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Impact of Environmental Modifications and Fertility Regimes on Nutritional Quality and Nutrient Use Efficiency of Quality Protein Maize (QPMH-1)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Maize (Zea mays L.) is a globally important cereal crop, providing staple food for humans and feed for livestock. Although rich in carbohydrates and high in caloric energy, its protein is deficient in essential amino acids like lysine and tryptophan. Quality Protein Maize (QPM) has been developed to improve these nutritional limitations, offering enhanced protein quality while retaining the crop's traditional benefits. The present study was conducted during Kharif season of 2023 at the Agronomy Research Farm, Division of Agronomy, Faculty of Agriculture, SKUAST-K, Wadura, Sopore, to evaluate the effects of sowing dates and fertility levels on nutrient use efficiency and grain quality of Quality Protein Maize. The experiment was laid out in a split-plot design with three replications, comprising three sowing dates corresponding to the 16th, 19th, and 22nd Standard Meteorological Weeks as main-plot treatments, and four fertility levels including control, 75% RDF, 100% RDF, and 125% RDF as sub-plot treatments. The maize variety tested was Shalimar QPMH-1. The results indicated that sowing dates and fertility levels had no significant effect on nutrient concentration, but exerted a pronounced influence on nutrient uptake, nutrient use efficiencies, and grain protein content. Sowing on 12 May resulted in the highest nitrogen, phosphorus, and potassium uptake in both grain and stover, along with superior agronomic, physiological, and recovery efficiencies. Among fertility treatments, application of 125% RDF recorded the maximum nutrient uptake and nutrient-use efficiencies, accompanied by enhanced grain protein and lysine content. The interaction between sowing during the 19th Standard Meteorological Week and application of 125% RDF proved most effective in enhancing nutrient utilization and grain quality, indicating this combination as the optimal agronomic practice for improving nutrient use efficiency and nutritional quality of Quality Protein Maize (QPMH-1) under the temperate agro-climatic conditions of the Kashmir Valley.

Keywords: Maize; fertility levels; nutrient uptake; nutrient use efficiency; grain quality; quality protein maize.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as both a staple food for humans and a vital source of feed and fodder for livestock. Owing to its versatility and wide adaptability, maize is often referred to as the "Queen of Cereals." It is cultivated on about 140 million hectares across diverse agro-climatic zones worldwide, producing approximately 1147.7 million tonnes annually (FAO, 2020). In India, maize occupies 9.47 million hectares with an annual production of 28.64 million tonnes and an average productivity of 29.45 q ha^{-1} (DES, 2020). In Jammu and Kashmir, it is grown on about 2.6 lakh hectares with an average yield of 5.75 t ha^{-1}, making it an important cereal crop in the region's rainfed and temperate ecosystems.

Although maize is rich in carbohydrates and provides substantial caloric energy, its protein quality is nutritionally inadequate due to a deficiency of essential amino acids, particularly lysine and tryptophan. Populations heavily dependent on maize as a staple food are therefore vulnerable to protein-energy malnutrition and related disorders such as kwashiorkor. This limitation prompted the development of *Quality Protein Maize (QPM)*—a nutritionally improved version of conventional maize—through breeding efforts initiated at CIMMYT. QPM possesses a balanced amino acid profile, higher biological value (≈80%), and superior digestibility compared to normal maize (Sofi et al., 2009). It contains nearly twice the lysine and tryptophan levels found in traditional maize, thereby enhancing its nutritional quality without compromising yield potential (Nuss and Tanumihardjo, 2011).

Despite these advantages, the productivity of QPM, like that of conventional maize, is strongly influenced by soil fertility and nutrient management. Fertilizers contribute approximately 50–60% of the total increase in crop production (Timsina et al., 2010). However, nutrient use efficiency (NUE) in maize-based systems remains suboptimal, particularly under intensive cultivation and climate variability, due to imbalanced fertilization, declining soil fertility, and suboptimal nutrient management practices. Nitrogen (N), phosphorus (P), and potassium (K) are the most critical macronutrients for maize growth. Nitrogen enhances chlorophyll formation and grain protein synthesis, phosphorus supports energy transfer and root development, while potassium regulates enzymatic activity and water balance (Singh et al., 2003). Hybrid maize, being a high nutrient-demanding crop, requires adequate and balanced NPK supply to achieve its genetic yield potential (Banerjee et al., 2014). Nevertheless, excessive or poorly timed fertilizer application can lower NUE and increase production costs as well as environmental risks. Recent studies emphasize that improving NUE is essential for sustaining maize productivity while minimizing nutrient losses and environmental footprints (Govindasamy et al., 2023; Wang et al., 2024). Therefore, optimizing fertilizer application rates is essential to ensure both economic and ecological sustainability.

Apart from fertility, the *sowing date* represents another crucial environmental factor influencing maize productivity. Sowing time determines the crop's exposure to temperature, radiation, and moisture regimes during critical growth stages. Delayed sowing generally shortens the crop growth period, reduces leaf area development, and decreases grain yield (Birun Ara et al., 2011; Safavi Fard et al., 2018). Early or late sowing can expose the crop to unfavorable thermal and photoperiodic conditions, resulting in reduced ear formation and kernel filling (Panahi et al., 2010). Recent evidence suggests that inappropriate sowing windows can also adversely affect nutrient uptake and nutrient use efficiency by altering crop–soil–climate interactions (Coelho et al., 2022; Rawal et al., 2024). Thus, identifying an optimal sowing window is vital for realizing the full yield potential and maintaining grain quality of maize under a given agro-climatic condition.

