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Stage-Specific Irrigation Scheduling Enhances Water Use Efficiency, Nitrogen Uptake and Grain Protein Yield in Hybrid Maize (*Zea mays* L.) under Semi-Arid Conditions

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Abstract

Water scarcity is one of the major constraints limiting maize productivity in semi-arid regions, necessitating irrigation strategies that maximize crop productivity while improving resource-use efficiency. A field experiment was conducted during the 2024 kharif season to evaluate the effect of stage-specific irrigation scheduling on dry matter accumulation, grain yield, water use efficiency (WUE), nitrogen uptake and grain protein yield of hybrid maize (*Zea mays* L.). Eight irrigation schedules comprising different combinations of irrigation at seedling, knee-height, pre-tasseling, silking, grain-filling and physiological maturity stages were evaluated in a randomized block design with three replications. Irrigation scheduling significantly influenced dry matter production, grain yield, WUE, nitrogen uptake and grain protein yield, whereas grain protein concentration remained statistically unaffected. The irrigation schedule involving irrigation at seedling, knee-height, pre-tasseling, silking and grain-filling stages (T₅) recorded the highest total dry matter accumulation (284.8 g plant⁻¹), grain yield (5.5 t ha⁻¹), biological yield (20.2 t ha⁻¹), water use efficiency (19.20 kg ha⁻¹ mm⁻¹), total nitrogen uptake (159.6 kg ha⁻¹) and protein yield (571.14 kg ha⁻¹). However, these responses were statistically comparable with T₆ for several parameters, indicating that irrigation schedules including the major reproductive stages were similarly effective under the experimental conditions. Improved crop performance under optimum irrigation scheduling was attributed to enhanced soil moisture availability during critical growth stages, which promoted greater biomass accumulation, efficient nitrogen uptake and improved assimilate translocation during grain filling. Although grain protein concentration varied only slightly among treatments, the substantial increase in grain yield resulted in significantly greater protein yield under optimum irrigation. The findings demonstrate that irrigation synchronized with critical phenological stages is more effective than indiscriminate irrigation frequency in improving water use efficiency and nitrogen utilization. Therefore, irrigation at seedling, knee-height, pre-tasseling, silking and grain-filling stages can be considered an effective strategy for enhancing maize productivity and resource-use efficiency under moisture-limited environments.

Keywords: Critical growth stages, Grain protein yield, Hybrid maize, Irrigation scheduling, Nitrogen uptake, Resource-use efficiency, Semi-arid agriculture, Water use efficiency

1. Introduction

Maize (*Zea mays* L.) is among the most widely cultivated cereal crops worldwide because of its exceptional yield potential, broad adaptability to diverse agro-climatic environments and versatility of utilization. It serves as an important source of food, animal feed and fodder, while also providing raw material for starch, bioethanol and several other agro-industrial products. Owing to its multiple uses and high productivity, maize makes a substantial contribution to global food security and agricultural sustainability. In India, it occupies a prominent position among cereal crops and is increasingly recognized as an important component of diversified cropping systems, particularly in regions experiencing groundwater depletion, climatic variability and changing production environments (FAOSTAT, 2024; Ministry of Agriculture and Farmers Welfare, 2024). The sustainability of maize production is increasingly threatened by declining freshwater availability.

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In semi-arid and sub-humid regions, irregular rainfall patterns coupled with rising evaporative demand frequently expose the crop to moisture stress during critical periods of growth. Ongoing climate change has further intensified these challenges through more frequent droughts, prolonged dry spells and increasing temperature extremes, thereby increasing uncertainty in crop productivity and placing greater pressure on already limited water resources (IPCC, 2023). Since agriculture consumes nearly 70% of the world's freshwater withdrawals, improving irrigation efficiency has become an essential requirement for ensuring future food production without further aggravating water scarcity (FAO, 2024).

