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Research Article

Interactive Influence of Varied Irrigation and Urea Application on Maize Growth and Yield

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Abstract— A pot experiment was conducted from November 2021 to March 2022 at the net house of Precision and Automated Agriculture Laboratory, University of Rajshahi, to evaluate the effects of different irrigation levels and urea doses on maize growth and yield. The experiment followed a Completely Randomized Design (CRD) with three replications and included two urea treatments: 100% of the recommended dose (N_1) and 50% of the recommended dose (N_2), and four irrigation regimes as: irrigation amount equivalent to 125% of field capacity (I_1), 100% of field capacity (I_2), 75% of field capacity (I_3) and 50% of field capacity (I_4). Data were collected on plant height, leaf area index, chlorophyll content, cob length, grain number per cob, 1000-grain weight, grain yield, straw yield, biological yield, and harvest index across different growth stages and analyzed using STATVIEW software and Duncan's Multiple Range Test (DMRT). The results indicated that the N_1 treatment (100% urea) significantly improved several growth and yield parameters, including plant height (172.08 cm), leaf area index (4410.13 cm²), cob length (16.14 cm), and grain yield (154.00 g pot⁻¹). In contrast, the highest harvest index (41.35%) was observed with the N_2 treatment (50% urea). Among the irrigation treatments, I_1 (125% of field capacity) produced the highest values for plant height (176.67 cm), cob length (16.89 cm), and grain yield (161.62 g pot⁻¹). The interaction between urea and irrigation levels was significant, with the I_1N_1 combination yielding the highest results for most parameters, including plant height (180.33 cm), leaf area index (4635.89 cm²), and grain yield (169.18 g pot⁻¹). This study highlights the importance of optimizing irrigation and nitrogen management to maximize maize yield. The findings provide valuable insights for enhancing productivity and sustainability in precision agriculture.

Keywords— Maize Yield; Irrigation Levels; Nitrogen Management, Precision Agriculture; Growth Parameters

1. Introduction

Maize (*Zea mays* L.) is a vital global staple crop, essential for the nutrition of billions, and widely used in industrial applications like biodiesel and cattle feed, underscoring its importance in food security and economic stability [1]. Its adaptability across diverse agroecological zones makes it crucial in addressing challenges such as population growth, climate change, and limited resources. As a high-yield, cost-effective crop, maize is key in combating hunger and malnutrition, particularly in regions where it is a dietary staple [2], thus supporting global food security and sustainable agricultural development [3].

Irrigation is essential for agricultural productivity, influencing crop growth, yield, and water use efficiency. It mitigates water shortages, ensuring optimal physiological processes and improved yields. The effectiveness of irrigation depends on factors like water availability, soil characteristics, and crop needs [4]. With growing water scarcity, advanced techniques such as drip and precision irrigation are vital for conserving water and enhancing productivity, crucial for sustaining global food security [5].

Urea is a crucial nitrogen fertilizer in maize production, promoting growth, nutrient uptake, and yield. It plays a key role in essential biochemical processes like photosynthesis and protein synthesis [6]. Urea's conversion to ammonium provides a steady nitrogen supply, enhancing vegetative growth and yield potential. It also improves nutrient efficiency and reduces environmental impacts such as nitrogen leaching and greenhouse gas emissions, making it vital for sustainable agriculture and global food security [7].

However, nitrogen management in agricultural systems presents several challenges, including nutrient loss, environmental degradation, and economic inefficiency. Inefficient nitrogen use can lead to losses through leaching, volatilization, and denitrification, resulting in water contamination, soil degradation, and greenhouse gas emissions. Excessive nitrogen application can also disrupt nutrient balance, exacerbate environmental impacts, and compromise crop quality [8]. To address these issues, improved urea application methods, such as controlled-release and coated urea, offer promising solutions by enhancing nitrogen use efficiency and minimizing environmental impacts. By carefully managing the timing, placement, and dosage of urea, farmers can reduce nitrogen losses and increase crop uptake, leading to more sustainable and productive agricultural practices [9].

Despite extensive research on irrigation systems and urea application, there is a lack of comprehensive studies that systematically examine the combined effects of these factors on maize growth and yield. While many studies have explored the individual impacts of irrigation or urea on maize, few have investigated their interactions. Understanding how different irrigation methods interact with various urea application techniques is crucial for optimizing crop management practices. Research is needed to explore the complex relationships between irrigation and urea application and their combined effects on maize growth, development, and yield, considering the dynamic nature of environmental conditions, soil properties, and crop responses. This study aims to address this gap in the literature by evaluating the individual and combined effects of varied irrigation methods and urea application techniques on maize growth and yield. By elucidating these interactions, the research findings have the potential to significantly improve agricultural practices, particularly in the development of more efficient and sustainable irrigation and fertilization systems for maize cultivation. The objectives of this study are to assess the individual effects of varied irrigation methods, evaluate the individual effects of varied urea application techniques, and investigate the combined effects of different irrigation methods and urea application techniques on maize growth parameters, biomass accumulation, and yield components, including grain yield and quality traits.

2. Experimental Method

2.1 Experimental Site and Duration:
The study was conducted at the net house of the Precision and Automated Agriculture Laboratory, Department of Agronomy and Agricultural Extension, University of Rajshahi, Rajshahi, from December 2021 to April 2022. The research aimed to investigate the impacts of irrigation and urea on maize growth and yield.

