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Research article

Effect of irrigation regimes on nutrient uptake and nitrate leaching in maize (Zea mays L.) production at Birr-Farm, Upper Blue Nile, Ethiopia

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ABSTRACT

Sustainably managed irrigation water is essential to agriculture. In order to identify the best irrigation strategies for maximizing agricultural productivity and environmental health, this study examines the effects of various irrigation depths on nutrient uptake, nitrate leaching, and maize yield. The study was carried out at Birfarm, in the Jabitehnan District, Amhara, Ethiopia, throughout the irrigation periods of 2022/23 and 2023/24. The experiment used a (RCBD) with three replications testing five application depths to apply irrigation (50 %, 75 %, 100 %, 125 % and 150 % ETc). ANOVA was performed to determine the influences of irrigation levels on nutrient uptake and nitrate leaching. Irrigation levels significantly impacted N, P and K uptake. Maximum nutrient uptake occurred at 150 % ETc with higher nutrient uptake observed in the second experimental season. Irrigation levels significantly affected nitrate leaching, with the highest leaching at 150 % ETc. Excessive irrigation increased nitrate leaching, aligning with findings from other studies. Maize yield, thousand grain weight (TGW) and above-ground biomass yield (ABY) were significantly influenced by irrigation depth. Optimal irrigation (100 % ETc) produced the maximum yield of 6.08 and 5.83 tha^{-1}, the maximum thousand grain weight of 682.51 g and 685.12 g, and the highest above-ground biomass yield of 31.41 and 32.74 tha^{-1} in the second and first experiments, respectively, while excessive and deficit irrigation reduced yield. The study highlights the importance of optimizing irrigation depth for nutrient uptake, nitrate leaching and maize yield. While increased irrigation improved nutrient uptake and yield, excessive irrigation led to higher nitrate leaching, emphasizing the need for balanced irrigation practices to enhance productivity and environmental sustainability. Farmers should implement 100%ETc to enhance productivity, ensure efficient nutrient utilization, and protect the environment from the adverse effects of nitrate leaching.

1. Introduction

Maize is a field crop, recognized as a resilient and suitable for various agro-ecosystems [1]. Efficient soil water management is imperative to achieve optimum yield and save water while improving environmental health. Decreased soil moisture levels can reduce nutrient availability and utilization [2]. The decline in water supply exposes crops to drought, resulting in poor nutrient uptake, and

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consequently, reduced yield and quality [3,4].

In Ethiopia, particularly in the North Western part, maize is vital for food security and the economy [5,6]. However, poor water application methods and water scarcity pose significant challenges [7,8]. Recent climatic variability has exacerbated these issues, highlighting the need for optimized irrigation water application to enhance nutrient uptake and minimize environmental damage, especially in regions like Birr Farm [9].

Effective water and nutrient management is critical for crop productivity, particularly in maize production [10]. Nitrogen and other nutrients availability significantly enhance the grain yield of cereal crops, emphasizing the importance of optimum irrigation water application and nutrient management [3] Crops absorb nutrients along with water, highlighting the critical interaction between water and nutrients in modern agriculture. Irrigation significantly impacts soil nitrogen availability [11]. Crop yield response to nitrogen fertilization improves with higher soil water content, especially when high nitrogen rates are applied. Additionally, water availability profoundly affects nutrient uptake and nitrate leaching, with high levels of irrigation and precipitation leading to increase nitrate leaching [12].

Conversely, deficit irrigation reduces yield even if nitrogen supply is high [13]. [14] Suggested that balanced levels of soil water lead to more efficient nutrient use. Adequate soil water conditions allow nitrogen application to increase yield, while deficient soil water conditions decrease yield [11]. Shown that an average yield increase of approximately 100 % with adequate nitrogen levels and with adequate water supply compared to deficit conditions.

Moreover, achieving higher water and nitrogen productivity is essential for appropriate irrigation and fertilization [14]. But, global concerns about agro-hydrological sustainability are rising due to nitrate contamination of groundwater from intensive agricultural practices [15,16]. The transport of water and nitrate solutes from the surface of the soil to beneath the surface is regulated by deep soil layers, which buffer, filter, adsorb, transfer, and attenuate pollutants. Precipitation, irrigation and nitrogen application rates are the main causes of water and solute transport below the root zone into deeper soil layers.

Nevertheless, adequate soil moisture is essential for maize to maximize nutrient uptake, as water transports dissolved nutrients to the roots [10,17]. However, overwatering can cause nutrient leaching, moving nutrients below the root zone and preventing absorption. This issue is particularly significant for highly soluble nutrients like nitrate [10,18]. This study presents the optimal irrigation depths for maximizing maize yield and nutrient uptake while minimizing nitrate leaching. It also explores the relationship between irrigation levels and nutrient recovery efficiency, suggesting balanced irrigation strategies to optimize crop production and environmental sustainability at Birr Farm."