Under the temperate conditions of the Kashmir Valley, high inter-annual climatic variability, erratic rainfall distribution, and fluctuating temperature regimes often constrain maize productivity and nutrient utilization. Therefore, there is a pressing need to determine the most suitable sowing date and fertility regime that can enhance nutrient uptake, NUE, and grain quality of Quality Protein Maize (QPMH-1). However, systematic information on the combined effects of sowing time and fertility levels on nutrient dynamics and quality attributes of QPM under temperate agro-ecosystems remains limited. The present study was undertaken to evaluate the effect of sowing dates and fertility levels on growth, nutrient dynamics, and quality attributes of QPM under the temperate agro-ecosystem of Kashmir.

2. Materials and Methods

2.1 Experimental Site

The experiment was conducted during the Kharif season of 2023 at the Agronomy Research Farm, Faculty of Agriculture, SKUAST-K, Wadura, Sopore, Jammu and Kashmir, under the temperate agro-ecosystem of Kashmir (Fig. 1). The experimental field was characterized by well-drained soil and uniform topography, ensuring suitability for the study.

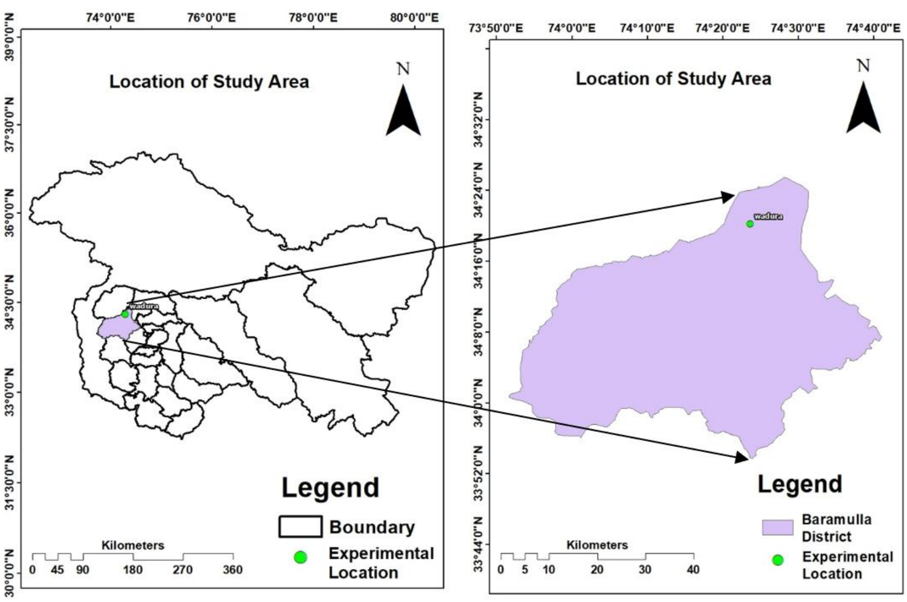

Fig. 1. Location of experimental location

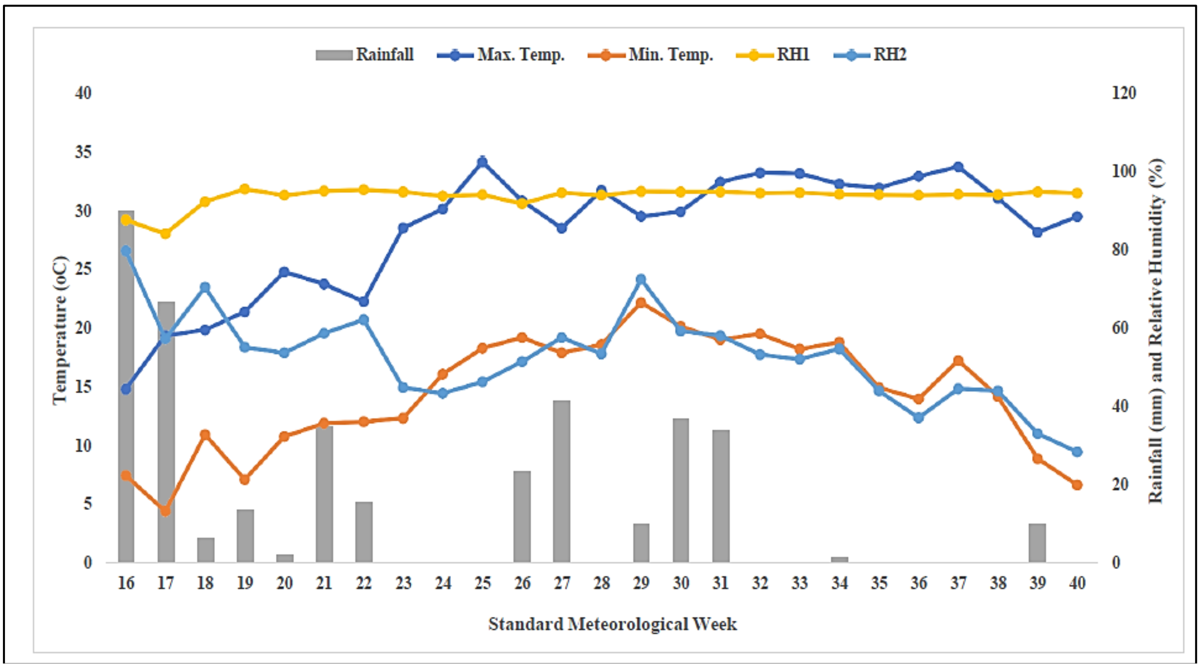

Fig. 2. Weekly meteorological trends observed during Kharif 2023

Table 1. Treatment structure and fertility levels used in the experiment

Factor	Treatment Code	Description
Sowing date (Main plot)	S_1	17th April (16th SMW)
	S_2	12th May (19th SMW)
	S_3	3rd June (22nd SMW)
Fertility level (Sub plot)	F_0	Control
	F_1	75 % RDF (90:45:22.5)
	F_2	100 % RDF (120:60:30)
	F3	125 % RDF (150:75:37.5)

Wadura is geographically situated at 34° 34' N latitude and 74° 40' N longitude, at an altitude of approximately 1580 m above mean sea level. Weather data for the Kharif season of 2023 was recorded at the local Meteorological Observatory. During the crop growth period, weekly minimum temperatures ranged from 4.49°C to 22.21°C, while maximum temperatures varied between 14.86°C and 34.17°C (Fig. 2). The total rainfall received during the cropping season was 386.80 mm.