2.2 Plant Materials and Growth Conditions: Soil was obtained from the experimental site, pulverized, and cleaned of inert materials, insects, pests, and weeds. Maize variety NK-14, marketed by Syngenta Limited Bangladesh, was utilized. Seeds were treated with 4g provax-200 wp/kg to prevent seed and soil-borne diseases before sowing. Sowing occurred on December 2, 2021, with two seeds per pot. Drainage was conducted as needed. Apart from urea, plots received recommended doses of triple super phosphate (12g pot^{-1}), muriate of potash (7.5g pot^{-1}), and cow dung (100g pot^{-1}). Urea application followed specific treatments and irrigation followed treatment requirements during the crop's growth period. Clean, dried soil pots of 12-liter capacity were employed, each filled with 10 kg of prepared soil.

2.3 Experimental Treatments:
The experiment consisted of two urea fertilizer doses (N_1: 100% recommended dose, N_2: 50% recommended dose) and four irrigation levels (I_1: 125% of field capacity, I_2: 100% of field capacity, I_3: 75% of field capacity, I_4: 50% of field capacity).

2.4 Design of Experiment and Layout:
A Completely Randomized Design (CRD) was adopted with three replications, totaling 24 pots. The clay pots used had a volume of approximately 8181.25 cm^3, perforated at the bottom for drainage. Each pot measured 30 cm in upper diameter, 25 cm in lower diameter, and 25 cm in depth. Ten kg of air-dried soil was placed in each pot.

2.5 Data Collection:
At maturity (April 20, 2022), crops were harvested pot-wise. Plant samples were selected and uprooted for data recording. Harvested crops were collected separately, tagged, and brought to a clean threshing floor. Subsequently, crops were sun-dried, shelled, and grains cleaned pot-by-pot. Grain yield was adjusted to 14% moisture content, and both grain and stover yields were calculated as g/plant.

2.6 Experimental Data Collection:
Data on plant growth parameters, yield, and yield components were collected from each pot. Plant growth parameters included plant height, leaf area, and leaf chlorophyll content. Yield components comprised cob length, number of grains cob^{-1}, 1000-grain weight, grain yield, stover yield, biological yield, harvest index, crude protein content, total carbohydrate content, and ash content.

2.7 Crude protein content:
Dried maize and grain samples (1 g. each) were weighed and transferred into Micro-Kjeldahl digestion tubes, followed by the addition of 15 ml of 98% sulfuric acid. The tubes were heated at 400°C for one hour. After cooling, the digested solutions were diluted to 100 ml. For distillation, 15 ml of 4% boric acid with indicator was placed in a conical flask. The digested samples were diluted to 25 ml, and 5 ml of this was added to the distillation tube, followed by 10 ml of 40% sodium hydroxide. Distillation for 5 minutes produced a light green color, confirming the process was successful.

2.8 Total Carbohydrate Content:
Dried maize and grain samples were weighed and transferred into test tubes. Each tube received 5 ml of 2.5N hydrochloric acid (HCl), sealed with aluminum foil, and incubated in a water bath at 90-100°C for three hours. After cooling, the solutions were diluted to 100 ml and centrifuged at 8000 rpm for three minutes. Standard glucose solutions were prepared, and varying volumes were treated with Anthrone reagent, followed by incubation at 90-100°C for 17 minutes. After cooling, total carbohydrate content was determined using a spectrophotometer based on absorbance values.

2.9 Ash content: Ash content of maize grain was determined by burning in the finely grinded grain using an electric crucible. [10]

2.10 Statistical Analysis: Collected data underwent statistical analysis using the analysis of variance (ANOVA) technique. Mean differences were determined using Duncan's Multiple Range Test (DMRT) with the STATVIEW statistical software package.