2. Material and methods

2.1. Description of the research area

Birfarm, located in Jabitehnan District of Amhara, Ethiopia, was the site of the trial. It was carried out during the irrigation seasons of October–February (2022/23), Ethiopia's dry season, and March–May (2023/24), Ethiopia's spring season. The farm is located at latitude 10.78 N, longitude 37.59 E, and is 1265 m latitude. The study site's location map is shown in Fig. 1. This map is created using the WGS 1984 datum and UTM coordinates in 2024, the map was created with ArcGIS 10.3 and Google Earth. With an average yearly precipitation of 826.2 mm, the research area was categorized as semi-arid. Average monthly low and high temperatures were 13.8 °C and 28.6 °C, respectively. The area's predominant soil types are those with a silt texture. A common technique for implementing irrigation is furrow irrigation, which uses groundwater as its supply of water.

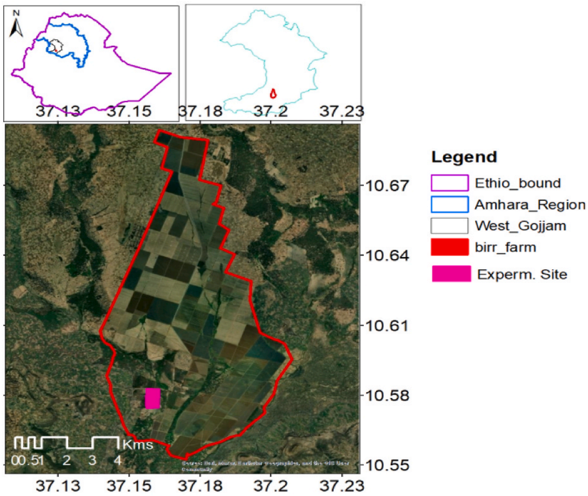

Figure: 1. Study site location map [19].

2.2. Experimental design

Five irrigation application depths (i.e., 50 %, 75 %, 100 %, 12 %, and 15 % ETc) were used in the experiment, and they were randomly assigned to each plot. Three replications and a randomized complete block design (RCBD) were used to set up the experiment. The experiment's net plot was $2.4\ m\ x\ 120\ m = 288\ m^2$, while the overall plot area was $4\ m\ x\ 120\ m\ = 480\ m^2$. The distances are as follows: 1 m for block spacing, 0.5 m for plot spacing, 25 cm for crop spacing, and 80 cm for rows. This water enters the system at the location marked PF, where the Parshall flume measures the flow rate (Fig. 2). This measurement is crucial for monitoring and controlling the flow of water through the system. The placement of the Parshall flume at the beginning allows for accurate measurement of the water entering the system. This helps in regulating the flow and ensuring that the system operates efficiently.

2.3. Crop husbandry

The district of study area approach's recommended maize production package served as the basis for all other agronomic crop management tasks such as weeding, plot preparation, fertilizer application, pest and disease control and smoothing of the soil. The planting date for the first irrigation season (2022/2023) was October 1, with the harvest occurring on February 14. For the second irrigation season (2023/2024), planting took place on February 17, and the harvest is scheduled for May 30. The application of NPK rate was applied based on local practice of, 200 kg ha^{-1} of Nitrogen, with 70 kg ha^{-1} at sowing stage, 65 kg ha^{-1} at the 4–6 leaf stage and 65 kg ha^{-1} at the 8–10 leaf stage. Use 80 $kgha^{-1}$ of Phosphorus (P_2O_5), all at planting. Apply 100 kg ha^{-1} of Potassium (K_2O), with 50 kg ha^{-1} at planting and 50 kg ha^{-1} at the 4–6 leaf stage.

2.4. Soil data

Soil samples were collected from the experimental field and analyzed in the lab to determine physical characteristics. The maize crop's root zone was set at a depth of 0.75 m, with layers at 0–0.2 m, 0.2–0.4 m and 0.4–0.75 m. Bulk density was measured using oven-drying, and a pressure plate device assessed moisture content at the wilting point and field capacity. The proportion of sand, clay, and silt was determined using a hydrometer and classified using the USDA soil texture method. Three specific locations within the aforementioned depth ranges were used to collect individual soil samples. The soil in the study area consisted of 80 % silt, 20 % clay, and 40 % sand. Therefore, loam soil was the dominated soil texture Table 1. This loam texture facilitated adequate drainage and root penetration, contributing to the observed improvements in maize growth and yield.