Although maize possesses remarkable biomass-producing ability, its productivity is highly dependent on an adequate and timely supply of water. Moisture deficits during key developmental stages such as seedling establishment, knee-height, tasseling, silking and grain filling adversely affect leaf expansion, root growth, photosynthetic activity, assimilate translocation and reproductive development, ultimately resulting in lower grain yield and inferior grain quality (Grant *et al.*, 1989; Cakir, 2004) ^[2, 4]. Among these growth stages, the flowering phase comprising tasseling and silking is regarded as the most water-sensitive period because even brief episodes of drought can disrupt pollination, reduce kernel formation and substantially diminish final grain production.

Conventional irrigation scheduling in maize generally relies on fixed irrigation intervals, irrigation water to cumulative pan evaporation (IW/CPE) ratios or evapotranspiration-based estimates. While these methods provide practical guidance, they often fail to synchronize irrigation events with the crop's changing physiological water requirements under fluctuating weather conditions. As a result, excessive irrigation may lead to runoff, deep percolation and evaporation losses, whereas delayed or inadequate irrigation during critical growth stages limits nutrient uptake, biomass production and grain development. In recent years, stage-specific irrigation scheduling has gained considerable attention as a more efficient management strategy because it focuses water application during the crop's most sensitive phenological stages, thereby improving water use efficiency while maintaining productivity under conditions of limited water availability.

Efficient irrigation management also governs the availability and utilization of nutrients within the soil–plant continuum. Adequate soil moisture promotes nutrient dissolution, enhances root proliferation and facilitates nutrient movement towards the rhizosphere, resulting in greater nitrogen, phosphorus and potassium uptake by plants. Improved nutrient acquisition supports chlorophyll formation, photosynthetic efficiency, dry matter accumulation and the effective translocation of assimilates to developing grains. Conversely, moisture stress restricts nutrient mobility, suppresses root activity and reduces fertilizer-use efficiency, ultimately impairing grain nutritional quality, particularly protein accumulation (Blum, 2009; Djaman *et al.*, 2013) ^[1, 3].

With increasing pressure on finite water resources, maximizing grain yield alone is no longer considered an adequate measure of irrigation success. Modern irrigation strategies are expected to improve water use efficiency while simultaneously enhancing nutrient uptake, grain quality and farm profitability. Despite growing interest in precision irrigation, information regarding the performance of different stage-specific irrigation schedules under the semi-arid agro-ecological conditions of north-western India remains relatively limited. Moreover, only a few studies have comprehensively examined crop growth, nitrogen uptake, water

use efficiency and grain quality together under contrasting irrigation schedules within a single experimental investigation.

Keeping these research gaps in view, the present study was undertaken to evaluate the effect of stage-specific irrigation scheduling on growth, productivity, water use efficiency, nitrogen uptake and grain protein yield of hybrid maize under semi-arid conditions. It was hypothesized that providing irrigation at carefully selected critical growth stages would ensure better soil moisture availability during periods of maximum physiological demand, thereby improving crop growth, enhancing nitrogen acquisition, increasing water use efficiency and maintaining grain quality. The findings are expected to provide scientifically sound evidence for developing water-efficient irrigation strategies capable of improving maize productivity while promoting climate-resilient and sustainable crop production in water-limited environments.

2. Materials and Methods

A field experiment was conducted during the kharif season of 2024 at the Agricultural Research Farm, Invertis University, Bareilly, Uttar Pradesh, India (28°29' N, 79°49' E; 252 m above mean sea level), situated in the semi-arid agro-ecological region of north India. The experimental soil was sandy loam in texture, slightly alkaline in reaction (pH 7.78) with an electrical conductivity of 0.384 dS m⁻¹, low in organic carbon (0.31%) and available nitrogen (188.1 kg ha⁻¹), and medium in available phosphorus (18.8 kg ha⁻¹) and potassium (147.2 kg ha⁻¹). Initial soil samples (0–15 cm depth) were collected before sowing and analysed following standard procedures described by Jackson (1973) ^[6].