3. Results and Discussion

3.1 Plant Height (cm):

Plant height was measured on 30, 60, 90 and 120 DAS, which are presented in Table 1. The plant height differed significantly in all the observations (30, 60, 90, and 120). At 30 DAS, the highest plant height (96.83 cm) was observed in urea application at 100% of the recommended dose (N_1) which was significantly reduced by 6.19% in urea at 50% of the recommended dose (N_2). At 60 DAS, 151.42 cm plant height was observed as highest in N_1 which is reduced significantly by 6.27 % in N_2. In N_1, the highest plant height (162.58cm) was found at 90 DAS; in N_2, the plant height was reduced significantly by 6.20 %. At 120 DAS, the highest plant height (172.08cm) was observed in N_1, which was significantly reduced by 6.14 % in N_2. Irrigation shows a remarkable variation in the plant height of maize in all cases (Table. 1). The highest value was observed in I_1, but the height is almost the same in I_2 and I_3 and significantly reduced in I_4. At 30 DAS, the highest plant height (98.67cm) was observed in I_1 and it was reduced only by 1.18% and 4.9% in I_2 and $I_{3,}$ respectively but significantly by 13.51% in I_4. At 60 DAS, 155.17cm plant height was observed as the highest in $I_{1,}$ which was slightly reduced by 2.04% and 6.23% in I_2 and $I_{3,}$ respectively but reduced significantly by 13.64% in I_4. In $I_{1,}$ the highest plant height (167.67cm) was found at 90 DAS; in I_2 and I_3 the plant height was slightly reduced by 2.38% and 7.25%, respectively. Finally, at 120 DAS, the highest plant height (176.67cm) was found in $I_{1,}$ which was reduced by 1.51% and 7.26% in I_2 and $I_{3,}$ respectively, but significantly by 13.58% in I_4. The results of the experiment confirm that the amount of irrigation water greatly influences the plant height of maize. The variation was obtained when comparing the results of the plant height of maize due to the interaction between irrigation and urea levels (Table 1). At 30 DAS, the maximum plant height (100cm) was found in the interaction between N_1 and I_1 (N_1= Urea 100% of the recommended dose and I_1= irrigation equivalent to 125% of field capacity) and the lowest plant height (79.33cm) in the interaction in between N_2 and I_4 (N_2= Urea 50% of the recommended dose and I_4= irrigation equivalent to 50% of field capacity). AT 60 DAS, 158.00cm plant height was observed as the maximum in the interaction of N_1 with I_1, where 127.00 cm plant height was found as the lowest in N_2 with I_4. In the interaction between N_1 and $I_{1,}$ the maximum plant height (170.00cm) at 90 DAS, whereas the lowest plant height (135.33cm) was observed in the interaction of N_2 with I_4. At 120 DAS, the highest plant height (180.33cm) was obtained in the interaction of N_1 with I_1 and the lowest (146.00cm) in N_2 with I_4. From this table, a huge comparison was observed in plant height of maize by the effect of interaction between irrigation and urea levels.

Baloch et al. [11] found the effect of different Nitrogen (N) levels and application scheduling on maize's growth and grain yield in a field trial. The results showed that the growth and grain yield of maize were significantly influenced by different urea levels and application schedules. The highest urea level of 180 kg / ha resulted in the highest plant height, number of leaves, leaf area, cobs per plant, grains per cob, biomass yield, and grain yield per ha. The lowest urea level of 60 kg per ha resulted in the lowest values for these traits. [12] also showed that maize growth, yield, and WUE were significantly influenced by irrigation quotas, with the highest values observed with maximum irrigation. The research results provide valuable insights for optimizing water-saving irrigation and increasing maize yield in northwest China. When combined, high nitrogen and high irrigation can synergistically affect plant height. Nitrogen uptake and utilization are optimized by sufficient water. This ensures the plant can fully utilize the applied nitrogen for growth. Water availability mitigates the negative effects of high nitrogen. Excess nitrogen can sometimes burn plants, but adequate water dilutes the concentration and prevents damage [13].

3.2 Leaf Area (cm^2):

Because of applying two different urea doses, the leaf area of maize showed statistically significant results on 30, 60 and 90 DAS (Table 1). At 30 DAS, the greatest leaf area (234.5cm^2) was measured in $N_{1,}$ which was reduced slightly in N_2. AT 60 DAS, the maximum (3597.25cm^2) leaf area was observed in $N_{1,}$ where the leaf area (3408.72cm^2) reduced significantly by 5.24% in N_2. In the case of N_1, the maximum leaf area (4410.13cm^2) was found at 90 DAS, whereas the leaf area turned low significantly by 5.16% in N_2. The leaf area of maize was measured in 30, 60 and 90 DAS by different irrigation frequencies. From the observation, a remarkable result of leaf area was found (Table. 1) . At 30 DAS the highest leaf area (247.78cm^2) was observed in I_1 which reduced slightly 4.03% and 11.49% in I_2 and I_3 respectively but significantly by 22.89% in I_4. At 60 DAS' the leaf area was observed as the highest in I_1 (3668.59 cm^2), where the leaf area turned low by 1.31% and 5.53% in I_2 and $I_{3,}$ respectively, but significantly by 11.22% in I_4. In the case of $I_{4,}$ the highest leaf area (4550.46cm^2) was measured at 90 DAS, whereas the leaf area reduced only 2.63% and 7.05% in I_2 and $I_{3,}$ respectively but significantly 12.65% in I_4. A noticeable variation was yielded by comparing the leaf area result due to the interaction between urea fertilizer (urea) rates and irrigation frequencies (Table. 1). The maximum leaf area (252.03cm^2) was recorded in the combination of N_1 with $I_{1,}$ where the lowest (179.41cm^2) was found in the combination N_2 and I_4. At 60 DAS, leaf area was measured as the highest (3751.63cm^2) due to the combination of N_1 with I_1 and area as the lowest (3135.45cm^2) due to the combination of N_2 with I_4. In the case of interaction between N_1 and I_1, leaf area was recorded as the highest (4635.89cm^2) at 90 DAS, whereas the lowest leaf area (3847.84cm^2) was found due to the interaction between N_2 and I_4.