2.5. Estimation of reference evapotranspiration

The determination of irrigation schedules and crop water requirements both depend on the estimation of reference evapotranspiration. Although reference evapotranspiration (ET0) is crucial for studying global ecosystems, its spatial distribution is still not well understood in general. One issue is that because ET_0 depends on a number of climatic characteristics that are only seen at big sites, it is challenging to determine directly [20]. Using the FAO Penman-Monteith approach Equation (1), the reference evapotranspiration can be computed using real climate, humidity, temperature, sunshine/radiation, and wind speed measurements.

$$ET_O = \frac{Y \times \frac{900}{T+273} \times U_2 \times (e_s - e_a) + 0.48\Delta \times (Rn - G)}{\Delta + Y \times (1 + 0.34 \times U_2)} \tag{1}$$

T represents the mean daily air temperature (°C), U_2 is the wind speed measured at a 2-m height (ms^{-1}), and es – ea denotes the saturation vapor pressure deficit (kPa). Δ is the slope of the vapor pressure curve ($kPa^\circ C^{-1}$), while γ is the psychrometric constant ($kPaC^{-1}$). ETo stands for reference evapotranspiration ($mmday^{-1}$), Rn is the net radiation at the surface ($MJm^{-2}day^{-1}$), and G is the soil heat flux density ($MJm^{-2}day^{-1}$).

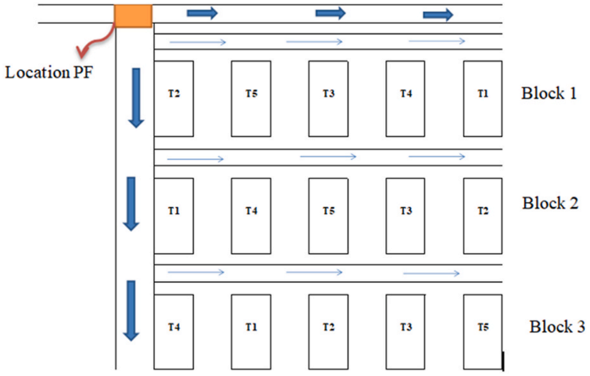

Figure: 2. Experimental design layout [19].

Table 1
Soil profiles in the experimental plots: their physical and chemical characteristics.

Soil sample location	depth of soil (cm)	Bulk density (gm/cm3	FC (%)		PWP (%)		PH	N03 (ugN/g)	C-Organic (%)	Soil group
			w/w	v/v	w/w	v/v				
Block 1	0–20	1.34	35.75	49.23	16.4	22.4	5.6	1.4	1.2	Loam
	20–40	1.22	38.66	47.62	16.7	24.35	5.8	1.4	0.95	Loam
	40–75	1.55	40.02	58.22	17.43	28.8	6.1	1.4	0.71	Loam
Block 1	0–20	1.34	35.87	49.85	17.5	24.65	5.5	1.4	1.2	Loam
	20–40	1.22	38.96	47.33	18.45	21.92	5.8	1.4	0.95	Loam
	40–75	1.55	41.2	59.22	19.44	30.3	5.7	1.4	0.71	Loam
Block 1	0–20	1.34	35.5	49.33	16.55	21.33	5.6	1.4	1.2	Loam
	20–40	1.22	38.7	46.62	16.95	22.5	5.7	1.4	0.95	Loam
	40–75	1.55	40.04	57.32	17.01	27.07	5.9	1.4	0.71	Loam

Equation (2) can be used to calculate crop water requirement for the growing period based on ET_o and estimations of crop evaporation rates, which were given as coefficient of the crop.

$$ET_C\ (CWR) = \text{Cropcoefficient}\ (K_c) \times \text{R. evapotranspiration}(ET_o\ ) \tag{2}$$

2.6. Irrigation depth

A digital moisture sensor and the gravimetric approach were employed to quantify the initial soil moisture content. Irrigation was applied based on the effective root zone depth to bring soil moisture to field capacity. Soil moisture levels were monitored every ten days, prior to irrigation, and at harvest. Furrow irrigation with a gravity system was used for all plots. The depth of irrigation water was calculated using Equation 3

$$d = \frac{F_c - M_{ci}}{100} \times A_s \times D \tag{3}$$

where: Mci is initial moisture level of the soil at the time of irrigation, %; Fc is the moisture content, %; and d is the depth of water applied, mm; As is the soil's apparent specific gravity; D is the root zone's depth in millimeters.