2.2 Experimental Details

The experiment comprised 12 treatment combinations, replicated three times, and was laid out in a split-plot design. The maize variety Shalimar QPMH-1 was cultivated at a spacing of 75 × 20 cm across 36 experimental plots. Standard and uniform agronomic and cultural practices, along with appropriate plant protection measures, were followed throughout the crop growth period to ensure optimal crop establishment. Details of the treatment structure, including sowing dates and fertility levels along with their respective symbols, are presented in Table 1.

3. Results

3.1 Nutrient Content and Uptake

3.1.1 Nitrogen Content (%) and Uptake (kg ha^{-1}) in Grain and Stover

In the present study, nitrogen content in both grain and stover of QPMH-1 was not significantly influenced by either sowing date or fertility levels (Table 2), indicating that the nitrogen concentration remained relatively stable in maize tissues across the different agronomic treatments. This implies that nitrogen partitioning in the plant tissues may be more strongly regulated by physiological and genetic processes than by moderate changes in sowing time or fertilization rate alone. Similar observations have been made in other maize studies where genotype and environment interactions sometimes exert greater influence on nutrient concentration than fertilization level per se (Djalovic et al., 2024).

While concentration per unit mass remained stable, total nitrogen uptake showed clear and significant responses to both sowing date and fertilizer rate. Sowing on 12 May (S2) enhanced N uptake in grain (67.52 kg ha^{-1}) and stover (22.33 kg ha^{-1}) compared to both earlier and later dates. The superior uptake under this sowing date can be attributed to favourable temperature and moisture conditions, which enhanced root development, nutrient absorption, and dry matter accumulation. Conversely, the 3rd June sowing (S3) recorded the lowest uptake of N in each grain and stover. The nitrogen uptake dynamics in maize has been reported to be sensitive to environmental conditions, with optimized phenological timing enhancing cumulative N uptake and redistribution during the growth cycle (Davies et al., 2020).

Likewise, increasing fertility level progressively improved nitrogen uptake, with the highest value recorded under 125 % RDF (F3: 70.50 kg ha^{-1} in grain and 23.27 kg ha^{-1} in stover) and the lowest in unfertilized control (F0: 47.79 kg ha^{-1} in grain and 16.99 kg ha^{-1} in stover). This increase reflects improved nitrogen availability in the soil and enhanced crop growth under higher fertilizer application. The control treatment (F0) recorded the lowest uptake of N in each of grain and stover, with 47.79 kg ha^{-1} and 16.99 kg ha^{-1}, respectively, highlighting the limitations of nutrient availability without supplemental fertilizers (Witt et al., 1999). Increased N fertilizer rates have been consistently shown to elevate plant N uptake, though efficiency often plateaus or declines at very high application rates (Ji et al., 2025).

The interaction effect of sowing dates and fertility levels on nitrogen uptake in grain was observed to be significant (Table 3). Significantly highest nitrogen uptake (79.97 kg ha^{-1}) was outlined in the S2F3 (12th May, 125% RDF), indicating a strong synergistic effect between optimum sowing time and adequate nutrient supply, and lowest nitrogen uptake (43.20 kg ha^{-1}) was observed in treatment combination of S3F0 (3rd June, Control). These findings align with prior reports that maize responds strongly to synchronized provision of nutrients and favorable growing conditions, which maximize root growth, photosynthesis, and nutrient assimilation (Adediran and Banjoko, 1995; Brar and Cheema, 1988; Srivastava et al., 2018).

Table 2. Nitrogen content and uptake in grain and stover of QPM as influenced by sowing dates and fertility levels

Treatment	N Content (%)	N Uptake (kg ha^{-1})		
	Grain	Stover	Grain	Stover
Main factor: Sowing date				
S1 (17 April)	1.24	0.32	58.24	19.98
S2 (12 May)	1.25	0.35	67.52	22.33
S3 (3 June)	1.22	0.31	52.30	17.59
SE (m±)	0.01	0.02	0.39	0.50
CD (p ≤ 0.05)	NS	NS	1.52	1.96
Sub-factor: Fertility level				
F0 (No NPK)	1.21	0.30	47.79	16.99
F1 (90:45:22.5)	1.22	0.32	54.22	18.72
F2 (120:60:30)	1.24	0.33	64.91	20.89
F3 (150:75:37.5)	1.25	0.34	70.50	23.27
SE (m±)	0.01	0.02	0.52	0.08
CD (p ≤ 0.05)	NS	NS	1.80	0.28
Interaction (S × F)	NS	NS	S	NS

Table 3. Interaction effect of sowing dates and fertility levels on nitrogen uptake in grain of QPM (Main × Sub plots)

Fertility Levels	S1 (17 April)	S2 (12 May)	S3 (3 June)
F0 (No NPK)	46.10	54.06	43.20
F1 (90:45:22.5)	52.71	61.68	48.28
F2 (120:60:30)	64.35	74.38	55.99
F3 (150:75:37.5)	69.82	79.97	61.71
Factor (B) at same level of A	SE (m±): 0.77 • CD (p ≤ 0.05): 3.30		
Factor (A) at same level of B	SE (m±): 0.98 • CD (p ≤ 0.05): 3.11		

