International Journal of Plant & Soil Science

Volume 38, Issue 7, Page 266-281, 2026; Article no.IJPSS.160434
ISSN: 2320-7035

Influence of Hydrogel Levels and Integrated Nutrient Management on Soil Fertility Dynamics Nutrient, Uptake and Grain Quality of Rabi Maize (*Zea mays* L.)

Nitish Gautam [a*], Mohammad Faisal [a] and Moinuddin [b]

[a] School of Agriculture Forestry & Fisheries, Jigyasa University, Dehradun, India.
[b] School of Agricultural Sciences, Shri Guru Ram Rai University, Dehradun, India.

Authors' contributions

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i76158

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/160434

Original Research Article

Received: 30/04/2026
Published: 27/06/2026

Abstract

A field experiment was conducted during the rabi seasons of 2024–25 and 2025–26 at the Research Farm, Jigyasa University, Dehradun, Uttarakhand, India, to evaluate the influence of hydrogel application and nutrient management on nutrient uptake, grain protein content and post-harvest soil fertility in rainfed maize. The experiment was laid out in a factorial randomised block design with three replications. The treatments comprised four hydrogel levels: no hydrogel, 5 kg ha^{-1}, 7.5 kg ha^{-1} and 10 kg ha^{-1}, combined with four fertility levels: 100% recommended dose of fertiliser, 100% recommended dose of fertiliser + farmyard manure at 5 t ha^{-1}, 75% recommended dose of fertiliser + farmyard manure at 10 t ha^{-1} and 50% recommended dose of fertiliser + farmyard manure at 15 t ha^{-1}. Hydrogel application significantly improved nitrogen, phosphorus and potassium concentrations and uptake in grain and stover. The highest hydrogel level, 10 kg ha^{-1}, recorded the greatest pooled nitrogen uptake in grain and stover, with corresponding values

---

[*] *Corresponding author: E-mail: gautamnitish0011@gmail.com;*

Cite as: *Gautam, N., Faisal, M., & Moinuddin. (2026). Influence of Hydrogel Levels and Integrated Nutrient Management on Soil Fertility Dynamics Nutrient, Uptake and Grain Quality of Rabi Maize (Zea mays L.). International Journal of Plant & Soil Science, 38(7), 266–281. https://doi.org/10.9734/ijpss/2026/v38i76158*

of 76.91 and 128.35 kg ha⁻¹, respectively. It also recorded higher phosphorus and potassium uptake and improved grain protein content compared with the control. Among fertility treatments, 100% recommended dose of fertiliser generally produced the highest nutrient concentration and uptake, followed closely by 100% recommended dose of fertiliser combined with farmyard manure at 5 t ha⁻¹. Post-harvest soil fertility also improved under hydrogel application, with the 10 kg ha⁻¹ level recording pooled available nitrogen, phosphorus, potassium and soil organic carbon values of 221.54 kg ha⁻¹, 34.04 kg ha⁻¹, 249.92 kg ha⁻¹ and 0.597%, respectively. The results indicate that hydrogel application with balanced nutrient management can improve nutrient availability, crop nutrient uptake and soil fertility status in rainfed rabi maize.

Keywords: Hydrogel; integrated nutrient management; rabi maize (Zea mays L.); rainfed agriculture; nutrient uptake; soil fertility dynamics; grain protein; farmyard manure; recommended dose of fertiliser; soil organic carbon.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally because of its high yield potential, wider adaptability and diversified utilisation in food, feed and industrial sectors. In India, maize is predominantly cultivated under rainfed conditions, where productivity is often constrained by erratic rainfall, low soil organic carbon and poor nutrient use efficiency. Recent studies have highlighted that moisture stress and declining soil fertility are major factors limiting sustainable maize production under subtropical agro-ecosystems (Mozafari et al., 2020). Efficient management of soil moisture and nutrients has therefore become essential for maintaining crop productivity and soil health under rainfed agriculture.

Under moisture-limited conditions, nutrient availability and nutrient transport in soil are severely restricted, resulting in poor nutrient uptake and reduced grain quality. Water stress during critical crop growth stages adversely affects root proliferation, photosynthesis and assimilate translocation in maize (Fahad et al., 2017). Moreover, continuous and imbalanced use of chemical fertilisers alone often leads to nutrient losses, soil degradation and reduced microbial activity, thereby affecting long-term soil fertility (Mahmood et al., 2017). Integrated nutrient management, involving the combined application of organic and inorganic nutrient sources, has been recognised as an effective strategy for improving nutrient synchronisation, nutrient use efficiency and residual soil fertility in maize-based systems.