The experiment was laid out in a randomized complete block design with eight irrigation scheduling treatments and three replications. Hybrid maize cultivar Dekalb 9208 was sown on 6 June 2024 using a spacing of 60 × 25 cm and a seed rate of 22 kg ha⁻¹. A uniform fertilizer dose of 150:60:40:10 kg ha⁻¹ N:P₂O₅:K₂O:Zn was applied to all treatments. Half of the nitrogen along with the full doses of phosphorus, potassium and zinc were applied as basal, while the remaining nitrogen was top-dressed in two equal splits at the knee-height and pre-tasseling stages. All other agronomic and plant protection practices were followed uniformly throughout the crop-growing period.

The irrigation treatments consisted of T₁ (no irrigation), T₂ (knee-height + pre-tasseling), T₃ (seedling + knee-height + silking), T₄ (seedling + knee-height + pre-tasseling + silking), T₅ (seedling + knee-height + pre-tasseling + silking + grain filling), T₆ (seedling + knee-height + silking + grain filling), T₇ (knee-height + pre-tasseling + silking + physiological maturity) and T₈ (seedling + knee-height + pre-tasseling + grain filling). Irrigation was applied at each designated growth stage with a depth of 7 cm.

Growth observations were recorded periodically, while grain yield was determined from the net plot at physiological maturity and adjusted to 14% grain moisture. Water productivity was calculated as the ratio of grain yield to the total amount of water used during the crop season (Molden *et al.* 2007). Grain and stover samples collected at harvest were oven dried, ground and analysed for nitrogen by the modified Kjeldahl method (Jackson 1973), phosphorus by the vanado-molybdate yellow colour method (Jackson 1973) ^[6] and potassium using a flame photometer (Jackson 1973) ^[6]. Total nutrient uptake was computed by multiplying nutrient concentration with the corresponding dry matter yield. Grain protein content was estimated by multiplying grain nitrogen concentration by a conversion factor of 5.85 (Prasad *et al.* 2006) ^[9].

The experimental data were subjected to analysis of variance (ANOVA) for a randomized complete block design following the procedure described by Gomez and Gomez (1984). Treatment means were compared using the least significant difference (LSD) test at the 5% level of significance.

3. Results & Discussion

3.1 Dry matter accumulations

Stage-specific irrigation scheduling significantly influenced dry matter accumulation and its partitioning into leaves, stems and cobs at harvest (Table 1). The highest total dry matter accumulation was recorded under T₅ (284.8 g plant⁻¹), followed by T₆ (278.1 g plant⁻¹), T₄ (270.2 g plant⁻¹), T₈ (258.8 g plant⁻¹) and T₃ (256.6 g plant⁻¹), whereas the lowest value was observed under the rainfed treatment T₁ (207.3 g plant⁻¹). Similarly, T₅ recorded the highest dry matter accumulation in leaves (39.1 g plant⁻¹), stems (83.4 g plant⁻¹) and cobs (162.3 g plant⁻¹), while T₁ consistently produced the lowest biomass in all plant components. Based on the LSD values, T₅ remained statistically comparable with T₆ for leaf, stem, cob and total dry matter accumulation, indicating that both irrigation schedules were equally effective in promoting biomass production under the prevailing environmental conditions.

The greater biomass accumulation under T₅ was primarily associated with the availability of adequate soil moisture throughout both vegetative and reproductive growth stages, particularly from pre-tasseling to grain filling, when maize exhibits its highest water demand. Continuous moisture

availability likely maintained leaf turgor, delayed senescence and sustained photosynthetic activity, resulting in greater assimilate production and efficient partitioning towards vegetative tissues and developing cobs. Improved soil moisture also enhances root activity and nitrogen availability, thereby supporting higher biomass production and sink development. In contrast, the lower dry matter accumulation observed under T₁ reflected the adverse effects of prolonged moisture stress, which restricted vegetative growth, reduced assimilate production and limited dry matter translocation to reproductive organs.