2.7. Measurements of irrigation time and discharge

To determine different irrigation levels by using a calibrated PF measurement with specific dimensions and a defined head range ensuring accurate flow measurement. The flume having a three-inch (3″) opening and a 2-m length operated within a head range of three to 33 cm (3–33 cm). This setup allowed precise control of water discharge into the furrow following the principles outlined by Michael (2008). By using equation (4), d is water level in centimeters, T is application time in hours, L is length of furrow in meters, W is spacing of furrow in meters and q is rate of flow in liters per second, was calculated the appropriate irrigation duration (Equation (4)). During experiment the head measured was 9 cm, corresponding to a discharge of 4.239 l/s for a three-inch flume, the flow rate q could be directly obtained from Table 2. This discharge value when input into the equation along with the known parameters of depth, furrow length, and spacing, allowed for the precise determination of application time, thereby achieving varied irrigation levels as required.

Table: 2
Measured discharge versus flow head in a 3 inch partial flume.

Head (cm)	Through width (inches)				
	1	2	3	6	9
	Discharge (l/s)				
2	0.14	0.281			
3	0.263	0.526	0.772	1.496	2.504
4	0.411	0.822	1.206	2.357	3.889
5	0.581	1.162	1.705	3.354	5.471
6	0.771	1.541	2.261	4.473	7.232
7	0.979	1.957	2.872	5.707	9.155
8	1.205	2.407	3.532	7.047	11.231
9	**1.446**	**2.889**	**4.239**	**8.489**	**13.448**
10	1.702	3.402	4.991	10.027	15.801
11	1.973	3.943	5.786	11.656	18.281
12	2.258	4.513	6.621	13.374	20.885

$$T = \frac{w \times d_{net} \times l}{6 \times q} \tag{4}$$

Where: T = duration of irrigation water application (hours), d = depth of water applied (cm).

W = Spacing of furrow (m), L = length of furrow (m) and q = the rate flow (l/s)

2.8. *Suction cup installation*

Ten suction cups arranged in a V-shape beneath the root zone of 80 cm in catchments with a predominance of sand, and 120 cm in catchments with predominance of loamy soil make up a soil water station [21].Provides a description of the materials used and how they were installed. The DAMPSC states that throughout the leaching season, which normally lasts from October to February, weekly irrigation water samples from all suction cups within a station were pooled for nitrate analysis [22].

2.9. *Nitrate leaching measurement*

The leaching of nitrate (kg ha^{-1}) was computed using a measured NO^{-3} content (mg L^{-1}) in the soil moisture, taken using suction cups, and the predicted percolation (mm). Total 8 suction cups per treatment were produced by the two suction cups per plot. The installation was done at a depth of 0.8 m which is beneath the root zone, as stated in Ref. [23]. Using an auto-analyzer, the soil water was sampled and examined in accordance with the guidelines provided in Ref. [24]. The nitrate concentrations in the suction cups are assumed by this method to represent flux-average conditions [23]. The model Eva crop was utilized to calculate percolation using (Equation (5)), following the methodology outlined by Ref. [25].

$$L = \sum_{i=1}^{n} \frac{C_i + C_{i+1}}{2} \times D_i \tag{5}$$

Where C_i is content of nitrate (mg NO^{-3} N^{-1}) in the extracted soil water on day i, and D_i is the depth of percolation (l m^2) over the two testing dates (i, i + 1).

Nitrogen loss by leaching varies widely depending on factors such as type of soil, climate, agricultural practices and crop types. In this study nitrogen loss by leaching was determined using equation (6): This equation considers the function of nitrate leaching and total applied nitrogen during the trial.

$$\text{Nirogen Loss }(\%) = \frac{\text{Nitrate Leaching Loss }\left(\text{kg ha}^{-1}\right)}{\text{Total nitrogn applied}\left(\text{kg N ha}^{-1}\right)} \times 100 \tag{6}$$

2.10. *Determination of nutrient uptake*

At the time of harvesting of the crop, plant tests were taken from each plot, and these tests were over dried for 24 h at 70 ± 2 °C. The standard procedures were followed when grinding the dried plant samples to determine the percentages of N, P and potassium K. Using the CHNS apparatus the total N contents (%) in the plant were determined. The conventional technique of preparing tests into tiny pellet-shaped tin capsules was adhered to. Ten milligrams of ground plant samples were used for this, and they were put into tin capsules. The capsule's open end was cautiously sealed using the P curve's assistance. Following wet digestion an aliquot of the filtrate was obtained and a flame photometer (Model 126, Systronics India Limited) was used to calculate the K content (%) [26]. Plant tissue samples are first gathered dried at 60–70 °C in an oven until a steady weight is achieved, and then milled into a fine powder. To release phosphorus into a solution, the powdered samples are digested using a strong acid, such as sulfuric acid (H_2SO_4), occasionally with the help of a catalyst such as hydrogen peroxide (H_2O_2) or selenium. After removing particles with a filter the solution is diluted with distilled or deionized water to a predetermined volume. Using techniques like colorimetry, which involves reacting a reagent with phosphorus to create a colored product that can be detected by a spectrophotometer, ICP-OES, or AAS, the concentration of phosphorus in the solution can be determined. The utilization of N, P, and K was estimated by multiplying the N, P, and K content (%) in their product. After harvesting the crop from a 288 m2 net plot (2.4 m × 120 m) area, measurements were taken of the crop's seed yield and stalk yield. A two-to three-day sun drying period was then followed by separating and examining.