Farmyard manure (FYM) plays a significant role in improving soil physical properties, microbial activity and nutrient buffering capacity. Long-term integrated nutrient management practices have been reported to enhance soil organic carbon, nutrient availability and crop productivity compared with sole inorganic fertilisation (Agegnehu et al., 2016). Similarly, the integrated application of FYM and recommended fertiliser doses significantly improved nutrient uptake and grain quality of maize under rainfed conditions (Hashim et al., 2015). Recent findings also suggest that integrated nutrient management contributes to sustainable nutrient cycling and improves post-harvest soil fertility in cereal-based cropping systems (Rajeshkumar et al., 2025).

Hydrogels or superabsorbent polymers (SAPs) have recently emerged as promising soil amendments for improving water retention and nutrient conservation under drought-prone environments. Superabsorbent polymers can absorb large quantities of water and gradually release it within the root zone during moisture stress conditions. Narjary et al. (2012) reported that hydrogel application improved water availability and crop performance in coarse-textured soils. Similarly, Guazzelli et al. (2022) emphasised that agricultural hydrogels function as water and nutrient reservoirs, thereby improving nutrient retention and fertiliser use efficiency. Recent reviews further indicate that hydrogels improve rhizospheric moisture availability, reduce nutrient leaching losses and enhance nutrient uptake under water-deficit conditions (Campanile et al., 2024).

Nutrient uptake and grain protein content in maize are strongly influenced by soil moisture availability and nutrient management practices. Nitrogen is directly associated with protein synthesis and grain quality development, while phosphorus and potassium regulate energy transfer and assimilate translocation. Improved nutrient availability under integrated nutrient management and hydrogel-mediated moisture conservation may therefore enhance nutrient uptake efficiency and post-harvest soil fertility. However, information on the combined influence of hydrogel and integrated nutrient management on nutrient uptake, grain quality and soil fertility dynamics in rainfed rabi maize under subtropical conditions remains limited (Singh, 2020; Campanile et al., 2024).

Therefore, the present investigation was undertaken to evaluate the effects of hydrogel and integrated nutrient management on nutrient uptake, grain quality and soil fertility dynamics in rainfed rabi maize under Doon Valley conditions.

2. Materials and Methods

The field experiment was conducted during two rabi seasons, namely 2024–25 and 2025–26, at the Research Farm of Jigyasa University, Dehradun, Uttarakhand, India (3036 N and 7783 E), at an altitude of 640 m above mean sea level. The soil of the experimental field belonged to the sandy loam textural class and had a neutral pH reaction; it was non-saline (pH 7.10 to 7.12, EC of 1.2 mS m), and 0.53–0.60% organic carbon, 230.20–233.21 kg ha^{-1} available N, 37.12–39.31 kg ha^{-1} available P and 250.31–254.12 kg ha^{-1} available K were recorded in the soil of the experimental field. The site has a humid subtropical climate in the Doon Valley region.

The experiment was designed as a factorial randomised block design with 16 treatment combinations and three replications. Four levels of hydrogel, namely no hydrogel (H0), hydrogel @ 5 kg ha^{-1} (H1), hydrogel @ 7.5 kg ha^{-1} (H2) and hydrogel @ 10 kg ha^{-1} (H3), were tested in combination with four fertility levels, namely 100% RDF (120:60:40 kg N:P_2O_5:K_2O ha^{-1}) (F1), 100% RDF + FYM @ 5 t ha^{-1} (F2), 75% RDF + FYM @ 10 t ha^{-1} (F3) and 50% RDF + FYM @ 15 t ha^{-1} (F4). Maize hybrid 'Kaveri KMH-8333' was hand-sown during the first week of November in both years at a seed rate of 20 kg ha^{-1}, with row-to-row spacing of 60 cm and plant-to-plant spacing of 20 cm. The required quantity of hydrogel for each treatment was mixed with fine soil and broadcast in the furrow just before sowing at 4–5 cm below the seed row. N, P and K were applied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively. The full doses of phosphorus and potassium and one-third dose of nitrogen, as per the treatment, were applied at sowing as a basal dose. The remaining nitrogen was top-dressed in two equal instalments in the form of urea at the knee-height and tasselling stages. Well-decomposed farmyard manure (FYM) mainly contains about 0.5% nitrogen (N), 0.2–0.3% phosphorus (P_2O_5) and 0.5% potassium (K_2O) and was applied just before sowing as per the treatment. The crop was grown purely under rainfed conditions. All recommended agronomic and plant protection practices were followed during crop growth.