The present findings agree with previous studies demonstrating that irrigation applied during critical phenological stages substantially improves biomass production in maize. Cakir (2004)^[2] reported that water stress during flowering and grain filling markedly reduced dry matter accumulation because of impaired photosynthesis and assimilate translocation. Similarly, Gheysari *et al.* (2017)^[5] observed greater biomass production under optimum irrigation schedules owing to improved crop water status and physiological efficiency. More recently, Li *et al.* (2022)^[7] and Nair *et al.* (2023)^[8] also reported that maintaining adequate soil moisture during reproductive growth enhanced canopy persistence, photosynthetic efficiency and dry matter partitioning, leading to greater biological productivity. In the present study, the higher dry matter accumulation recorded under T₅ provided the physiological basis for the subsequent improvements in grain yield, nitrogen uptake, water productivity and grain protein yield observed under the same irrigation schedule.

Table 1: Effect of stage-specific irrigation scheduling on dry matter partitioning of hybrid maize at harvest

Treatment	Leaf dry matter (g plant ⁻¹)	Stem dry matter (g plant ⁻¹)	Cob dry matter (g plant ⁻¹)	Total dry matter (g plant ⁻¹)
T ₁	28.4	60.7	118.1	207.3
T ₂	32.7	69.9	136.0	238.6
T ₃	35.2	75.2	146.3	256.6
T ₄	37.1	79.1	154.0	270.2
T ₅	39.1	83.4	162.3	284.8
T ₆	38.2	81.5	158.5	278.1
T ₇	34.6	74.0	143.9	252.5
T ₈	35.5	75.8	147.5	258.8
LSD (P = 0.05)	3.47	7.41	14.41	25.29

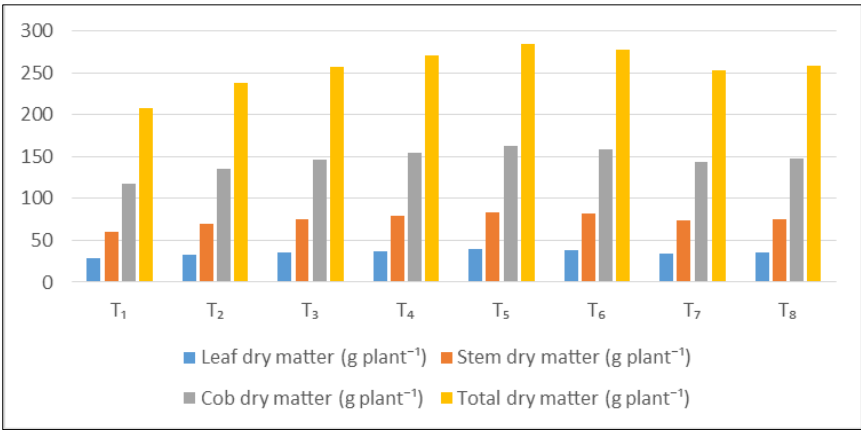


Fig 1: Effect of stage-specific irrigation scheduling on dry matter partitioning of hybrid maize at harvest

3.2 Water use efficiency

Water use efficiency (WUE) was significantly influenced by stage-specific irrigation scheduling (Table 3). The highest WUE was recorded under T₅ (19.20 kg ha⁻¹ mm⁻¹), followed by T₆ (18.84 kg ha⁻¹ mm⁻¹) and T₄ (18.14 kg ha⁻¹ mm⁻¹), whereas the lowest WUE was observed in the rainfed treatment (T₁, 9.33 kg ha⁻¹ mm⁻¹). Treatments T₃ (14.95 kg ha⁻¹ mm⁻¹), T₈ (15.51 kg ha⁻¹

mm⁻¹), T₂ (14.05 kg ha⁻¹ mm⁻¹) and T₇ (14.28 kg ha⁻¹ mm⁻¹) exhibited intermediate values. The higher WUE recorded under T₅ indicates that irrigation applied at the critical growth stages enabled the crop to produce greater grain yield per unit of water used, thereby maximizing the efficiency of water utilization under semi-arid conditions. Based on the LSD value (1.56 kg ha⁻¹ mm⁻¹), T₅ was statistically comparable with T₆ and T₄ but

significantly superior to the remaining irrigation schedules. The improvement in WUE under T₅ can be attributed to the synchronization of irrigation with the crop's peak water requirement during both vegetative and reproductive growth stages. Adequate soil moisture during knee-height, pre-tasseling, silking and grain-filling stages maintained favourable plant water status, sustained photosynthetic activity and enhanced assimilate production, resulting in higher grain yield without a proportional increase in water consumption. Furthermore, improved soil moisture conditions promoted greater nitrogen availability and uptake, thereby supporting biomass accumulation and efficient grain filling. In contrast, prolonged moisture stress under T₁ restricted physiological activity, reduced biomass production and grain development, leading to poor conversion of available water into economic yield. The superior WUE achieved under T₅ therefore reflects the combined benefits of improved crop growth, efficient nitrogen utilization and enhanced partitioning of assimilates towards grain production.