Table 1. Effects of urea fertilizer rates, irrigation and their interaction on plant height and leaf area of maize at different days after sowing (DAS)

Urea rate	Plant Height(cm)				Leaf area (cm^2)		
	30 DAS	60 DAS	90 DAS	120 DAS	30(DAS)	60(DAS)	90(DAS)
N_1	96.83±1.57	151.42±3.36	162.58±3.58	172.08±4.16	234.5±9.31a	3597.25±68.76a	4410..13±89.06a
N_2	90.83±2.96	141.92±3.71	152.50±4.37	161.50±4.09	213.47±9.51b	3408.72±66.85b	4182.71±86.54b
LS	0.05	0.05	0.05	0.05	NS	0.05	0.05
Irrigation							
I_1	98.67±1.98a	155.17±4.63a	167.67±4.88a	176.67±5.66a	247.78±12.94a	3668.59±96.51a	4550.46±118.40a
I_2	97.50±1.89a	152.00±4.1a	163.67±4.02a	174.00±4.95a	237.79±11.75ab	3620.63±77.57a	4430.60±91.27a
I_3	93.83±2.52ab	145.50±4.57ab	155.50±4.92ab	163.83±4.63ab	219.30±11.89ab	3465.63±77.18ab	4229.72±104.20ab
I_4	85.33±3.79b	134.00±4.06b	143.33±4.24b	152.67±4.75b	191.07±7.06b	3257.08±75.24b	3974.91±83.14b
LS	0.01	0.01	0.01	0.01	0.05	0.01	0.01
Interaction							
N_1I_1	100.00±2.65a	158.00±7.81a	170.00±8.08a	180.33±10.11a	252.03±22.34a	3751.63±174.11a	4635.89±222.01a
N_1I_2	98.67±2.40a	154.67±7.06a	166.33±6.36a	177.67±8.69ab	244.80±18.80ab	3688.93±128.00a	4509.97±140.54a
N_1I_3	97.33±3.28a	152.00±6.43ab	162.67±6.94ab	171.00±6.08ab	238.43±16.98ab	3569.73±91.65ab	4392.68±116.48ab
N_1I_4	91.33±2.96ab	141.00±3.79ab	151.33±5.48ab	159.33±5.81ab	202.73±6.75ab	3378.70±92.43ab	4101.97±117.38ab
N_2I_1	97.33±3.28a	152.33±6.17ab	165.33±6.94a	173.00±6.66ab	243.53±17.87ab	3585.55±96.75ab	4465.03±116.23a
N_2I_2	96.33±3.28a	149.33±5.21ab	161.00±5.77ab	170.33±5.78ab	230.78±16.98ab	3552.33±95.06ab	4351.23±124.89ab
N_2I_3	90.33±2.96ab	139.00±4.58ab	148.33±4.63ab	156.67±4.33ab	200.18±7.25ab	3361.53±102.71ab	4066.76±119.02ab
N_2I_4	79.33±5.21b	127.00±4.36b	135.33±6.57b	146.00±5.86b	179.41±8.23b	3135.45±70.51b	3847.84±68.07b
LS	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CV (%)	6.18	6.88	7.061	7.15	11.96	5.46	5.41

Mean values in a column having the same letters or without letter do not differ significantly as per Duncan's multiple range test (DMRT), NS= Non significant, CV= Co-efficient of variation, LS= Level of significant DAS=Day's after sowing, N_1 = 100% of recommended doses of urea, N_2 = 50% of recommended doses of urea. I_1= irrigation equivalent to 125%of field capacity, I_2= irrigation equivalent to 100%of field capacity, I_3= irrigation equivalent to 75% field capacity, I_4= irrigation equivalent to 50% of field capacity.

Tian et al. [14] found that plant height and leaf area increase with higher irrigation amounts. Amin [15] showed that increasing nitrogen availability promotes leaf growth, as plants can allocate more resources to producing larger and more numerous leaves when nitrogen is abundant. Yan et al. [16] observed a synergistic effect when high nitrogen levels were combined with frequent irrigation. Nitrogen fuels leaf growth, and sufficient water availability from frequent irrigation allows the plant to effectively utilize nitrogen, resulting in larger leaves.

Table 2. Effects of urea fertilizer rates, irrigation and their interaction on SPAD value of maize on different days after sowing (DAS)

Urea rate	SPAD value		
	30 (DAS)	60 (DAS)	90 (DAS)
N_1	25.95±1.45a	29.23±1.58a	32.18±2.14a
N_2	21.6±1.87b	23.51±2.02b	27.00±1.92b
LS	0.05	0.01	0.01
Irrigation			
I_1	28.82±1.82a	32.05±1.69a	34.91±2.93a
I_2	26.65±1.70a	29.65±1.44ab	33.03±2.37a
I_3	22.30±2.12ab	24.67±2.21b	28.02±2.33ab
I_4	17.35±1.55b	18.52±1.97c	22.40±1.80b
LS	0.01	0.01	0.01
Interaction			
N_1I_1	30.16±1.24a	33.96±2.32a	37.16±5.31a
N_1I_2	28.27±2.04ab	31.26±1.78ab	35.00±3.93a
N_1I_3	25.74±2.02ab	28.84±2.29abc	31.39±3.02ab
N_1I_4	19.63±2.28bc	22.05±1.54bcd	25.19±2.55ab
N_2I_1	27.48±3.64ab	30.14±2.28abc	32.65±3.12ab
N_2I_2	25.02±2.76ab	28.03±2.15abc	31.06±2.97ab
N_2I_3	18.85±2.56bc	20.89±1.81cd	24.64±2.58ab
N_2I_4	15.06±1.23c	14.99±2.13d	19.61±1.35b
LS	0.01	0.01	0.01
CV (%)	17.06	13.55	19.23