The observations on nutrient content, nutrient uptake, grain quality and post-harvest soil fertility were recorded as per standard analytical methods. Grain and stover samples at harvest were dried in an oven at 65 ± 5 °C to a constant weight and ground in the laboratory for chemical analysis. Nitrogen content was estimated by Nessler's reagent colourimetric method (Lindner, 1944), P content by the vanadomolybdate phosphoric yellow colour method and K content by the flame photometer method. Nutrient uptake by grain and stover was calculated by multiplying nutrient concentration by yield, as follows:

$$\text{Nutrient uptake (kg ha}^{-1}) = \frac{\text{Nutrient content (\%)} \times \text{Yield (kg ha}^{-1})}{100}$$

Protein content in grain was estimated by multiplying nitrogen concentration by a conversion factor of 6.25, following the micro-Kjeldahl digestion method.

$$\text{Protein content (\%)} = \text{Nitrogen content (\%)} \times 6.25$$

Post-harvest soil samples were collected from each treatment plot and analysed for pH, EC, organic carbon and available nitrogen, phosphorus and potassium using standard procedures. Soil pH and EC were determined using a 1:2.5 soil-water suspension, organic carbon by the rapid titration method, available N by the alkaline potassium permanganate method, available P by Olsen's method and available K by the flame photometer method.

The obtained data were subjected to analysis of variance (ANOVA) for a factorial randomised block design for the two years individually and then combined according to Panse and Sukhatme (1985). Treatment effects were assessed using the F-test at the 5% level of significance, and mean treatment effects were tested using CD where treatments were found to be significant.

3. Results

3.1 Effect of Hydrogel and Fertiliser Levels on Nutrient Concentration in Grain and Stover

3.1.1 Nitrogen Concentration

Data presented in Table 1 revealed that nitrogen concentration in grain and stover was significantly influenced by hydrogel and fertiliser levels during both years and in the pooled analysis. Nitrogen concentration increased progressively with increasing hydrogel levels. Among hydrogel treatments, H_3 (hydrogel @ 10 kg ha^{-1}) recorded the highest pooled nitrogen concentration in grain (1.790%) and stover (0.856%), whereas the lowest values of 1.465 and 0.721%, respectively, were observed under H_0 (control). Among fertility levels, F_1 (100% RDF) recorded significantly higher nitrogen concentration in grain (1.655%) and stover (0.796%), which remained statistically at par with F_2 (100% RDF + FYM @ 5 t ha^{-1}). The interaction effect between hydrogel and fertilisation levels remained non-significant; however, H_3 × F_1 recorded numerically higher nitrogen concentration in both grain and stover.

3.1.2 Phosphorus Concentration

Phosphorus concentration in grain and stover was significantly affected by hydrogel and fertility levels during both years and in the pooled analysis (Table 2). Treatment H_3 recorded the maximum pooled phosphorus concentration in grain (0.380%) and stover (0.178%), whereas the minimum values of 0.315 and 0.165%, respectively, were recorded under H_0. Fertility levels also significantly influenced phosphorus concentration, with F_1 recording the highest pooled phosphorus concentration in grain (0.355%) and stover (0.173%), followed by F_2. The interaction effect remained non-significant during both years and in the pooled analysis.

3.1.3 Potassium Concentration

Potassium concentration in grain and stover increased significantly with increasing hydrogel levels (Table 3). The highest pooled potassium concentration in grain (0.464%) and stover (1.342%) was recorded under H_3, whereas H_0 recorded the lowest values of 0.451 and 1.283%, respectively. Among fertility treatments, F_1 recorded significantly higher potassium concentration in grain (0.459%) and stover (1.319%), remaining statistically comparable with F_2. Interaction effects were non-significant for potassium concentration in both grain and stover during individual years and in the pooled analysis.

3.2 Effect of Hydrogel and Fertility Levels on Nutrient Uptake by Grain and Stover

3.2.1 Nitrogen Uptake

Nitrogen uptake by grain and stover was significantly influenced by hydrogel and fertility levels during both years and in the pooled analysis. Nitrogen uptake increased progressively with increasing hydrogel levels. Treatment H_3 recorded the highest pooled nitrogen uptake by grain (76.91 kg ha^{-1}) and stover (128.35 kg ha^{-1}), whereas the lowest values of 51.59 and 84.12 kg ha^{-1}, respectively, were recorded under H_0. Among fertility levels, F_1 recorded significantly higher nitrogen uptake by grain (67.30 kg ha^{-1}) and stover (112.03 kg ha^{-1}), followed by F_2. The interaction effect was significant for pooled grain nitrogen uptake; H_3 × F_1 recorded the highest uptake (80.09 kg ha^{-1}), whereas H_0 × F_4 recorded the lowest value (Table 4 and Fig. 1).