3.1.2 Phosphorus Content (%) and Uptake (kg ha^{-1}) in Grain and Stover

Data pertaining to phosphorus content (grain and stover) illustrated that changes in sowing dates and fertility levels did not markedly alter phosphorus content (Table 4). This non-significant variation indicates that phosphorus concentration in maize tissues remains relatively stable and is less sensitive to external changes in sowing time and fertilizer application. However, total P uptake was significantly affected by both sowing date and fertilizer application (Table 4). The 12th May sowing (S2) resulted in the highest phosphorus uptake, with 10.36 kg ha^{-1} in grain and 7.18 kg ha^{-1} in stover, whereas the delayed sowing (S3) on 3rd June recorded the minimal uptake in both grain and stover. This outcome likely resulted from more favorable environmental conditions during early vegetative development at the optimum sowing window, which can enhance root growth and P acquisition. Early phosphorus uptake is critical for establishing vigorous early growth in maize because P is relatively immobile in soil and limited root exploration at late sowing constrains P acquisition (Anonymous, 2019).

Among the fertility levels, the application of 125% RDF (F3) led to the highest phosphorus uptake, with 10.93 kg ha-1 in grain and 7.78 kg ha-1 in stover. Higher phosphorus uptake under increased fertility levels reflects improved phosphorus availability in the soil and enhanced dry matter production. In contrast, the control treatment (F0) recorded the lowest phosphorus uptake with 6.07 kg ha^{-1} in grain and 4.07 kg ha^{-1} in stover, highlighting the limitations of nutrient availability without supplemental fertilizers (Witt et al., 1999).

Table 4. Phosphorus content and uptake in grain and stover of QPM as influenced by sowing dates and fertility levels

Treatment	P Content (%)	P Uptake (kg ha^{-1})		
	Grain	Stover	Grain	Stover
Main factor: Sowing date				
S1 (17 April)	0.17	0.09	8.13	5.62
S2 (12 May)	0.19	0.11	10.36	7.18
S3 (3 June)	0.16	0.08	6.92	4.69
SE (m±)	0.01	0.01	0.40	0.43
CD (p ≤ 0.05)	NS	NS	1.59	1.67
Sub-factor: Fertility levels				
F0 (No NPK)	0.15	0.07	6.07	4.07
F1 (90:45:22.5)	0.16	0.08	7.26	4.90
F2 (120:60:30)	0.18	0.10	9.63	6.56
F3 (150:75:37.5)	0.19	0.11	10.93	7.78
SE (m±)	0.01	0.01	0.07	0.02
CD (p ≤ 0.05)	NS	NS	0.26	0.08
Interaction (S × F)	NS	NS	S	S

Table 5. Interaction effect of sowing dates and fertility levels on P uptake in grain of QPM (Main × Sub plots)

Fertility Levels	S1 (17 April)	S2 (12 May)	S3 (3 June)
F0 (No NPK)	5.68	7.48	5.04
F1 (90:45:22.5)	6.84	8.97	5.96
F2 (120:60:30)	9.35	11.80	7.73
F3 (150:75:37.5)	10.63	13.21	8.96
Factor (B) at same level of A	SE (m±): 0.59		
	CD ($p \leq 0.05$): 0.81		
Factor (A) at same level of B	SE (m±): 0.42		
	CD ($p \leq 0.05$): 1.67		

Table 6. Interaction effect of sowing dates and fertility levels on P uptake (kg ha^{-1}) in stover of QPM (Main × Sub plots)

Fertility Levels	S1 (17 Apr)	S2 (12 May)	S3 (3 June)
F0 (No NPK)	3.86	5.26	3.10
F1 (90:45:22.5)	4.73	6.15	3.82
F2 (120:60:30)	6.36	8.00	5.33
F3 (150:75:37.5)	7.55	9.29	6.49
Factor B at same level of A	SE (m±)	0.18	
	CD ($p \leq 0.05$)	0.85	
Factor A at same level of B	SE (m±)	0.42	
	CD ($p \leq 0.05$)	1.72	

The interaction impact of sowing dates and fertility levels on uptake of P was obtained to be significant in grain and stover (Table 5 and 6). Phosphorus absorption in grain and stover was 13.21 and 9.29 kg ha^{-1} respectively evident in the S2F3 (12th May, 125%RDF), demonstrating a synergistic effect of optimum sowing time and adequate phosphorus supply, while the lowest uptake in grain (5.04 kg ha^{-1}) and stover (3.10 kg ha^{-1}) was observed in the treatment combination of S3F0 (3rd June, Control). Similar improvements in phosphorus uptake under favourable sowing conditions and higher fertility levels have been reported by Mishra et al. (1994) and Zhao et al. (2025).

3.1.3 Potassium Content (%) and Uptake (kg ha^{-1}) in Grain and Stover

The potassium content (Table 7) was not profoundly altered by various sowing times and fertility dosages. This indicates that potassium concentration in maize tissues remains relatively stable across sowing environments and fertilizer levels, suggesting internal regulation of potassium accumulation. The Stable concentration of K despite external changes have also been noted in a study (Singh et al., 2023) where tissue K levels were less responsive to moderate variation in fertilization rates.

Uptake of K varied significantly across different sowing dates and fertility levels. The significant variation in potassium uptake can largely be attributed to differences in biomass production and yield rather than changes in potassium concentration. The 12th May sowing (S2) led to the highest potassium uptake, with 19.53 kg ha^{-1} (grain) and 78.86 kg ha^{-1} (stover), which may be due to favourable climatic conditions promoting enhanced root growth, improved soil moisture availability, and efficient potassium absorption. In contrast, the 3rd June sowing (S3) recorded the lowest uptake of K in grain and stover, as delayed sowing likely curtailed the duration for effective nutrient uptake and exposed the crop to less favourable growth conditions. The findings align with study (Abaza et al., 2023) showing that sowing timing can affect nutrient uptake patterns in cereal crops.