Other details are as described in Table 1

3.3 SPAD value (Ch N $_{SPAD}$):

The leaf greenness or SPAD value of maize was measured on 30, 60 and 90 DAS, presented in Table. 2 by applying two different urea doses. The SPAD value of maize differed significantly in all the observations (30, 60, 90DAS). At 30 DAS, the highest SPAD value (25.95) was observed in $N_{1,}$ significantly reduced by 16.76% at N_2 (21.6). At 60 DAS, a maximum (29.23) SPAD value was found in N_1 and a minimum (23.51) in N_2, significantly reduced by 19.57%. At 90 DAS, the SPAD value was found to be maximum (32.18), significantly reduced by 16.10% in N_2. The SPAD value of maize showed statistically significant results due to different irrigation frequencies (Table 2). At 30 DAS, the highest SPAD value (28.82) was observed in $I_{1,}$ which reduced slightly by 7.53% and 22.62% in I_2 and $I_{3,}$ respectively, but significantly by 37.80 % in I_4. At 60 DAS, the highest SPAD value (32.05) was observed in $I_{1,}$ which reduced slightly by 7.49% in I_2 and marginally 23.03% in I_3, but significantly by 42.22% in I_4. AT 90 DAS, the highest SPAD value (34.91) was observed in $I_{1,}$ which reduced only by 5.39% in I_2 and continuously by 19.74% in I_3 but significantly by 55.85% for I_4. An important interaction effect was identified between urea levels and irrigation frequencies with SPAD value (as presented in Table 2). Specifically, at the 30 DAS, the highest SPAD value (30.16) was observed when urea level N_1 was combined with irrigation frequency I_1. At the same time, the lowest content (15.06) was recorded for urea level N_2 connected with irrigation frequency I_4. Similarly, at the 60-day mark, the maximum SPAD value (33.96) was found in the combination of $N_1$and I_1, whereas the minimum (14.99) was observed for N_2 and I_2. Finally, at 90 DAS, the highest SPAD value (37.17) was noted for the combination of N_1 and I_1, while the lowest content (16.61) was observed for N_2 and I_4. This suggests that the interaction between urea levels and irrigation frequencies has a notable influence on SPAD value at different stages of growth.

Table 3. Effects of urea fertilizers rates, irrigation and their interaction on yield components and yield of maize

Nitrogen	Cob length (cm)	No. of grains cob^{-1}	1000 grain weight (g)	Grain yield (g pot^{-1})	Stover yield (g pot^{-1})	Biological yield (g pot^{-1})	Harvest index (%)
N_1	16.14±0.54a	280.18±23.18a	109.79±2.79a	154.00±7.08a	229.45±13.90a	383.45±20.60a	40.43±0.54a
N_2	15.24±0.56b	214.61±26.16b	101.45±3.33b	139.42±6.32b	199.41±10.60b	338.83±16.51b	41.35±0.54b
LS	NS	0.01	0.05	NS	0.05	NS	NS
Irrigation							
I_1	16.89±0.83a	324.05±27.85a	113.51±3.39a	161.62±9.99a	252.44±19.69a	415.06±28.68a	39.56±1.02b
I_2	16.62±0.72ab	293.09±27.38ab	111.25±3.31a	156.98±9.00ab	230.67±14.48ab	387.65±22.84ab	40.63±0.63ab
I_3	15.33±0.64ab	225.51±28.74bc	104.39±3.45ab	141.99±8.58ab	202.76±9.89ab	344.75±18.31ab	41.16±0.22ab
I_4	13.93±0.30b	146.93±13.31c	93.31±3.61b	125.26±4.00b	171.84±9.93b	297.10±13.79b	42.21±0.75a
LS	0.01	0.01	0.01	0.01	0.01	0.01	0.05
CV%	10.43	21.9	7.21	13.86	15.76	14.48	4.2
Interaction							
N_1I_1	16.89±1.31a	349.94±43.15a	115.55±6.08a	169.18±16.49a	264.16±41.04a	433.34±56.44a	39.55±2.01b
N_1I_2	16.89±1.31a	319.62±20.22a	114.03±5.34a	161.76±14.10ab	245.05±27.15a	406.81±41.00ab	40.01±1.13b
N_1I_3	16.39±0.86ab	277.93±21.03ab	110.12±3.65a	154.47±12.91abc	218.95±10.60ab	373.42±23.48abc	41.34±0.38ab
N_1I_4	14.39±0.34ab	173.20±13.27bc	99.44±3.59ab	130.58±6.80abc	189.65±12.09ab	320.23±18.89bc	40.81v0.28ab
N_2I_1	16.89±1.31a	298.15±36.68ab	11.47±4.05a	156.06±13.58abc	240.73±10.79ab	396.78±24.35ab	39.56±1.06b
N_2I_2	16.35±0.892ab	266.56±51.33ab	108.47±4.32a	152.19±13.52abc	216.29±10.23ab	368.48±23.68abc	41.25±0.53ab
N_2I_3	14.27±0.42ab	173.08±30.66bc	98.67±3.65ab	129.51±6.78bc	186.58±10.66ab	316,08±17.39bc	40.99±0.25ab
N_2I_4	13.47±0.35b	120.65±4.42c	87.18±3.84b	119.94±2.32c	154.03±5.48b	273.97±7.67c	43.60±0.90a
LS	0.05	0.01	0.01	0.05	0.01	0.05	0.05
CV%	10.43	21.9	7.21	13.86	15.76	14.48	4.2