3.2.2 Phosphorus Uptake

Phosphorus uptake by grain and stover increased significantly with increasing hydrogel levels during both years and in the pooled analysis (Table 5 and Fig. 1). Treatment H_3 recorded the highest pooled phosphorus uptake by grain (16.64 kg ha^{-1}), whereas the lowest uptake was observed under H_0 (11.09 kg ha^{-1}). Fertility levels significantly affected phosphorus uptake, with F_1 recording maximum uptake and remaining statistically at par with F_2. Similar trends were observed for phosphorus uptake by stover.

3.2.3 Potassium Uptake

Potassium uptake by grain and stover was significantly influenced by hydrogel and fertility levels during both years and in the pooled analysis (Table 6 and Fig. 1). Higher hydrogel levels significantly enhanced potassium uptake, with H_3 recording the maximum uptake values, whereas H_0 recorded the minimum values. Among fertility treatments, F₁ and F₂ recorded significantly higher potassium uptake compared with lower fertility levels. Enhanced nutrient uptake under hydrogel application may be attributed to improved soil moisture retention and greater nutrient availability under rainfed conditions.

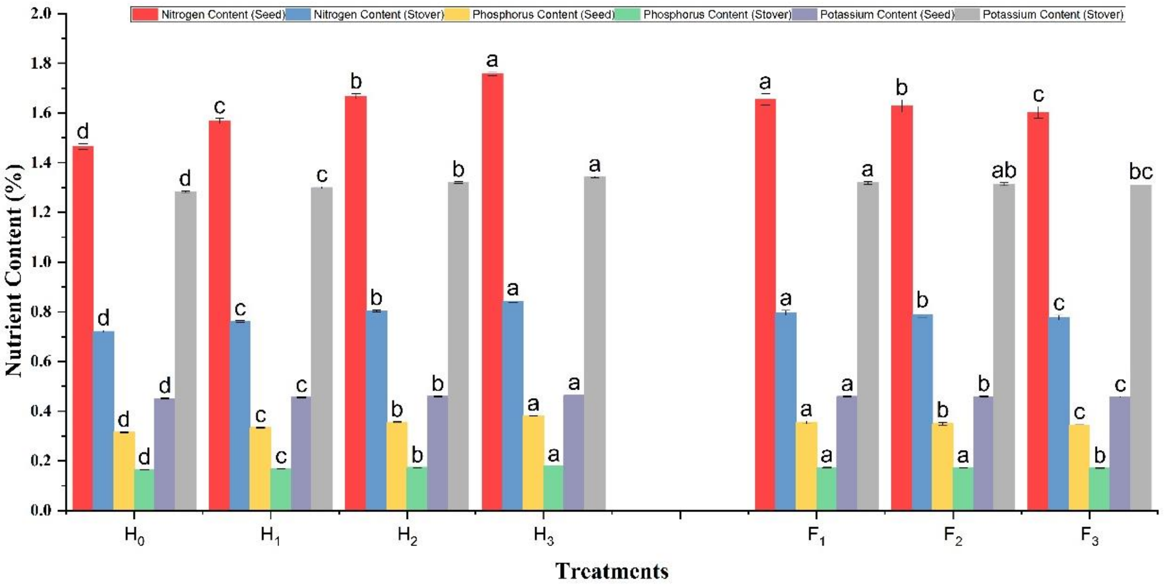

Fig. 1. Effect of hydrogel and fertility levels on nutrient content (%) in seed and stover of *Rabi* maize

3.3 Effect of Hydrogel and Fertility Levels on Grain Protein Content

Protein content in grain was significantly influenced by hydrogel and fertility levels during both years and in the pooled analysis (Fig. 2). Treatment H₃ recorded the highest protein content, whereas the minimum value was observed under H₀. Among fertility levels, F₁ recorded significantly higher protein content, followed by F₂. Although the interaction effect remained non-significant, H₃ × F₁ recorded numerically superior protein content over other treatment combinations. The increase in protein content under higher hydrogel levels may be attributed to enhanced nitrogen uptake and improved assimilate translocation towards grain development.

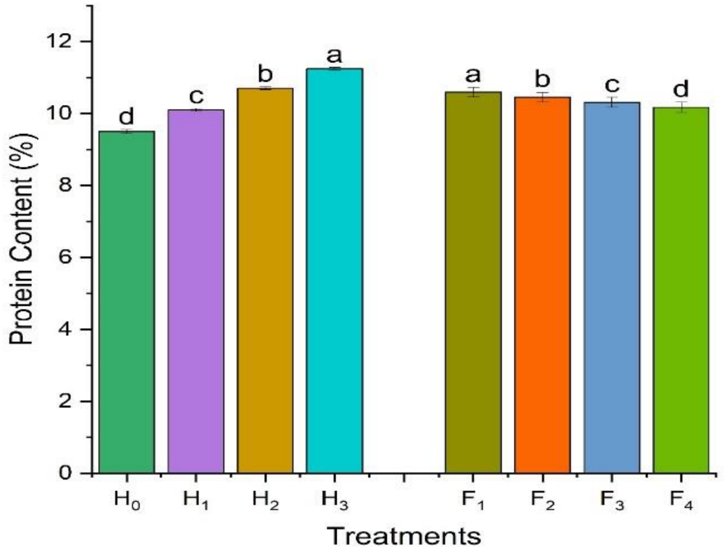

Fig. 2. Effect of hydrogel and fertilizer levels on protein content (%) of *Rabi* maize