Nutrient intake by Stover = total nutrient uptake (kg ha-1) Nutrient uptake by seeds or Stover (kg ha-1) + Nutrient uptake by seeds = [Nutrient content in seed or Stover (%) × Seed or Stover yield (kg ha-1)] × 10-2.

2.11. *Nutrient recovery efficiency under different irrigation depth*

To determine nitrogen N, P and K recovery under different irrigation depths (50 %, 75 %, 100 %, 125 % and 150 % ETc), begin by designing an experiment with uniform test plots for each irrigation treatment. Select a representative crop ensuring uniformity across all treatments and prepare the soil to have similar characteristics and nutrient levels. Collect initial soil and plant tissue samples from each plot to establish baseline N, P, and K levels. Implement the specified irrigation regimes (50 % ETc, 75 % ETc, 100 % ETc, 125 % ETc and 150 % ETc) and carefully monitor water application. Apply a consistent amount of N, P and K fertilizers across all plots and then regularly monitor plant growth and periodically collect soil and plant tissue samples throughout the growing season. At harvest, collect final soil and plant tissue samples to analyze N, P, and K content. Calculate total nutrient uptake for each plot and determine nutrient recovery efficiency using equation (7) [27]:

$$RE_{npk} = \frac{\text{Total nutrient uptake in plant } \left(\text{kgha}^{1}\right)}{\text{Total nutrient applied to plant } \left(\text{kgha}^{1}\right)} \times 100 \tag{7}$$

2.12. Statistical analyses

First, each experimental season and experiment was subjected to an ANOVA for the effects of the five irrigation level treatments using a RCBD with three replications. Based on $LSD_{0.5}$ significant differences in mean values were distinguished. In both cases, the GLM approach in SAS software was employed. Pearson correlation coefficient was used for each pair of variables.

3. Result

3.1. Nutrient uptake during the experimental season

The influence of different irrigation levels on nitrogen, phosphorus and potassium uptake was evaluated across two growing seasons, 2022/23 and 2023/24 Table 3. The results are summarized below: Nitrogen Uptake **(N)**: In 2022/23 N uptake increased with increasing irrigation levels, ranging from 47.48 kg N ha^{-1} at 50 % ETc to 121.47 kg ha^{-1} at 150 % ETc. A similar trend was observed in 2023/24 with values ranging from 48.66 kg ha to 1 at 50 % ETc to 128.50 kg ha^{-1} at 150 % ETc. There were highly significant differences between most irrigation trials at ($p < 0.001$) as indicated by the LSD values. Phosphorus Uptake (P): P uptake also increased with higher irrigation levels. In 2022/23 it ranged from 12.90 kg ha^{-1} at 50 % ETc to 22.93 kg ha^{-1} at 150 % ETc. In 2023/24, the trend continued with values from 12.94 kg N ha^{-1} at 50 % ETc to 24.15 kg ha^{-1} at 150 % ETc. Significantly differences were identified between irrigation water level trials, with higher irrigation levels generally resulting in higher P uptake. Potassium Uptake (K): K uptake followed a similar pattern, increasing from 37.47 kg ha^{-1} at 50 % ETc to 61.12 kg ha^{-1} at 150 % ETc in 2022/23. In 2023/24 K uptake ranged from 37.84 kg N ha^{-1} at 50 % ETc to 62.73 kg ha^{-1} at 150 % ETc. The differences among treatments were statistically significant, highlighting the impact of irrigation levels on K uptake (Tables 5 and 6).

3.2. Nitrate and nitrogen leaching during the experimental season

Different irrigation levels very highly significant effect on nitrate leaching at ($P > 0.001$) Tables 5 and 6 Nitrate Leaching (NL): Nitrate leaching was significantly affected by irrigation levels, with higher irrigation levels leading to increased leaching: In 2022/23 NL increased from 3.89 kg ha^{-1} at 50 % ETc to 93.81 kg ha^{-1} at 150 % ETc. Similarly, in 2023/24 NL ranged from 4.54 kg N ha^{-1} at 50 % ETc to 94.29 kg ha^{-1} at 150 % ETc. The LSD values indicate significant differences between most treatments, with higher irrigation levels resulting in substantially higher nitrate leaching Table 4. In the same way, larger irrigation water applications throughout the irrigation season resulted in a distinctly higher nitrate concentration in the soil water.