Mean values in a column having the same letters or without letter do not differ significantly as per Duncan's multiple range test (DMRT), NS= Non significant, CV= Co-efficient of variation, LS= Level of significant DAS=Day's after sowing, N_1 = 100% of recommended doses of urea, N_2 = 50% of recommended doses of urea. I_1= irrigation equivalent to 125%of field capacity, I_2= irrigation equivalent to 100%of field capacity, I_3= irrigation equivalent to 75% field capacity, I_4= irrigation equivalent to 50% of field capacity.

Da Silva et al. [17] observed that nitrogen is a crucial element for chlorophyll production, with chlorophyll content directly correlating with SPAD readings.

Therefore, supplying adequate nitrogen generally increases SPAD values, indicating healthier leaves and potentially higher yields. Ramachandiran and Pazhanivelan [18] demonstrated that higher irrigation frequencies can lead to increased SPAD values in maize. Higher chlorophyll content, as indicated by SPAD values, suggests enhanced photosynthetic activity, leading to better production of sugars and carbohydrates. Maresma et al. [19] found that combining a maximized nitrogen dose with more frequent irrigation can result in higher SPAD values in maize. Adequate nitrogen availability promotes chlorophyll production, directly translating to higher SPAD readings, while frequent irrigation ensures consistent water availability, preventing stress and optimizing nitrogen uptake and use.

3.4 Yield and Yield Component

3.4.1 Cob length (cm):

There was no significant difference in cob length due to the application of the two urea doses. The highest cob length, measuring 16.14cm, was observed in the N_1 treatment, while the lowest, measuring 15.24cm, was recorded in the N_2 treatment (Table 3). Differences in maize cob lengths were observed across different irrigation frequencies, as detailed in Table 2. The greatest cob length (16.89cm) was recorded in the I_1 treatment. In the I_2 treatment, there was a slight decrease of 1.60% in cob length compared to I1 and 9.24% in I_3. However, a more substantial reduction of 17.53% was noted in the I_4 treatments. These results highlight the significant influence of varying irrigation frequencies on maize cob length, with the highest measurements found in the I_1 treatment and considerable reductions observed in the I_4 treatments. A significant interaction effect in the cob length of maize was obtained between urea and irrigation frequencies (Table 3). Maximum cob length (16.89cm) was recorded in N_1 when combined with I_1. It reduced by 20.25% from N_1I_1 when nitrogen level N_2 was combined with irrigation frequency I_4, resulting in the minimum cob length (13.47cm).

Singh et al. [20] observed that the length of the cob in maize has a positive correlation with the level of nitrogen applied, with higher levels of nitrogen resulting in maximum cob length. Awe et al. [21] showed that higher irrigation frequencies often lead to longer cobs, with the optimal frequency depending on factors such as soil type, climate, variety, and management practices. Frequent irrigation ensures a consistent water supply, preventing stress and enabling the plant to prioritize cob development. Wang et al. [22] found that when nitrogen and irrigation are combined optimally, they can synergistically benefit cob development. Adequate nitrogen uptake allows for efficient water utilization, while sufficient water availability facilitates nitrogen uptake and transport. This balance promotes proper cob development, ultimately leading to longer cobs.

3.4.2 Number of Grains cob^{-1}:

When comparing two different urea doses, there were significant variations in all observations regarding the number of grains per cob. The highest number of grain cob^{-1} (280.18) was obtained in N_1 and the lowest (214.61) in N_2 (Table 3). As a result, N_1 was reduced by 23.40% compared with N_2. Significant differences in the number of grains cob^{-1} were observed for different irrigation frequencies, as detailed in Table 3. The maximum number of grain cob^{-1} (324.05) was recorded in I_1, which was reduced slightly by 9.55% in I_2, but significantly by 30.41 and 54.66% in I_3 and I_4, respectively. Significant interaction in the number of grains cob^{-1} was obtained between urea and irrigation frequencies (Table 3). The maximum number of grain cob^{-1} (349.94) was found in N_1 when combined with I_1, which was reduced by 65.52% in combination of N_2I_4.

Studies have shown that increasing nitrogen application up to an optimal level can lead to more grains per cob than nitrogen-deficient conditions [23]. When corn plants receive more water through frequent irrigation, it allows them to maintain better cell turgor and photosynthesis, leading to improved kernel development and filling. This often results in more grains per cob than plants under water stress [24]. Higher urea and irrigation can potentially increase the number of grains per cob in maize under specific conditions and with proper management [25].