Table 1. Effect of hydrogel and fertility levels on nitrogen content (%) in seed and stover of rabi maize

Fertility/ Hydrogel	**Nitrogen Content**									
	Grain					**Stover**				
	H$_0$	**H$_1$**	**H$_2$**	**H$_3$**	**Mean**	**H$_0$**	**H$_1$**	**H$_2$**	**H$_3$**	**Mean**
F$_1$	1.518 ± 0.015^{ij}	1.603 ± 0.021^{fg}	1.707 ± 0.007^{bc}	1.790 ± 0.011^{a}	1.655 ± 0.022^{a}	0.737 ± 0.007^{ij}	0.776 ± 0.007^{f}	0.817 ± 0.007^{cd}	0.856 ± 0.011^{a}	0.796 ± 0.010^{a}
F$_2$	1.477 ± 0.023^{jk}	1.578 ± 0.025^{gh}	1.685 ± 0.009^{cd}	1.772 ± 0.016^{a}	1.628 ± 0.025^{b}	0.726 ± 0.007^{jk}	0.766 ± 0.007^{fg}	0.810 ± 0.007^{d}	0.849 ± 0.006^{ab}	0.788 ± 0.010^{b}
F$_3$	1.458 ± 0.010^{k}	1.548 ± 0.014^{hi}	1.653 ± 0.014^{de}	1.750 ± 0.012^{ab}	1.603 ± 0.024^{c}	0.716 ± 0.008^{kl}	0.756 ± 0.007^{gh}	0.797 ± 0.007^{e}	0.838 ± 0.006^{b}	0.777 ± 0.010^{c}
F$_4$	1.407 ± 0.018^{l}	1.543 ± 0.013^{hi}	1.625 ± 0.031^{ef}	1.720 ± 0.017^{bc}	1.574 ± 0.026^{d}	0.706 ± 0.008^{l}	0.746 ± 0.007^{hi}	0.790 ± 0.007^{e}	0.826 ± 0.006^{c}	0.767 ± 0.010^{d}
Mean	**1.465 ± 0.012^{d}**	**1.568 ± 0.010^{c}**	**1.668 ± 0.011^{b}**	**1.758 ± 0.009^{a}**		**0.721 ± 0.004^{d}**	**0.761 ± 0.004^{c}**	**0.803 ± 0.004^{b}**	**0.842 ± 0.004^{a}**	
	Hydrogel	Fertility	H × F			Hydrogel	Fertility	H × F		
SEm	0.008	0.008	0.016			0.002	0.002	0.004		
SEd	0.011	0.011	0.022			0.003	0.003	0.006		
CD (LSD) 5%	0.022	0.022	0.044			0.006	0.006	0.011		

Table 2. Effect of hydrogel and fertility levels on phosphorus content (%) in seed and stover of *Rabi* maize

	Phosphorus Content									
	Seed					**Stover**				
Fertility	**H$_0$**	**H$_1$**	**H$_2$**	**H$_3$**	**Mean**	**H$_0$**	**H$_1$**	**H$_2$**	**H$_3$**	**Mean**
F$_1$	0.324 ± 0.003^{i}	0.342 ± 0.004^{f}	0.364 ± 0.003^{d}	0.390 ± 0.002^{a}	0.355 ± 0.005^{a}	0.167 ± 0.001^{k}	0.171 ± 0.002^{ghi}	0.175 ± 0.001^{cde}	0.180 ± 0.001^{a}	0.173 ± 0.001^{a}
F$_2$	0.317 ± 0.002^{j}	0.335 ± 0.003^{g}	0.360 ± 0.003^{d}	0.384 ± 0.001^{b}	0.349 ± 0.005^{b}	0.167 ± 0.001^{k}	0.170 ± 0.002^{hij}	0.174 ± 0.001^{def}	0.178 ± 0.001^{ab}	0.172 ± 0.001^{a}
F$_3$	0.313 ± 0.002^{j}	0.331 ± 0.003^{gh}	0.352 ± 0.003^{e}	0.376 ± 0.001^{c}	0.343 ± 0.005^{c}	0.164 ± 0.001^{l}	0.169 ± 0.001^{ijk}	0.173 ± 0.002^{efg}	0.177 ± 0.001^{bc}	0.171 ± 0.001^{b}
F$_4$	0.306 ± 0.002^{k}	0.328 ± 0.003^{hi}	0.346 ± 0.004^{ef}	0.371 ± 0.002^{c}	0.338 ± 0.005^{d}	0.162 ± 0.001^{l}	0.168 ± 0.002^{jk}	0.172 ± 0.002^{fgh}	0.176 ± 0.001^{bcd}	0.169 ± 0.001^{b}
Mean	**0.315** ±	**0.334** ±	**0.356** ±	**0.380** ±		**0.165** ±	**0.169** ±	**0.174** ±	**0.178** ±	