The percentage of nitrogen leaching followed a similar pattern to nitrate leaching. At the lowest irrigation level of 50%ETc nitrogen leaching was 1.945 % in 2022/23 and slightly higher at 2.27 % in 2023/24. As irrigation levels increased to 75%ETc nitrogen leaching increased to 6.26 % and 5.965 % for the respective years. At the standard irrigation level of 100%ETc nitrogen leaching significantly increased to 31.415 % in 2022/23 and 31.05 % in 2023/24. Further increases in irrigation to 125%ETc and 150%ETc resulted in nitrogen leaching percentages of 44.075 % and 46.9 % in 2022/23, and 44.05 % and 47.145 % in2023/24, respectively (Table 4). The result reveals that the significant influence of irrigation levels on both nitrate and nitrogen leaching. Lower irrigation levels (50%ETc) minimized leaching, while higher levels (125%ETc and 150%ETc) substantially increased leaching. This trend highlights the importance of optimizing irrigation levels to balance crop water needs and minimize environmental impacts related to nutrient leaching. Efficient irrigation management is crucial for sustainable agricultural practices, as excessive irrigation not only wastes water but also leads to higher nutrient leaching, which can contaminate groundwater and surface water bodies.

Table 3
The influence of irrigation level on nutrient uptake in the 2023/22 and 2023/24.

Irrigation Level	N (kg N ha^{-1})		P (kg P ha^{-1})		K (kg K ha^{-1})	
	2022/23	2023/24	2022/23	2023/24	2022/23	2023/24
50%ETc	47.48^{d}	48.66^{c}	12.90^{c}	12.94c	37.47^{d}	37.84^{d}
75%ETc	55.68^{c}	57.13^{c}	16.33b^{c}	18.13^{b}	40.58^{c}	41.20^{c}
100%ETc	88.85^{b}	84.02^{b}	20.15b^{a}	19.48^{b}	51.31^{b}	51.21^{b}
125%ETc	92.10^{b}	93.52^{b}	22.49^{a}	24.07^{a}	60.72^{a}	62.72^{a}
150%ETc	121.47^{a}	128.50^{a}	22.93^{a}	24.15^{a}	61.12^{a}	62.73^{a}
LSD	7.53	16.97	5.28	3.96	2.18	2.58
CV	4.94	10.94	12.77	10.64	2.31	2.68

a, b, c, and d According to the LSD test, means that are separated in the alike letters in the similar column do not change at the 0.05 % level statistically.

Table 4

Effect of irrigation level on nitrogen and nitrate leaching.

Irrigation regime	Nitrate Leaching (kg ha$^{-1)}$		Nitrogen leaching (%)	
	2022/23	2023/24	2022/23	2023/24
50%ETc	3.89^{e}	4.54^{e}	1.95^{d}	2.27^{e}
75%ETc	12.52^{d}	11.93^{d}	6.26^{c}	5.97^{d}
100%ETc	62.83^{c}	62.1^{c}	31.42^{b}	31.05^{c}
125%ETc	88.15^{b}	88.1^{b}	44.08^{a}	44.05^{b}
150%ETc	93.8^{a}	94.29^{a}	46.9^{a}	47.15^{a}
LSD	3.37	4.09	3.36	4.1
CV	3.42	4.18	3.42	4.18

a, b, c, and d According to the LSD test, means that are separated in the alike letters in the similar column do not change at the 0.05 % level statistically.

Table 5

Mean squares of nutrient up take and nitrate leaching in the growing season of 2022/23.

Source of variation	Mean squares				
	Df	N	P	K	NL
Replication	2	18.87***	2.51***	8.52***	10.22***
Treatment	4	2690.81***	54.94***	364.36***	5283.64***
Error	8	16.03	7.85	1.34	3.19
CV (%)		4.94	12.77	2.31	3.42

Where: Df = Degree of freedom; *** = significant ($P < 0.001$); CV (%) = Coefficient of variation

Table 6

Mean squares of nutrient up take and nitrate leaching in the growing season of 2023/24.

Source of variation	Mean squares				
	Df	N	P	K	NL
Replication	2	16.19[a]	5.79[a]	13.84[a]	8.33[a]
Treatment	4	3021.63[a]	65.27[a]	408.02[a]	5287.99[a]
Error	8	81.19	4.42	1.88	4.71
CV (%)		10.94	10.64	2.68	4.18

Where: Df = Degree of freedom.