Regarding fertility levels, the application of 125% RDF (F3) achieved the highest potassium uptake, with 20.38 kg ha^{-1} in grain and 84.06 kg ha^{-1} in stover. Higher potassium uptake under increased fertility levels reflects improved nutrient availability in the soil and enhanced dry matter accumulation. In contrast, the control treatment (F0) recorded the lowest potassium uptake, with 12.58 kg ha^{-1} in grain and 64.44 kg ha^{-1} in stover, highlighting the limitations of nutrient availability without supplemental fertilizers. This result aligns with multiple studies showing that potassium fertilization increases nutrient uptake and yield components in maize. (Witt et al., 1999; Kumar et al., 2015; Wang et al., 2025).

The interaction effect of sowing dates and fertility levels on potassium uptake in grain was observed to be significant (Table 8). Significantly highest potassium uptake (23.91 kg ha^{-1}) was observed in the treatment combination of S2F3 (12th May, 125% RDF), demonstrating a synergistic effect between optimum sowing time and adequate potassium supply, while the lowest potassium uptake (10.80 kg ha^{-1}) was observed in the treatment combination of S3F0 (3rd June, Control). This pattern is consistent with research showing that potassium nutrition enhances root growth and photosynthate transport, leading to improved nutrient uptake and biomass accumulation under favorable growing conditions (Mohamed et al., 2025).

3.2 Nitrogen use Efficiencies

Nitrogen use efficiencies, expressed as agronomic efficiency (AE), apparent nitrogen recovery (ANR), partial factor productivity (PFP), and physiological efficiency (PE), were significantly influenced by sowing dates and fertility levels (Table 9). Among sowing dates, 12th May (S_2) recorded the highest AE (10.55 kg grain kg^{-1} N), ANR (17.37 %), PFP (48.79 kg grain kg^{-1} N), and PE (60.95 kg grain kg^{-1} N uptake), while delayed sowing on 3rd June (S_3) resulted in the lowest values for most of efficiency indices. The improved efficiencies under S_2 can be attributed to favourable thermal and moisture conditions during early crop growth, which enhanced root development, nitrogen uptake, and its effective conversion into grain yield. Similar improvements in nitrogen use efficiency under favourable sowing conditions have been widely reported in maize, where improved crop–environment interactions enhanced nutrient uptake dynamics and reduced nitrogen losses (Hulmani et al., 2022; Govindasamy et al., 2023; Rawal et al., 2024).

Table 7. Potassium content and uptake in grain and stover of QPM as influenced by different sowing dates and fertility levels

Treatment	**K Content (%)**		**K Uptake (kg ha^{-1})**	
	Grain	**Stover**	**Grain**	**Stover**
Main Factor: Sowing date (A)				
S_1 (17th April)	0.34	1.20	16.14	74.03
S_2 (12th May)	0.36	1.22	19.53	78.86
S_3 (3rd June)	0.32	1.18	13.81	67.93
SE (m±)	0.01	0.01	0.48	1.21
CD (p≤0.05)	NS	NS	1.88	4.73
Sub-Factor: Fertility level (B)				
F_0 (No NPK)	0.31	1.17	12.58	64.44
F_1 (90:45:22.5 NPK)	0.33	1.19	14.67	69.49
F_2 (120:60:30 NPK)	0.35	1.21	18.34	76.44
F_3 (150:75:37.5 NPK)	0.36	1.23	20.38	84.06
SE (m±)	0.02	0.02	0.17	0.20
CD (p≤0.05)	NS	NS	0.57	0.68
Interaction (A×B)	NS	NS	**S**	NS

Table 8. Interaction effect of sowing dates and fertility levels on K uptake in grain of QPM (Main × Sub plots)

Fertility levels	**S_1 (17 Apr)**	**S_2 (12 May)**	**S_3 (3 Jun)**
F_0 (No NPK)	11.98	14.95	10.80
F_1 (90:45:22.5)	14.26	17.42	12.33
F_2 (120:60:30)	18.18	21.83	15.01
F_3 (150:75:37.5)	20.13	23.91	17.09
SE (m ±)	0.95		
Factor B at same level of A	SE (m±)	0.95	
	CD (p≤0.05)	1.25	
Factor A at same level of B	SE (m±)	0.55	
	CD (p≤0.05)	2.09	

Table 9. Nitrogen use efficiencies of QPM as influenced by different sowing dates and fertility levels

Treatment	Agronomic Efficiency (kg grain kg^{-1} nutrient applied)	Partial Factor Productivity (kg grain kg^{-1} nutrient)	Apparent Nutrient Recovery (%)	Physiological Efficiency (kg grain kg^{-1} nutrient uptake)
Main Factor: Sowing date (A)				
S_1 (17 Apr)	9.78	42.68	16.25	58.74
S_2 (12 May)	10.55	48.79	17.37	60.95
S_3 (3 Jun)	7.10	38.43	12.29	57.48
SE (m ±)	0.64	0.44	0.88	1.79
CD (p ≤ 0.05)	2.61	1.77	3.54	NS
Sub-Factor: Fertility level (B)				
F_0 (No NPK)	–	–	–	–
F_1 (90:45:22.5 NPK)	5.40	49.01	9.07	57.92
F_2 (120:60:30 NPK)	10.74	43.44	17.51	61.02
F_3 (150:75:37.5 NPK)	11.29	37.45	19.32	58.24
SE (m ±)	0.50	0.49	0.65	1.58
CD (p ≤ 0.05)	1.58	1.53	2.04	NS
Interaction (A×B)	NS	NS	–	NS

Fertility levels also exerted a pronounced effect on nitrogen use efficiency. AE and ANR increased progressively with increasing nitrogen supply, reaching their highest values under 125% RDF (F_3), reflecting improved nitrogen availability and enhanced uptake by the crop. These results corroborate findings from long-term maize studies showing that higher nitrogen inputs improve recovery and yield response up to an optimum level, beyond which marginal benefits decline due to reduced efficiency (Wang et al., 2024; Wang et al., 2025). In contrast, PFP declined with increasing nitrogen rates, with the highest PFP recorded under 75 % RDF (F_1), indicating more efficient grain production per unit of applied nitrogen at lower fertilizer rates. This inverse relationship between fertilizer rate and PFP is a well-established phenomenon in maize nutrient management, attributed to diminishing returns at higher nitrogen inputs (Wang et al., 2024).