Phosphorus Content										
	Seed					Stover				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
	0.002^{d}	**0.002^{c}**	**0.002^{b}**	**0.002^{a}**		**0.001^{d}**	**0.001^{c}**	**0.001^{b}**	**0.001^{a}**	
	Hydrogel	Fertility	H × F							
SEm	0.001	0.001	0.002					Hydrogel = 0.001	Fertility = 0.001	H × F = 0.001
SEd	0.001	0.001	0.003					Hydrogel = 0.001	Fertility = 0.001	H × F = 0.001
CD (LSD) 5%	0.003	0.003	0.006					Hydrogel = 0.001	Fertility = 0.001	H × F = 0.003

Table 3. Effect of hydrogel and fertility levels on potassium content (%) in seed and stover of rabi maize

Potassium Content										
	Seed					Stover				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	0.453 ± 0.004^{g}	0.457 ± 0.004^{e}	0.461 ± 0.004^{c}	0.466 ± 0.004^{a}	0.459 ± 0.002^{a}	1.291 ± 0.006^{jkl}	1.307 ± 0.006^{ghi}	1.328 ± 0.006^{cde}	1.351 ± 0.006^{a}	1.319 ± 0.006^{a}
F_2	0.452 ± 0.004^{g}	0.456 ± 0.004^{e}	0.459 ± 0.004^{d}	0.465 ± 0.004^{a}	0.458 ± 0.002^{b}	1.286 ± 0.006^{klm}	1.302 ± 0.012^{hij}	1.323 ± 0.006^{def}	1.345 ± 0.006^{ab}	1.314 ± 0.006^{ab}
F_3	0.451 ± 0.004^{h}	0.455 ± 0.004^{f}	0.459 ± 0.004^{d}	0.463 ± 0.004^{b}	0.457 ± 0.002^{c}	1.281 ± 0.009^{lm}	1.297 ± 0.006^{ijk}	1.318 ± 0.009^{efg}	1.340 ± 0.006^{abc}	1.309 ± 0.006^{bc}
F_4	0.449 ± 0.004^{i}	0.454 ± 0.004^{f}	0.458 ± 0.004^{d}	0.463 ± 0.004^{b}	0.456 ± 0.002^{d}	1.276 ± 0.007^{m}	1.292 ± 0.006^{jkl}	1.312 ± 0.006^{fgh}	1.333 ± 0.006^{bcd}	1.303 ± 0.005^{c}
Mean	**0.451 ± 0.002^{d}**	**0.455 ± 0.002^{c}**	**0.459 ± 0.002^{b}**	**0.464 ± 0.002^{a}**		**1.283 ± 0.004^{d}**	**1.299 ± 0.004^{c}**	**1.320 ± 0.004^{b}**	**1.342 ± 0.003^{a}**	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	0.000	0.000	0.001			0.002	0.002	0.004		
SEd	0.000	0.000	0.001			0.003	0.003	0.006		
CD (LSD) 5%	0.001	0.001	0.001			0.006	0.006	0.012		

Table 4. Effect of hydrogel and fertility levels on organic carbon content and available nitrogen content in soil after harvest of rabi maize