[a] = significant ($P < 0.001$); CV (%) = Coefficient of variation

3.3. Nutrient recovery efficiency under different irrigation regime

The results in Table 7 illustrated that the influence of different irrigation levels on nutrient recovery efficiency for **N, P and K** over two growing periods (2022/23 and 2023/24). As irrigation levels increase from 50 % ETc to 150 % ETc, nutrient recovery efficiencies for all three nutrients significantly improve. The lowest recovery efficiencies are consistently observed at 50 % ETc, while the highest efficiencies are at 150 % ETc for both years. Nitrogen recovery ranges from 23.74 kg ha to 1 at 50 % ETc in 2022/23 to 60.74 kg ha−1 at 150 % ETc showing a marked increase with higher irrigation. Similar trends are seen with phosphorus and potassium though phosphorus recovery appears more variable across different irrigation levels compared to potassium. The Least Significant Difference

Table 7

Nutrient recovery efficiency under different irrigation regime.

Irrigation Level	N (kg N ha^{-1})		P (kg P ha^{-1})		K (kg K ha^{-1})	
	2022/23	2023/24	2022/23	2023/24	2022/23	2023/24
50%ETc	23.74^{d}	24.33^{c}	16.13^{c}	16.19^{c}	37.47^{d}	37.84^{d}
75%ETc	27.84^{c}	28.565^{c}	20.41^{c}	22.66^{b}	40.58^{c}	41.2^{c}
100%ETc	44.43^{b}	42.01^{b}	25.19^{a}	24.35^{b}	51.31^{b}	51.21^{b}
125%ETc	46.05^{b}	46.76^{b}	28.11_{a}	30.09^{a}	60.72^{a}	62.72^{a}
150%ETc	60.74^{a}	64.25^{a}	28.66_{a}	30.19^{a}	61.12^{a}	62.73^{a}
LSD	7.03	15.33	5.78	3.86	2.68	2.50
CV	4.15	9.67	12.57	10.67	2.38	2.74

a, b, c, and d According to the LSD test, means that are separated in the alike letters in the similar column do not change at the 0.05 % level statistically.

(LSD) values indicate that these differences are statistically significant. The Coefficient of Variation (CV) percentages suggest that the variability in the data is relatively low for potassium but higher for phosphorus, reflecting more consistency in potassium recovery across the irrigation levels. Overall, the data suggest that increased irrigation levels lead to more efficient nutrient recovery, with 150 % ETc being the most effective.

3.4. Effect of irrigation depth nutrient uptake, nitrate leaching on maize yield

Optimizing irrigation depth and nutrient management can positively impact maize yield [28–30]. Table 8 demonstrates that the level was highly significant at ($P < 0.001$) impacted on grain yield, above biomass output, and thousand grain weights (TGW). Particularly, in both seasons, Optimal irrigation (100 % ETc) produced the maximum grain yield of 6.08 t/ha and 5.83 t/ha, the highest thousand grain weight of 682.51 g and 685.12 g, and the highest above-ground biomass yield of 31.41 t/ha and 32.74 t/ha in the second and first experiments, respectively, while excessive and deficit irrigation reduced yield.

3.5. Correlation analysis

The correlation matrix highlights the dual impact of irrigation levels on agricultural practices Table 9. While increasing irrigation levels boosts the absorption of vital nutrients N, P and K by crops, it also increases nitrate leaching, posing environmental risks. This underscores the need for balanced irrigation management to optimize crop production while minimizing negative environmental impacts.

4. Discussion

Dysfunctions in photosynthetic apparatus [31], plant pigments deterioration and stomata limitations, shrinking CO2 flow to the photosynthesis cycle, and inappropriate alternation in light reaction [32] are produced from water shortage. Furthermore, deficit irrigation caused cellular disorders in nutrients uptake and utilization with critical issues in osmotic potential [33]. Herein, it has been found that overproduction of hazard molecules (ROS) because of deficit water have an injured impact to damage, plant pigments, photosynthetic efficiency and metabolism [31]. Therefore, crop growth and yield losses associated deficit irrigation tactic [34].

These study reveals a clear relationship between irrigation levels and nutrient uptake, as well as nitrate leaching (Table 3). Increased irrigation levels generally led to higher nutrient uptake for N, P, and K across both growing periods. This can be attributed to improved availability of moisture which facilitates nutrient absorption by plants [35]. However, excessive irrigation (beyond 100 % ET_c) did not proportionally increase nutrient uptake, suggesting potential diminishing returns or have adverse effects at very high irrigation levels. Higher irrigation levels significantly increased N uptake, which is crucial for plant development and growth. However, the uptake maintained at higher irrigation levels (125 % and 150 % ET_c), indicating that beyond a certain point, additional water does not correspond to proportional increases in N uptake. P uptake was similarly enhanced by increased irrigation, with the highest values observed at 125 % and 150 % ET_c. The plateau effect was less pronounced than with N [36], suggesting that P uptake might be more sensitive to irrigation levels. K followed the same trend, with significant increases observed with higher irrigation. The highest uptake occurred at the 150 % ET_c level, indicating that K uptake might continue to benefit from increased water availability to a certain extent.