However, PE remained statistically unaffected by either sowing dates or fertility levels, although numerically higher values were observed under optimum sowing (S_2) and moderate nitrogen supply (100 % RDF). This suggests that once nitrogen was absorbed by the crop, its internal utilization efficiency remained relatively stable across treatments, being governed more by plant physiological processes than by external management factors.

3.3 Phosphorus use Efficiencies

Phosphorus use efficiencies, expressed as agronomic efficiency (AE), apparent phosphorus recovery (APR), partial factor productivity (PFP), and physiological efficiency (PE), were significantly influenced by sowing dates and fertility levels (Table 10). Among sowing dates, 12th May (S_2) recorded the highest AE (21.11 kg grain kg^{-1} P), APR (10.02 %), and PFP (97.58 kg grain kg^{-1} P), while delayed sowing on 3rd June (S_3) resulted in the lowest values for most efficiency indices. The improved efficiencies under S_2 can be attributed to favourable soil temperature and moisture conditions during early crop establishment, which promoted rapid root proliferation and enhanced phosphorus acquisition. Since phosphorus is relatively immobile in soil, early and vigorous root growth is critical for improving P uptake, and delayed sowing restricts this opportunity, thereby reducing efficiency. Similar responses of phosphorus use efficiency to sowing time have been reported in maize, where optimum planting enhanced early P uptake and yield response (Kuneski et al., 2020; Coelho et al., 2022).

Fertility levels exerted a marked influence on phosphorus use efficiencies. Agronomic efficiency and apparent phosphorus recovery increased progressively with increasing fertilizer level, reaching their highest values under 125 % RDF (F_3), reflecting improved soil P availability and enhanced crop uptake. These findings align with field studies showing that adequate and balanced phosphorus fertilization improves yield response and nutrient recovery in maize, particularly under medium to low soil P conditions (Ma et al., 2023; Wang et al., 2024). In contrast, the lowest AE (10.81 kg grain kg⁻¹ P) and APR (4.48 %) observed under 75 % RDF (F_1) highlight the constraints imposed by insufficient phosphorus supply on crop productivity and nutrient recovery.

PFP exhibited an inverse response to phosphorus application rate. The highest PFP was recorded under 75 % RDF (F_1), while PFP declined with increasing fertilizer dose, reaching the lowest value under 125 % RDF (F_3). This decline reflects diminishing returns in grain yield per unit phosphorus applied at higher fertilizer rates, a well-established phenomenon in phosphorus management studies where yield increments do not proportionally match increases in nutrient input (Gheith et al., 2022; Wang et al., 2024). Among sowing dates, S_2 recorded the highest PFP, indicating that optimum crop establishment improved yield per unit of phosphorus applied through better crop growth and nutrient utilization.

PE was not significantly affected by sowing dates or fertility levels, although numerically higher values were observed under early sowing (S_1) and lower phosphorus supply (F_1). This suggests that once phosphorus was absorbed, its internal utilization efficiency remained relatively stable across treatments and was governed more by inherent physiological processes than by external management factors. Similar observations have been reported in maize and other cereals, where physiological efficiency showed limited responsiveness to increasing fertilizer rates, particularly when nutrient application exceeded optimal crop demand, leading to reduced internal utilization efficiency despite higher uptake (Wu et al., 2021).

3.4 Potassium use Efficiencies

Potassium use efficiencies, expressed in terms of agronomic efficiency (AE), apparent potassium recovery (AKR), partial factor productivity (PFP), and physiological efficiency (PE), were significantly influenced by sowing dates and fertility levels (Table 11). Among sowing dates, 12th May (S_2) recorded the highest AE (42.22 kg grain kg^{-1} K), AKR (57.76 %), PFP (195.17 kg grain kg^{-1} K), and PE (74.43 kg grain kg^{-1} K). In contrast, delayed sowing on 3rd June (S_3) markedly reduced potassium use efficiencies, which can be attributed to a shortened growth period, reduced biomass accumulation, and suboptimal soil moisture conditions limiting K uptake and translocation. Similar improvements in potassium use efficiency under optimum sowing windows have been reported in maize, where favourable temperature and moisture regimes enhanced root growth and K absorption (Kuneski et al., 2020; Coelho et al., 2022).