Organic Carbon and Nitrogen Content After Harvest										
	Organic Carbon Content					**Nitrogen Content (Kg h^{-1})**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	0.533 ± 0.006^{hij}	0.555 ± 0.006^{defg}	0.573 ± 0.011^{bcd}	0.615 ± 0.011^{a}	0.569 ± 0.008^{a}	170.45 ± 3.04^{jk}	188.30 ± 4.13^{fgh}	204.92 ± 6.94^{de}	232.07 ± 2.80^{a}	198.93 ± 5.18^{a}
F_2	0.524 ± 0.006^{ij}	0.551 ± 0.007^{efgh}	0.569 ± 0.015^{bcde}	0.610 ± 0.012^{a}	0.563 ± 0.008^{a}	168.09 ± 3.51^{kl}	183.20 ± 5.86^{ghi}	199.94 ± 5.48^{def}	225.89 ± 3.53^{ab}	194.28 ± 4.98^{ab}
F_3	0.512 ± 0.006^{jk}	0.544 ± 0.006^{fghi}	0.563 ± 0.006^{cdef}	0.585 ± 0.011^{b}	0.551 ± 0.007^{b}	156.56 ± 2.52^{lm}	182.39 ± 5.94^{hij}	199.08 ± 7.32^{def}	217.48 ± 2.30^{bc}	188.87 ± 5.22^{bc}
F_4	0.499 ± 0.006^{k}	0.540 ± 0.007^{ghi}	0.557 ± 0.007^{cdefg}	0.578 ± 0.010^{bc}	0.543 ± 0.007^{b}	153.08 ± 5.39^{m}	175.15 ± 2.27^{ijk}	195.52 ± 3.00^{efg}	210.74 ± 6.22^{cd}	183.62 ± 4.99^{c}
Mean	0.517 ± 0.004^{d}	0.547 ± 0.003^{c}	0.566 ± 0.005^{b}	0.597 ± 0.006^{a}		162.04 ± 2.34^{d}	182.26 ± 2.44^{c}	199.86 ± 2.85^{b}	221.54 ± 2.52^{a}	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	0.004	0.004	0.008			2.18	2.18	4.37		
SEd	0.005	0.005	0.011			3.09	3.09	6.18		
CD (LSD) 5%	0.011	0.011	0.021	C.V.	3.313	6.18	6.18	12.35	C.V.	5.59

Table 5. Effect of hydrogel and fertility levels on available potassium and phosphorus content in soil after harvest of *Rabi* maize

Organic Carbon and Nitrogen Content After Harvest										
	Available Potassium Content					**Available Phosphorus Content**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	201.69 ± 2.16^{ij}	219.96 ± 7.03^{fg}	235.63 ± 2.30^{cd}	259.94 ± 3.92^{a}	229.31 ± 4.89^{a}	24.25 ± 0.72^{hi}	28.49 ± 0.44^{ef}	32.01 ± 0.96^{bcd}	35.88 ± 0.94^{a}	30.16 ± 0.97^{a}
F_2	199.33 ± 3.22^{j}	216.25 ± 3.53^{fg}	230.81 ± 5.31^{de}	252.76 ± 4.43^{a}	224.79 ± 4.54^{b}	22.02 ± 0.59^{ij}	27.34 ± 0.74^{fg}	30.59 ± 0.97^{cde}	33.78 ± 0.97^{ab}	28.43 ± 0.99^{b}
F_3	188.96 ± 3.17^{k}	214.08 ± 5.29^{gh}	223.19 ± 3.60^{ef}	244.62 ± 5.76^{b}	217.71 ± 4.68^{c}	20.94 ± 0.95^{jk}	26.07 ± 0.61^{gh}	30.39 ± 0.75^{de}	33.74 ± 1.31^{ab}	27.78 ± 1.09^{bc}
F_4	183.44 ± 1.81^{k}	208.02 ± 1.02^{hi}	220.39 ± 2.72^{fg}	242.35 ± 1.36^{bc}	213.55 ± 4.52^{d}	19.33 ± 1.42^{k}	25.67 ± 0.85^{gh}	29.70 ± 0.74^{def}	32.76 ± 0.56^{bc}	26.86 ± 1.14^{c}
Mean	193.35 ±	214.58 ±	227.51 ±	249.92 ±		21.64 ±	26.89 ±	30.67 ±	34.04 ±	

Organic Carbon and Nitrogen Content After Harvest										
	Available Potassium Content					**Available Phosphorus Content**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
	1.99^{d}	2.40^{c}	2.12^{b}	2.43^{a}		0.59^{d}	0.39^{c}	0.44^{b}	0.52^{a}	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	1.41	1.41	2.83			0.42	0.42	0.84		
SEd	2.00	2.00	4.00			0.59	0.59	1.18		
CD (LSD) 5%	4.00	4.00	8.00	C.V.	3.13	1.18	1.18	2.37	C.V.	7.24

Table 6. Effect of hydrogel and fertility levels on nitrogen uptake (kg ha^{-1}) by seed and stover of *Rabi* maize