3.4.3 Thousand (1000) grains weight (g):

Both urea fertilizers have different effects on 1000 grains weight. The highest 1000 grain weight (109.79g) was obtained in N_1 and the lowest (101.45g) was observed in N_2 (Table 3). This result clearly shows that N_1 was reduced by 7.60% from N_2. Significant differences in 1000 grains weight were illustrated for different irrigation frequencies (Table 3). The highest 1000-grain weight was recorded (113.51g) in I_1. This 1000 grain weight slightly decreased by 1.99% and 8.03% in I2 and I3, respectively, but significantly by 17.80% in I_4. A significant effect was recorded in 1000grains weight due to the interaction between urea fertilizer and irrigation frequencies (Table 3). The maximum 1000 grains weight (115.55g) was found in the combination of N_1 with $I_{1,}$ and the minimum (87.18g) was found in N_2 with I_4. Here, 1000 grains weight in N_1I_1 reduced significantly 24.55% in N_2I_4.

Nitrogen plays a major role in carbohydrate metabolism and starch accumulation within the kernels, which contributes to grain weight [26]. Water is essential for various physiological processes within the plant, including cell division and expansion. This is crucial for kernel development and grain weight [27].

3.4.4 Grain Yield (g pot^{-1}):

Both urea fertilizers didn't differ significantly concerning grain yield. The highest grain yield (154.00g pot-^{1}) was observed in N_1 and the lowest (139.42 gpot^{-1}) in N_2 (Table 3). Table 3 illustrates the notable variations in grain yield resulting from varying irrigation frequencies. In I_1, the highest grain yield recorded was 161.62 g pot^{-1}. This yield showed a slight decrease of 2.87% and 12.15% in I_2 and I_3, respectively, but significantly 22.50% in I_4. A significant interaction effect of maize grain yield was found between urea fertilizer and irrigation frequency (Table 3). Maximum grain yield (169.18 gpot^{-1}) was observed in N_1, combined with I_1, and minimum (119.94 gpot^{-1}) was recorded in N_2 with I_4. These results clearly show that the combination N_1I_1 was reduced by 29.11% from the combination N_2I_2.

Nitrogen promotes vegetative growth, ear development, and increased potential kernel formation, and contribute to higher grain yield when applied at optimal levels [28]. Low irrigation rate can reduce grain yield by hindering various physiological processes. Optimum irrigation helps mitigate stress and maintain growth conditions that favor higher yields. When applied in optimal amounts, urea provides essential nitrogen for plant growth. Combined with adequate irrigation, which supports nutrient uptake and various physiological processes, this can lead to a synergistic effect and maximize grain yield [29].

3.4.5 Stover Yield (g pot^{-1}):

Our result demonstrated that the stover yield differed significantly due to the application of two different doses of urea fertilizer (Table 2). The maximum stover yield (229.45gpot^{-1}) was observed in N_1 and the minimum (199.41gpot^{-1}) in N_2. This may explain why N_1 yielded 13.09% lower stover yield than N_2. Irrigation shows a remarkable variation in maize stover yield in all cases (Table 2). The highest value was noted in I_1 (252.44gpot^{-1}). It was reduced slightly by 8.62% and 18.89% in I2 and I3, respectively, but significantly by 31.93% in I_4. Variation was obtained when comparing the result of the stover yield of maize due to the interaction between urea fertilizer and irrigation frequencies. The highest stover yield (264.16gpot^{-1}) was measured in the combination of N_1 with I_1 and the lowest (154.03gpot^{-1}) in the combination of N_2 with I_4 (Table 2). Nitrogen plays a role in chlorophyll production, which is essential for photosynthesis. Increased photosynthesis leads to greater carbohydrate production, ultimately contributing to more biomass in stover [30]. Reduced irrigation frequency can lead to water stress in maize plants and impede photosynthesis. This leads to less energy available for plant growth and ultimately, lower stover yield [31].

3.4.5 Biological yield (g pot^{-1}):

Urea fertilizer effect didn't differ significantly with respect to biological yield. The highest biological yield (383.45gpot^{-1}) was observed in N_1 and the lowest (338.83gpot^{-1}) in N_2. (Table 2) Due to the different irrigation frequencies, variation in the biological yield of maize was recorded. In the case of $I_{1,}$ the highest biological yield (415.06gpot-1) was measured, which turned low by 6.60% and 16.94% in I_2 and $I_{3,}$ respectively but significantly by 28.42% in I_4. (Table 2) A remarkable variation was recorded by comparing the result of biological yield due to the interaction between urea fertilizer and irrigation frequencies. (Table 2) In the combination of N_1 with I_1, the highest value (433.34gpot^{-1}) was observed and the lowest value (273.97gpot^{-1}) was found in the combination of N_2 with I_4.

Applying the right amount of urea at the right time can significantly boost biological yield by providing the necessary nitrogen for increased vegetative growth, enhanced photosynthesis, and ultimately, greater biomass production [32]. Maize requires water for various physiological processes, including cell division and expansion, nutrient uptake, and photosynthesis. These processes contribute significantly to biomass production, which is the primary component of biological yield [33].

3.4.6 Harvest Index (%):

From the result of urea fertilizer effect, no significant difference in harvest index (%) was observed (Table 2). The maximum harvest index (41.35%) was measured in N_2 and the lowest (40.43%) was found in N_1. Table 2 demonstrates the variation in the harvest index due to the effect of different irrigation frequencies. In the case of $I_{4,}$ the highest harvest index (42.21%) was measured, which was slightly decreased by 2.49% and 3.74% in I_3 and $I_{2,}$ respectively but significantly by 6.28% in I_1. The variation was obtained when comparing the harvest index of maize due to the interaction between urea fertilizer and irrigation frequencies. In the interaction between N_1 and I_1, the lowest harvest index (39.55%) was recorded and the highest harvest index (43.60%) was found in the combination of N_2 and I_4 (Table 2) .