Table 10. Phosphorus use efficiencies of QPM as influenced by different sowing dates and fertility levels

Treatment	Agronomic Efficiency (kg grain kg^{-1} nutrient applied)	Partial Factor Productivity (kg grain kg^{-1} nutrient)	Apparent Nutrient Recovery (%)	Physiological Efficiency (kg grain kg^{-1} nutrient uptake)
Main Factor: Sowing date (A)				
S_1 (17 Apr)	19.56	85.36	8.77	223.88
S_2 (12 May)	21.11	97.58	10.02	216.69
S_3 (3 Jun)	14.21	76.87	7.19	202.84
SE (m ±)	1.29	0.88	0.15	17.13
CD (p ≤ 0.05)	5.23	3.55	0.62	NS
Sub-Factor: Fertility level (B)				
F_0 (No NPK)	–	–	–	–
F_1 (90:45:22.5 NPK)	10.81	98.02	4.48	234.34
F_2 (120:60:30 NPK)	21.48	86.88	10.08	211.80
F_3 (150:75:37.5 NPK)	22.59	74.91	11.42	197.28
SE (m ±)	1.01	0.98	0.19	13.15
CD (p ≤ 0.05)	3.16	3.07	0.60	NS
Interaction (A×B)	NS	NS	NS	NS

Table 11. Potassium use efficiencies of QPM as influenced by different sowing dates and fertility levels

Treatment	Agronomic Efficiency (kg grain kg⁻¹ nutrient applied)	Partial Factor Productivity (kg grain kg⁻¹ nutrient)	Apparent Nutrient Recovery (%)	Physiological Efficiency (kg grain kg⁻¹ nutrient uptake)
Main Factor: Sowing date (A)				
S_1 (17 Apr)	39.13	170.73	57.74	66.07
S_2 (12 May)	42.22	195.17	57.76	74.43
S_3 (3 Jun)	28.42	153.75	48.57	59.32
SE (m ±)	2.59	1.76	1.50	4.09
CD (p ≤ 0.05)	10.47	7.09	6.05	NS
Sub-Factor: Fertility level (B)				
F_0 (No NPK)	–	–	–	–
F_1 (90:45:22.5 NPK)	21.62	196.04	31.76	66.42
F_2 (120:60:30 NPK)	42.96	173.77	59.21	71.91
F_3 (150:75:37.5 NPK)	45.18	149.83	73.10	61.50
SE (m ±)	2.02	1.97	1.18	3.94
CD (p ≤ 0.05)	6.32	6.14	3.70	NS
Interaction (A×B)	NS	NS	NS	NS

Fertility levels exerted a pronounced influence on potassium use efficiencies. AE and AKR increased with increasing fertilizer dose, reaching their maximum under 125 % RDF (F_3), which reflects enhanced soil K availability and greater crop uptake. These results are consistent with earlier findings indicating that adequate potassium supply improves yield response and nutrient recovery in maize, particularly under intensive production systems (Gheith et al., 2022; Wang et al., 2024). Conversely, the lowest AE (21.62 kg grain kg^{-1} K) and AKR (31.76 %) observed under 75 % RDF (F_1) highlight the constraints imposed by inadequate potassium supply on crop performance.

PFP exhibited an inverse relationship with fertilizer rate. The highest PFP was recorded under 75 % RDF (F_1), while PFP declined progressively with increasing potassium application, reaching the lowest value under 125 % RDF (F_3). This trend reflects diminishing yield gains per unit of nutrient applied at higher fertilizer doses and has been widely reported in potassium management studies in maize and other cereals (Govindasamy et al., 2023; Wang et al., 2024). Among sowing dates, S_2 maintained the highest PFP, indicating that optimum planting time improved yield per unit K input through better crop growth and nutrient utilization.

PE of potassium was not significantly affected by sowing dates or fertility levels, although numerically higher values were observed under optimum sowing (S_2) and moderate fertilizer supply (F_2). This suggests that once potassium was absorbed, its internal utilization efficiency remained relatively stable and was regulated primarily by inherent physiological processes rather than external nutrient supply. Similar stability in potassium physiological efficiency has been reported in maize, where PE showed limited responsiveness to increased K application beyond optimum levels (Wang et al., 2024).

3.5 Quality Parameter

3.5.1 Protein Content (%)

Grain protein content of QPM was significantly influenced by sowing dates, fertility levels, and their interaction (Table 12 and 13). 12th May (S_2) produced the highest protein content (7.48%), while delayed sowing on 3rd June (S_3) resulted in the lowest value (7.30%). The improved protein content under S_2 can be attributed to favourable temperature and moisture conditions during vegetative growth and grain filling, which enhanced nitrogen uptake and its translocation to the developing grains. Optimum sowing has been reported to prolong photosynthetic activity and improve nitrogen assimilation, ultimately increasing grain protein concentration in maize (Koca & Canavar, 2014; Coelho et al., 2022).

Fertility levels also exerted a significant effect on protein content, with a progressive increase observed from the control to 125 % RDF (F_3). The highest protein content (7.50%) recorded under F_3 reflects enhanced nitrogen availability and assimilation, as nitrogen is a primary constituent of amino acids and grain proteins. Several studies have demonstrated that increased nitrogen supply enhances maize grain protein content by stimulating amino acid synthesis and protein accumulation in endosperm tissues (Snehlatan et al., 2016; Gheith et al., 2022). In contrast, the lowest protein content under the control treatment highlights the inability of native soil fertility to meet crop nitrogen demand.

The interaction between sowing dates and fertility levels was significant, indicating a strong synergistic effect of environmental conditions and nutrient availability on grain protein synthesis. The highest protein content (7.60%) was observed in the S_2F_3 combination, suggesting that optimum sowing coupled with adequate nutrient supply ensured synchronized nitrogen uptake and efficient partitioning of assimilates towards grain protein formation. Conversely, the lowest protein content (7.18%) recorded under S_3F_0 illustrates the detrimental effect of delayed sowing combined with nutrient deficiency. Similar synergistic effects of sowing time and nitrogen fertilization on protein content have been reported in Quality Protein Maize and other maize cultivars (Nuss and Tanumihardjo, 2011; Adeoluwa et al., 2022).