The present findings are consistent with previous studies demonstrating that irrigation timing is more critical than irrigation frequency for improving crop water productivity. Cakir (2004)^[2] reported that water stress during flowering and grain filling substantially reduced maize productivity because of impaired photosynthesis and reproductive development. Similarly, Gheysari *et al.* (2017)^[5] observed that irrigation synchronized with critical phenological stages significantly improved water use efficiency by maintaining optimum crop water status during periods of maximum physiological demand. More recently, Li *et al.* (2022)^[7] and Nair *et al.* (2023)^[8] also reported that strategic irrigation during reproductive growth enhanced water productivity through improved biomass production, assimilate translocation and grain filling. These findings indicate that stage-specific irrigation scheduling offers an effective strategy for maximizing water productivity while sustaining crop performance under water-limited environments.

Table 2: Effect of stage-specific irrigation scheduling on water use efficiency of hybrid maize under semi-arid conditions

Treatment	Water use efficiency (kg ha ⁻¹ mm ⁻¹)
T ₁	9.33
T ₂	14.05
T ₃	14.95
T ₄	18.14
T ₅	19.20
T ₆	18.84
T ₇	14.28
T ₈	15.51
LSD (P = 0.05)	1.56

3.3 Grain yield and biomass production

Stage-specific irrigation scheduling significantly affected grain yield, stover yield and biological yield, whereas harvest index remained statistically unaffected (Fig 2). The highest grain yield was obtained under T₅ (5.5 t ha⁻¹), followed by T₆ (5.0 t ha⁻¹), T₄ (4.8 t ha⁻¹) and T₈ (4.2 t ha⁻¹), while the rainfed treatment (T₁) recorded the lowest grain yield (1.8 t ha⁻¹). A similar trend was observed for stover and biological yields, with T₅ producing the maximum stover yield (14.7 t ha⁻¹) and biological yield (20.2 t ha⁻¹), whereas T₁ recorded the lowest values (4.7 and 6.5 t ha⁻¹, respectively). However, based on the LSD values, the grain, stover and biological yields obtained under T₅ were statistically comparable with those under T₆ and T₄, indicating that irrigation schedules including the major reproductive stages were equally effective in sustaining crop productivity. Harvest index ranged from 35.7 to 36.9% and was not significantly affected by irrigation scheduling, suggesting that irrigation proportionally increased both grain and vegetative biomass.

The greater productivity achieved under T₅ can be attributed to the maintenance of favourable soil moisture during the critical growth stages of maize, particularly from pre-tasseling through grain filling. Adequate water availability during these stages supports leaf expansion, prolongs canopy photosynthetic activity and enhances assimilate production, thereby increasing biomass accumulation and promoting efficient translocation of photosynthates towards developing kernels. Continuous moisture supply also favours nitrogen uptake and utilization, contributing to improved grain filling and greater dry matter partitioning into reproductive structures. In contrast, moisture deficit under the rainfed treatment restricted vegetative growth, reduced assimilate production and shortened the grain-filling period, ultimately resulting in lower grain and biological yields.

