلبية، بما في ذلك تراكم الملوحة وتسرب المياه. وبالتالي، يظهر تحسين استخدام المياه من خلال تبني أنظمة الري بالضغط كإجراء لابد منه.

تقدم تكنولوجيا الري المبتكرة والمعروفة بنظام الري بالرش الرذاذي (Laser Spray Irrigation System, LSIS) نموذجاً محتملاً لتعويض الأساليب التقليدية للري السطحي. يعمل نظام LSIS بضغط منخفض، محاكياً نمط المطر الخفيف أثناء الاستخدام. ورغم أن هذا النظام لا يزال في مراحله الأولى من التطبيق في مصر، إلا أنه يبرز إمكانيات واعدة لمختلف أنواع المحاصيل ويمكن أن يكمل تقنيات الري الدقيق الحالية مثل الري بالتنقيط والرش. وهناك حاجة ملحة لدى المزارعين في الأراضي القديمة للانتقال نحو طرق ري دقيقة أكثر تطوراً، ولا سيما نظام الري بالرش الرذاذي ، لزيادة الإنتاج وتحسين الأوضاع المالية للفلاح تحت ظروف الري المتناقص، من خلال تقليل الاستهلاك المائي للمحاصيل، خاصة في فصل الصيف.

تُعتبر أنظمة الري المتناقص للمياه أحدي التقنيات التي تهدف إلى تحقيق أقصى كفاءة في استخدام المياه وتحقيق إنتاجية أعلى لكل وحدة من المياه. وتسعى هذه الدراسة إلى تقييم الأداء الهيدروليكي لنظام LSIS تحت ضغوط تشغيل ومسافة تباعد بين الخطوط متغيرة، بالإضافة إلى دراسة فعالية LSIS كبديل لنظام الري السطحي بالخطوط (Surface Furrow Irrigation, SFI)فيما يتعلق بكفاءة استخدام المياه وإنتاجية نبات الذرة في ظل ظروف الري المتناقص وذلك بتطبيق معامل الإجهاد المائي

(Water Stress Coefficient, WSC)100٪ ، 80٪ ، و 60٪ من قيمة الاحتياجات المائية (ETc) في ظروف تربة الطين. تم إجراء التجارب في المعمل بقسم الهندسة الزراعية والنظم الحيوية، كلية الزراعة، جامعة الإسكندرية ، لتقييم الأداء الهيدروليكي لنظام LSIS تحت ضغوط (من 0.32، 0.53، 0.71، و 1 بار) وتباعد (3، 3.5، 4.0 و 4.5 متر) وذلك لتحديد أفضل الظروف التشغيلية. أوضحت النتائج أن استخدام نظام LSIS تحت ضغط تشغيل 0.71 ومسافة تباعد 4 أمتار بين خطوط الري (تغطية 100٪) أسفرعن نتائج مثالية، حيث كان متوسط معدل إضافة المياه 11.23 مم/ساعة، ومعامل التباين 8.9% (CV)، ومعامل التجانس 92.4% (Uc)، ومعامل توزيع 90.34% (Du).

أظهرت النتائج الحقلية التي اجريت بمنطقة ايتاي البارود محافظة البحيرة أن أعلى كمية من المياه المستخدمة كانت 908.7 مم عند استخدام نظام (SFI) بنسبة 100٪ منETc ، بينما بلغت أدنى كمية استخدام للمياه في نظام (LSIS) 409.3 مم عند نسبة إجهاد مائي 60٪ من ETc ومع ذلك، كانت أعلى عائدات من الحبوب 10.02 طن/هكتار ناتجة عنLSIS ، وأدنى عائدات من الحبوب 6.81 طن/هكتار من SFI وكانت أعلى قيم لكفاءة استخدام المياه هي 1.903، 1.803، و 1.436 كجم لكل متر مكعب من المياه وتم الحصول عليها من LSIS عند معامل الإجهاد المائي (WSC) بنسبة 80٪، 60٪، و 100٪ من ETc على التوالي. وكانت أقل قيم لكفاءة استخدام المياه هي 0.953، 1.073، و 1.129 لكل متر مكعب من المياه تم الحصول عليها عند استخدامSFI بنسب إجهاد مائي 100٪، 80٪، و 60٪ من ETc على التوالي.

ومع ذلك، أظهر LSIS أداءًا أفضل في إنتاجية المياه منSFI بنسبة 32.04٪ مع استخدام كمية أقل من المياه بنسبة 12.94٪. في الختام، يعد LSIS أحد أفضل وأحدث الوسائل للاستفادة الفعالة من المياه للري. إذ تعتمد على طريقة فعالة لتوزيع المياه بمعدل عال على مدى فترة زمنية قصيرة بواسطة نظام توصيل بضغط منخفض. وقد أظهرت النتائج المتحققة اختلافاً ملحوظاً بين مستويات الري المتناقص تحت النظامين عند مستوى معنوية 0.05، حيث تفوق الري بنسبة 80٪ بواسطة LSIS على جميع مستويات الري المتناقص في نفس النظام، بالإضافة إلى تفوق LSIS على جميع مستويات الري المتناقص تحت SFI وسُجِّلت أعلى قيم لنمو الذرة وإنتاجيتها عند اجهاد مائي WSC بنسبة 80٪ تليها نسبة 100٪ ، لذا يمكن استنتاج أن استخدام نظام حديث مثل LSIS يعزز من إنتاجية الذرة وكفاءة استخدام المياه. كذلك أظهرت النتائج أن نسبة الفاقد من المياه بلتسرب العميق عند استخدام معامل الإجهاد المائي 100% و80% من ETc تحت نظام الري السطحي بالخطوط SFI كانت 3.16 و31.66 مرة على التوالي مقارنة بـ LSIS ، ولكن عند استخدام معامل الإجهاد المائي 80% كان حجم الفاقد للمياه بالتسرب العميق 860 متر مكعب / هكتار تحت نظام SFI، وكان مساوياً صفر تحت نظام LSIS على الرغم من استخدام نظام LSIS لمياه أقل بكثير 409.3 مم مقارنة بـ 908.7 مم مع نظام SFI. كذلك أظهرت النتائج أن نسبة التناقص في المحصول نتيجة التأثير الناتج عن تداخل استخدام معامل الإجهاد المائي 80% و100% من ETc مع نظام الري بالرش الرذاذي LSIS كانت صفر و8.08% على التوالي ولكنها كانت 13.57 و17.77% عند نفس نسب معامل الإجهاد المائي مع نظام الري السطحي بالخطوط SFI.

وفي الختام، يمثل نظام الري بالرش الرذاذي (LSIS) نموذجاً مبتكراً وفعالاً بديلا عن الطرق التقليدية للري السطحي بالخطوط (SFI) كذلك تُعتبر أنظمة الري المتناقص تحت نظام LSIS إحدي التقنيات لتحقيق أقصى كفاءة لاستخدام المياه وزيادة انتاجية المحاصيل لكل وحدة من المياه المستخدمة.