3.5.2 Post-harvest Soil Available Nutrients (N, P and K)

Post-harvest soil nutrient availability was significantly influenced by sowing dates and fertility levels, while their interaction effects were non-significant (Table 14). Among sowing dates, delayed sowing on 3rd June (S_3) recorded the highest residual soil nitrogen, phosphorus, and potassium, whereas 12th May sowing (S_2) consistently showed the lowest nutrient availability. The reduced residual nutrient levels under S_2 indicate greater crop uptake and utilization, attributable to favourable growth

Table 12. Protein content of QPM as influenced by different sowing dates and fertility levels

Treatment	Protein Content (%)
Main Factor: Sowing date (A)	
S_1 (17 Apr)	7.39
S_2 (12 May)	7.48
S_3 (3 Jun)	7.30
SE (m ±)	0.04
CD (p ≤ 0.05)	0.17
Sub-Factor: Fertility level (B)	
F_0 (No NPK)	7.28
F_1 (90:45:22.5 NPK)	7.35
F_2 (120:60:30 NPK)	7.44
F_3 (150:75:37.5 NPK)	7.50
SE (m ±)	0.003
CD (p ≤ 0.05)	0.01
Interaction (A×B)	**S**

Table 13. Interaction effect of sowing dates and fertility levels on protein content of QPM (Main × Sub plots)

Fertility levels	S_1 (17 Apr)	S_2 (12 May)	S_3 (3 Jun)
F_0 (No NPK)	7.30	7.36	7.18
F_1 (90:45:22.5 NPK)	7.36	7.42	7.26
F_2 (120:60:30 NPK)	7.42	7.54	7.36
F_3 (150:75:37.5 NPK)	7.48	7.60	7.42
SE (m ±) (B at same level of A)	0.02		
CD (p ≤ 0.05) (B at same level of A)	0.08		
SE (m ±) (A at same level of B)	0.04		
CD (p ≤ 0.05) (A at same level of B)	0.17		

Table 14. N, P and K (kg ha^{-1}) after harvest as influenced by different sowing dates and fertility levels

Treatment	N	P	K
Main Factor: Sowing date			
S1 (17 Apr)	253.65	15.93	172.75
S2 (12 May)	242.02	15.65	166.93
S3 (03 June)	261.98	16.30	176.78
SE (m±)	3.83	0.12	1.33
CD (p≤0.05)	11.50	0.38	4.01
Sub-Factor: Fertility levels			
F0 (No NPK)	238.55	15.53	162.87
F1 (90:45:22.5)	242.22	15.70	165.23
F2 (120:60:30)	256.20	16.17	173.77
F3 (150:75:37.5)	273.23	16.43	186.73
SE (m±)	4.18	0.15	1.88
CD (p≤0.05)	12.55	0.47	5.64
Interaction	NS	NS	NS

conditions that enhanced biomass production and nutrient absorption. In contrast, delayed sowing shortened the effective growth period and limited nutrient uptake, resulting in higher residual soil nutrients. Similar trends have been reported in maize, where delayed planting increased post-harvest soil nutrient levels due to reduced crop demand (Kuneski et al., 2020; Abonmai and Luikham, 2022; Coelho et al., 2022).

Fertility levels markedly affected soil nutrient status, with 125 % RDF (F_3) recording the highest residual N, P, and K, indicating partial nutrient surplus beyond crop requirement. The control (F_0) and 75 % RDF (F_1) treatments showed the lowest residual nutrients, reflecting limited nutrient supply and higher proportional removal by the crop. These findings align with nutrient balance studies in maize showing increased residual soil nutrients at higher fertilizer rates (Witt et al., 1999; Wang et al., 2024).

4. Conclusion

The study demonstrated that while sowing dates and fertility levels did not significantly alter the nutrient concentration (N, P, K) in grain and stover of QPMH-1, they had a pronounced influence on nutrient uptake, nutrient use efficiencies, protein content, post-harvest soil nutrient status, and overall system performance. Among the sowing dates, 12th May (S2) consistently emerged as the most favourable planting window, producing the highest uptake of N, P and K, together with superior agronomic efficiency, apparent nutrient recovery, partial factor productivity, and physiological efficiency for most nutrients. The improved performance of this date can be attributed to more optimal environmental conditions during the vegetative and reproductive phases, which promoted better root development, nutrient acquisition, and grain formation.

Among fertility levels, 125% RDF (F3) proved most effective, recording the highest uptake of N, P, and K; the greatest agronomic efficiency and nutrient recovery for all three nutrients; and the highest protein content. These outcomes clearly highlight the benefit of supplying nutrients above the recommended dose to support vigorous growth, enhanced nutrient assimilation, and improved grain quality. However, partial factor productivity peaked at 75% RDF (F1), indicating that while higher fertilizer doses improve total uptake and recovery, they do not always maximize yield per unit of nutrient applied emphasizing the importance of balanced nutrient management for economic and environmental sustainability. Interaction effects were significant for the uptake of N, P, and K in grain and stover, as well as for protein content, with the combination S2F3 (12th May × 125% RDF) producing the highest values across these parameters. This combination represents the optimum integration of planting time and nutrient supply for maximizing nutrient acquisition and grain quality. Conversely, the S3F0 (3rd June × Control) treatment recorded the lowest uptake and protein content, illustrating the detrimental effect of delayed planting and inadequate nutrient supply.

Post-harvest soil analysis revealed that delayed sowing (3rd June) and higher fertility level (125% RDF) resulted in greater residual soil N, P, and K, while early sowing (12th May) and lower fertility levels showed reduced nutrient availability due to higher crop uptake. However, soil pH, EC, and OC remained largely unaffected by the treatments.

Overall, the findings suggest that sowing QPMH-1 on 12th May combined with 125% RDF is the most effective management practice for achieving higher nutrient uptake, superior NUE, improved protein quality, and better soil fertility balance. This integrated approach enhances both crop productivity and economic returns, offering a viable strategy for sustainable cultivation of quality protein maize under temperate conditions.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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