The present results are consistent with previous studies reporting that irrigation synchronized with critical phenological stages substantially enhances maize productivity under water-limited conditions. Cakir (2004)^[2] demonstrated that water stress during flowering and grain filling significantly reduced kernel development and grain yield owing to impaired photosynthesis and assimilate translocation. Similarly, Gheysari *et al.* (2017)^[5] observed that optimum irrigation scheduling improved biomass production and grain yield through sustained crop water status and greater physiological efficiency. Recent studies by Li *et al.* (2022)^[7] and Nair *et al.* (2023)^[8] further confirmed that irrigation during reproductive growth enhances biomass production, grain filling and final yield by maintaining favourable physiological processes throughout the crop cycle. The higher grain and biological yields obtained under T₅ in the present study therefore provide a strong physiological basis for the subsequent improvements in water productivity, nitrogen uptake and grain quality observed under the same irrigation schedule.

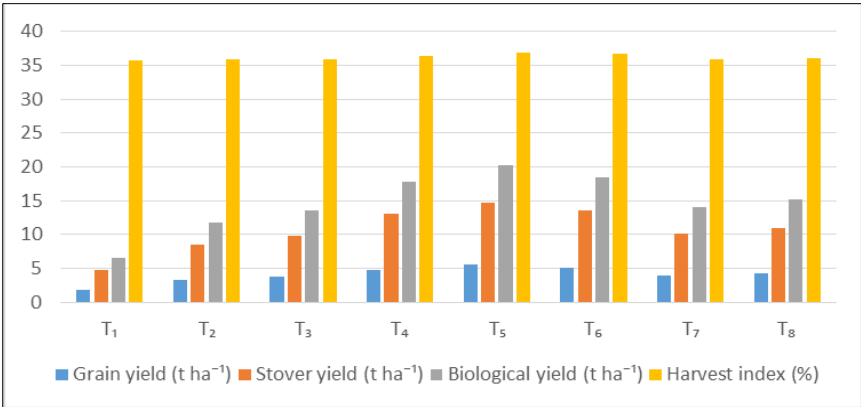


Fig 2: Effect of stage-specific irrigation scheduling on grain yield, stover yield, biological yield and harvest index of hybrid maize under semi-arid conditions

3.4 Nitrogen content and uptake

Nitrogen concentration in grain and stover was not significantly affected by irrigation scheduling, although numerically higher values were recorded under irrigation treatments receiving adequate water during the critical reproductive stages (Table 4). Grain nitrogen concentration ranged from 1.54% in the rainfed treatment (T_1) to 1.67% under T_5 , while stover nitrogen concentration varied from 0.57% to 0.63%. The absence of significant differences indicates that irrigation scheduling had only a limited influence on nitrogen concentration within plant tissues. In contrast, nitrogen uptake by grain, stover and the whole plant differed significantly among irrigation treatments, reflecting the combined effects of biomass production and nitrogen accumulation. The highest total nitrogen uptake was recorded under T_5 (159.6 kg ha⁻¹), followed by T_6 (150.2 kg ha⁻¹) and T_4 (145.1 kg ha⁻¹), whereas the lowest uptake (84.3 kg ha⁻¹) was observed under the rainfed treatment (T_1).

The substantial increase in nitrogen uptake under T_5 can be attributed to improved soil moisture availability during the crop's critical growth stages, which enhanced nitrogen transport to the root zone through mass flow and diffusion. Adequate soil moisture also maintained active root growth, increased nutrient absorption and supported greater photosynthetic activity, resulting in higher dry matter accumulation and grain production.

Since nitrogen uptake is a function of both nutrient concentration and biomass production, the significantly greater biomass produced under T_5 resulted in higher nitrogen accumulation despite relatively small differences in tissue nitrogen concentration. Conversely, moisture stress under T_1 restricted root activity, reduced nitrogen availability and limited dry matter production, thereby decreasing total nitrogen uptake.

The present findings are consistent with previous reports demonstrating the strong interaction between irrigation management and nitrogen acquisition in maize. Cakir (2004) [2] reported that water stress during flowering and grain filling substantially reduced nitrogen uptake because of restricted root growth and impaired physiological activity. Blum (2009) [1] emphasized that favourable plant water status enhances nutrient absorption and nitrogen utilization through sustained photosynthesis and assimilate production. Likewise, Gheysari *et al.* (2017) [5] observed that irrigation synchronized with crop water demand significantly improved nitrogen uptake and fertilizer-use efficiency under semi-arid conditions. The greater nitrogen uptake recorded under T_5 in the present study therefore provides a physiological explanation for the higher grain yield, improved water use efficiency and enhanced protein yield obtained under optimum irrigation scheduling.