If nitrogen deficiency is the limiting factor for grain yield, applying different urea doses can lead to significant differences in harvest index. Providing adequate nitrogen can improve grain filling and increase the proportion of dry matter in the grain, thereby raising the harvest index [34]. Lower urea application and reduced irrigation frequency can limit excessive vegetative growth. This can redirect resources towards grain development, potentially increasing the proportion of dry matter allocated to the grain and leading to a higher harvest index [35].

3.5 Crude protein content:

Significant differences were found between two urea fertilizers in crude protein content. The maximum crude protein content (11.82%) was observed in $N_{1,}$ which was reduced significantly by 6.43% in N_2 (Table 3). Different irrigation frequencies found a noticeable variation in crude protein (Table 3). The maximum crude protein (12.18%) was measured in I_1, which slightly decreased by 2.05% and 7.30% in I_2 and $I_{3,}$ respectively but significantly by 15.26% in I_4. Interaction between urea fertilizer and irrigation frequencies created a variation in crude protein. In the combination of N_1 with I_1, the highest crude protein (12.33%) was recorded and the lowest (9.71%) was found in a combination of N_2 and I_4 (Table 3).

Providing sufficient nitrogen through appropriate urea application rates supports the production of amino acids and ultimately contributes to higher crude protein content in the maize grain [36]. Ensuring adequate water availability facilitates nutrient uptake and translocation, further aiding protein synthesis and potentially increasing crude protein content.

3.6 Total carbohydrate:

Applying two different urea fertilizer doses yielded a remarkable variation in carbohydrate Content. The maximum total carbohydrate (60.69%) was observed in $N_{1,}$ which was reduced significantly by 6.54% in N_2 (Table 3). Different irrigation frequencies led to a noticeable variation in carbohydrate Content (Table 3). The highest carbohydrate content (62.37) was measured in $I_{1,}$ which was reduced by 1.67 and 6.99% in I_2 and $I_{3,}$ respectively but significantly by 14.88% in I_4. Interaction between urea fertilizer and irrigation frequencies created a variation in carbohydrate content (Table 3). The maximum total carbohydrate content (63.32%) was observed in the combination of N_1 with I_1 and the minimum (50.10%) in combination of N_2 with I_4.

Applying different urea doses can lead to varying levels of nitrogen availability for the plants. Higher urea application might lead to increased carbohydrate content due to enhanced photosynthesis and greater carbon fixation [37]. Adequate water availability can support enhanced plant growth and development, leading to increased biomass production. This can potentially lead to higher total carbohydrate content in the entire maize plant [38]. Both low nitrogen from insufficient urea and water stress from infrequent irrigation can limit plant growth and carbohydrate production, leading to a decrease in both total and grain-quality carbohydrate content.

3.7 Ash content:

Significant differences were found between two urea fertilizers in ash content (Table 3). The highest total ash content (2.02%) was obtained in $N_{1,}$ which was reduced significantly by 4.46% in N_2. There were significant differences in ash content (%) for different irrigation frequencies (Table 3). The maximum ash content (2.07%) was recorded in $I_{1,}$ which was reduced slightly by 1.93% and 5.31% in I_2 and I_3, respectively but significantly by 10.63% in I_4. A significant effect was observed in grain ash content (%) maize due to the interaction between urea fertilizer and irrigation frequencies in Table 3. The highest ash content (2.10%) was found in the combination of N_1 with I_1 and the lowest (1.79%) was observed in N_2 with I_4.

Urea fertilizer provides nitrogen (N), a crucial plant growth and development element. However, commercially available urea may contain impurities that contribute to ash content upon burning. Adequate irrigation ensures efficient nutrient uptake and translocation, potentially leading to lower grain ash content due to better utilization of available nutrients.

4. Conclusion and Future Scope

This study highlights the significant impact of irrigation and nitrogen management on maize growth and yield. The findings demonstrate that applying 100% of the recommended urea dose (N_1) and irrigating at 125% of field capacity (I_1) produced the best results across most growth and yield parameters, including plant height, leaf area index, cob length, and grain yield. The combination of these two treatments, N_1 and I_1, was particularly effective, leading to superior performance in nearly all measured attributes. Therefore, for farmers aiming to maximize yield in maize production, the application of full recommended urea doses combined with optimal irrigation practices is essential. This study provides valuable insights into precision agriculture, emphasizing the need for tailored management practices to achieve sustainable and high-yielding maize cultivation. Overall, the research contributes to a better understanding of how strategic irrigation and nitrogen management can enhance crop productivity, offering practical guidelines for improving agricultural practices and ensuring food security in maize-growing regions.

Conflict of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper. There are no financial, personal, or other relationships with people or organizations that could influence, or be perceived to influence, the work presented in this manuscript.

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Authors' Contributions
Author-1 conducted the literature review, wrote the first draft of the manuscript, and conceived the study. Author-2 was involved in the development of the protocol and data processing. Author-3 is the corresponding author, contributed to protocol development, and revised the final draft of the manuscript. All authors reviewed, edited, and approved the final version of the manuscript.

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