The data reveal a significant environmental concern: nitrate leaching increased dramatically with higher irrigation levels. At 150 % ET_c, nitrate leaching was over 20 times higher than at 50 % ET_c (Table 4), these aligned with the result of [37]. And also [16,38] indicated that while, increased irrigation can enhance nutrient uptake, it also substantially raises the risk of environmental contamination through nitrate leaching. As (Table 6) illustrated that increasing the irrigation level generally leads to higher nutrient recovery efficiency for N, P, and K, with the most pronounced effects observed in nitrogen recovery, similar to the result [39,40]. However, variability in recovery efficiency is notable, particularly for nitrogen, as indicated by the CV values (Table 6).

Maize yield is influenced by a multitude of factors, including irrigation, nutrient availability, pest and disease pressure, weather conditions, and agronomic practices [18,21]. Optimizing irrigation depth and nutrient management can positively impact maize yield by providing the necessary water and nutrients for optimal plant growth and development Table 7. However, excessive irrigation leading to waterlogging or nitrate leaching can have detrimental effects on yield. One of the main stresses that drastically limits plant growth and lowers yields in many areas is waterlogging [28–30].

5. Conclusion

To conclude study on nutrient uptake and nitrate leaching revealed that increasing irrigation levels generally enhanced the uptake of N, P and K in maize, with the most substantial gains observed up to 150 % of crop evapotranspiration (ETc). However, this benefit diminished slightly at higher irrigation levels. The experiment's statistical analyses confirmed significant differences in nutrient uptake and nitrate leaching across various irrigation treatments, underscoring the importance of irrigation management in influencing these parameters. Notably, deficits in irrigation resulted in reduced nitrate leaching, highlighting the potential for water-saving practices to mitigate environmental impacts. Excessive irrigation led to significantly higher nitrate leaching, raising environmental concerns. Maize yield data also indicated optimal performance at 100 % ETc, with yields declining both above and below this level. The correlation analysis underscored the dual effect of irrigation on nutrient uptake and nitrate leaching, emphasizing the need for balanced irrigation strategies to optimize crop production while minimizing environmental impact. Implementing optimal irrigation depths

Table: 8
Influence of applied irrigation depth on the total above-ground dry biomass yield, grain yield, and thousand grain yield of maize.

TRT	2022/23			2023/24		
	GY (tha^{-1})	TGY (g)	BY(tha^{-1})	GY (tha^{-1})	TGY (g)	BY(tha^{-1})
50 %	3.52^{d}	382.95^{d}	14.28^{d}	3.82^{e}	397.06^{d}	14.94^{d}
75 %	4.82^{c}	542.28^{c}	27.37^{c}	5.12^{d}	540.36^{c}	27.79^{c}
100 %	5.83^{a}	685.12^{a}	32.74^{a}	6.08^{a}	682.51^{a}	31.41^{a}
125 %	5.31^{b}	602.43^{b}	30.99^{ba}	5.7^{b}	620.56^{b}	29.46^{b}
150 %	5.11^{cb}	584.59^{cb}	29.07^{bc}	5.45^{c}	593.12^{cb}	27.91^{c}
LSD	0.38	55.65	2.92	0.19	61.01	1.181
CV	4.15	5.28	5.76	1.92	5.72	2.39

a, b, c, and d According to the LSD test, means that are separated in the alike letters in the similar column do not change at the 0.05 % level statistically.

Table 9
Correlation matrix between nutrient uptake and N leaching under different irrigation regime.

Variable (irrigation level+)	Correlation coefficient
N (2022/23)	*0.99*
N (2023/24)	*0.99*
P (202/23)	*0.98*
P (2023/24)	*0.98*
K (2022/23)	*0.98*
K (2023/24)	*0.98*
NL (2022/23)	*0.96*
NL (2023/24)	*0.96*

aligned with crop water needs can enhance nutrient uptake, minimize nitrate leaching, and maximize maize yield. Farmers should implement 100%ETc to enhance productivity, ensure efficient nutrient utilization, and protect the environment from the adverse effects of nitrate leaching.

Data availability Statement

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

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CRediT authorship contribution statement

Dessie G. Amare: Writing – original draft. **Fasikaw A. Zimale:** Writing – review & editing, Supervision. **Guchie G. Sulla:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this manuscript, titled "**Effect of Irrigation Regimes on Nutrient Uptake and Nitrate Leaching in Maize (Zea mays L.) Production at Birr-Sheleko, Amhara, North Western Ethiopia.**" All authors have approved the final version of the manuscript and have agreed to its submission to Heliyon.

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