Table 3: Effect of stage-specific irrigation scheduling on nitrogen content and uptake of hybrid maize under semi-arid conditions

Treatment	Grain N content (%)	Stover N content (%)	Grain N uptake (kg ha ⁻¹)	Stover N uptake (kg ha ⁻¹)	Total N uptake (kg ha ⁻¹)
T_1	1.54	0.57	39.9	44.4	84.3
T_2	1.55	0.58	58.8	49.2	108.0
T_3	1.56	0.59	67.6	53.8	121.4
T_4	1.65	0.60	85.4	59.7	145.1
T_5	1.67	0.63	97.8	61.8	159.6
T_6	1.63	0.62	89.9	60.3	150.2
T_7	1.59	0.59	69.7	57.2	126.9
T_8	1.58	0.59	75.3	55.9	131.2
LSD (P = 0.05)	NS	NS	7.28	5.57	12.43

3.5 Grain protein content and protein yield

Grain protein content was not significantly influenced by stage-specific irrigation scheduling, although numerical differences were observed among treatments (Table 5). Protein content varied from 9.625% under the rainfed treatment (T_1) to 10.438% under T_5 , while T_4 (10.313%) and T_6 (10.188%) also recorded comparatively higher values. Since the differences among treatments did not exceed the LSD value (0.990), irrigation scheduling had only a limited effect on grain nitrogen concentration. In contrast, protein yield was significantly affected by irrigation treatments and ranged from 175.56 kg ha⁻¹ under T_1 to 571.14 kg ha⁻¹ under T_5 , followed by T_6 (512.48 kg ha⁻¹) and T_4 (493.02 kg ha⁻¹). The greater protein yield obtained under these treatments primarily reflected their higher grain yield and improved nitrogen uptake rather than large changes in grain protein concentration.

The higher protein yield recorded under T_5 can be attributed to adequate soil moisture during the critical reproductive stages, particularly silking and grain filling, which favoured sustained photosynthesis, efficient nitrogen uptake and greater assimilate translocation to developing kernels. Improved soil moisture availability likely enhanced nitrogen remobilization from vegetative tissues to grains, thereby increasing protein accumulation on an area basis. Although irrigation had little

influence on protein concentration, the marked increase in grain yield under optimum irrigation substantially increased total protein production. Conversely, moisture stress under the rainfed treatment shortened the grain-filling period, restricted nitrogen translocation and reduced kernel development, resulting in lower grain yield and consequently lower protein yield.

The present findings agree with earlier reports indicating that optimum irrigation during reproductive growth improves grain quality primarily through enhanced nitrogen uptake and prolonged grain filling. Cakir (2004) [2] demonstrated that water stress during flowering and grain filling adversely affected kernel development and reduced grain quality in maize. Blum (2009) [1] also emphasized that favourable plant water status promotes efficient nitrogen utilization and assimilate partitioning, leading to improved grain nutritional quality. Likewise, Gheysari *et al.* (2017) [5] reported that irrigation synchronized with crop water demand enhanced nitrogen uptake and grain protein production by maintaining favourable physiological activity throughout reproductive development. The results of the present study therefore indicate that irrigation scheduling improves grain quality mainly by increasing nitrogen uptake and grain productivity rather than by substantially altering grain protein concentration.

Table 4: Effect of stage-specific irrigation scheduling on grain protein content and protein yield of hybrid maize under semi-arid conditions

Treatment	Protein content (%)	Protein yield (kg ha ⁻¹)
T ₁	9.625	175.56
T ₂	9.688	318.91
T ₃	9.750	368.85
T ₄	10.313	493.02
T ₅	10.438	571.14
T ₆	10.188	512.48
T ₇	9.938	387.66
T ₈	9.875	416.02
LSD (P = 0.05)	0.990	174.31

3.6 Integrated response of water use efficiency, nitrogen uptake and grain protein yield

The present study clearly demonstrated that stage-specific irrigation scheduling improved maize performance through a coordinated enhancement of water use efficiency, nitrogen uptake and grain protein production. Irrigation synchronized with the crop's critical phenological stages ensured continuous soil moisture availability during periods of maximum physiological demand, thereby promoting greater biomass accumulation and grain yield. The irrigation schedule involving irrigation at the seedling, knee-height, pre-tasseling, silking and grain-filling stages (T₅) consistently produced the highest dry matter accumulation, grain yield, water use efficiency, nitrogen uptake and protein yield. These responses indicate that timely irrigation not only increased crop productivity but also enhanced the efficiency with which water and nitrogen were utilized for biomass production and grain development.

Improved water use efficiency under T₅ was closely associated with favourable plant water status throughout the crop growth period. Adequate soil moisture maintained leaf turgor, prolonged photosynthetic activity and delayed premature leaf senescence, thereby sustaining assimilate production during both vegetative and reproductive phases. The increased biomass production created a greater sink demand for nutrients, while favourable soil moisture enhanced nitrogen availability and transport to the root zone through mass flow and diffusion. Consequently, plants receiving irrigation at the major growth stages absorbed greater quantities of nitrogen, which supported higher dry matter production and improved translocation of assimilates and nitrogenous compounds to developing kernels during grain filling.

Although irrigation scheduling did not significantly alter grain protein concentration, it markedly increased protein yield through substantial improvements in grain yield and nitrogen uptake. This indicates that the nutritional output of maize was determined primarily by enhanced productivity rather than by large changes in grain nitrogen concentration. The greater nitrogen uptake observed under optimum irrigation ensured a continuous supply of nitrogen for amino acid synthesis and protein deposition during kernel development, while prolonged grain filling under adequate moisture conditions facilitated efficient accumulation of storage proteins. In contrast, moisture stress reduced biomass production, restricted nitrogen acquisition and shortened the grain-filling period, resulting in lower grain yield and protein production.

Overall, the results suggest that the benefits of stage-specific irrigation arise from an integrated physiological response rather than from improvements in any single trait. Synchronizing irrigation with critical growth stages enhanced crop water use efficiency, supported greater nitrogen acquisition and improved grain protein yield by maintaining favourable conditions for photosynthesis, nutrient uptake and assimilate partitioning. These

findings emphasize that irrigation timing is more critical than irrigation frequency alone for maximizing resource-use efficiency and sustaining maize productivity under semi-arid conditions. The integrated improvement in water use efficiency, nitrogen uptake and grain protein yield observed under T₅ highlights the importance of adopting growth stage-based irrigation scheduling as a practical strategy for achieving higher productivity with efficient utilization of limited water resources.

4. Conclusion

Stage-specific irrigation scheduling markedly influenced the growth, productivity and nitrogen utilization of hybrid maize under semi-arid conditions. Irrigation applied at the seedling, knee-height, pre-tasseling, silking and grain-filling stages (T₅) produced the highest dry matter accumulation, grain yield, water use efficiency, total nitrogen uptake and grain protein yield, although several of these responses were statistically comparable with T₆. The higher productivity achieved under optimum irrigation scheduling was associated with improved soil moisture availability during the crop's critical developmental stages, resulting in enhanced biomass production, efficient nitrogen uptake and improved grain filling. While irrigation scheduling did not significantly alter grain protein concentration, the substantial increase in grain yield under T₅ resulted in significantly greater protein yield per unit area. These findings indicate that synchronizing irrigation with critical phenological stages improves the efficiency of water and nitrogen utilization rather than simply increasing irrigation frequency. Under the conditions of the present study, irrigation at seedling, knee-height, pre-tasseling, silking and grain-filling stages can therefore be recommended as an effective strategy for improving maize productivity and grain nutritional output in water-limited environments. Nevertheless, the conclusions are based on a single-season field experiment at one location. Further multi-season and multi-location studies across different soil types and climatic conditions are required to validate the consistency and wider applicability of these irrigation schedules before recommending them for broader adoption.

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