Nutrient Uptake (Nitrogen)										
	Seed					**Stover**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	55.728 ± 1.123^{m}	62.575 ± 1.204^{i}	70.815 ± 1.358^{e}	80.092 ± 1.290^{a}	67.303 ± 1.987^{a}	89.130 ± 2.296^{k}	105.318 ± 1.827^{g}	118.963 ± 1.740^{d}	134.707 ± 1.700^{a}	112.030 ± 3.618^{a}
F_2	52.753 ± 1.131^{n}	60.350 ± 1.362^{j}	69.020 ± 1.209^{f}	78.140 ± 1.345^{b}	65.066 ± 2.065^{b}	85.775 ± 2.004^{l}	100.492 ± 1.857^{h}	115.850 ± 1.541^{e}	130.277 ± 1.770^{b}	108.098 ± 3.571^{b}
F_3	50.343 ± 1.121^{o}	58.242 ± 1.267^{k}	66.832 ± 1.187^{g}	75.995 ± 1.254^{c}	62.853 ± 2.073^{c}	82.642 ± 2.094^{m}	96.097 ± 1.606^{i}	111.392 ± 2.092^{f}	126.850 ± 1.764^{c}	104.245 ± 3.562^{c}
F_4	47.517 ± 0.984^{p}	57.222 ± 1.114^{l}	64.832 ± 1.359^{h}	73.403 ± 1.335^{d}	60.743 ± 2.068^{d}	78.912 ± 1.820^{n}	92.738 ± 1.551^{j}	107.740 ± 2.704^{g}	121.558 ± 2.255^{d}	100.237 ± 3.477^{d}
Mean	51.585 ± 0.811^{d}	59.597 ± 0.720^{c}	67.875 ± 0.760^{b}	76.908 ± 0.800^{a}		84.115 ± 1.243^{d}	98.661 ± 1.269^{c}	113.486 ± 1.312^{b}	128.348 ± 1.333^{a}	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	0.155	0.155	0.310			0.474	0.474	0.947		
SEd	0.220	0.220	0.439			0.670	0.670	1.340		
CD (LSD) 5%	0.439	0.439	0.878	C.V.	1.188	1.340	1.340	2.680	C.V.	2.186

Table 7. Effect of hydrogel and fertility levels on phosphorus uptake (kg ha^{-1}) by seed and stover of *Rabi* maize

	Phosphorus Uptake									
	Seed					**Stover**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	11.873 ± 0.286^{l}	13.345 ± 0.326^{i}	15.100 ± 0.344^{e}	17.447 ± 0.325^{a}	14.441 ± 0.458^{a}	9.800 ± 0.245^{jk}	11.245 ± 0.204^{g}	12.212 ± 0.205^{de}	13.537 ± 0.219^{a}	11.698 ± 0.302^{a}
F_2	11.340 ± 0.251^{m}	12.810 ± 0.288^{j}	14.737 ± 0.323^{f}	16.943 ± 0.271^{b}	13.958 ± 0.458^{b}	9.672 ± 0.219^{k}	10.802 ± 0.204^{h}	11.967 ± 0.209^{e}	13.118 ± 0.211^{b}	11.390 ± 0.286^{b}
F_3	10.802 ± 0.241^{n}	12.450 ± 0.327^{k}	14.222 ± 0.300^{g}	16.342 ± 0.262^{c}	13.454 ± 0.450^{c}	9.280 ± 0.262^{l}	10.492 ± 0.190^{i}	11.668 ± 0.236^{f}	12.818 ± 0.213^{c}	11.065 ± 0.295^{c}
F_4	10.343 ± 0.221^{o}	12.145 ± 0.287^{kl}	13.833 ± 0.306^{h}	15.835 ± 0.309^{d}	13.039 ± 0.444^{d}	9.097 ± 0.209^{l}	10.065 ± 0.197^{j}	11.407 ± 0.295^{fg}	12.450 ± 0.229^{d}	10.755 ± 0.288^{d}
Mean	11.090 ± 0.167^{d}	12.688 ± 0.171^{c}	14.473 ± 0.180^{b}	16.642 ± 0.186^{a}		9.462 ± 0.125^{d}	10.651 ± 0.129^{c}	11.813 ± 0.128^{b}	12.981 ± 0.131^{a}	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	0.054	0.054	0.109			0.052	0.052	0.104		
SEd	0.077	0.077	0.154			0.073	0.073	0.147		
CD (LSD) 5%	0.154	0.154	0.308			0.147	0.147	0.294		

Table 8. Effect of hydrogel and fertility levels on potassium uptake (kg ha^{-1}) by seed and stover of *Rabi* maize

	Potassium Uptake									
	Seed					**Stover**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
F_1	16.608 ± 0.392^{k}	17.825 ± 0.418^{h}	19.137 ± 0.427^{e}	20.847 ± 0.434^{a}	18.604 ± 0.382^{a}	75.650 ± 1.709^{ij}	85.818 ± 1.323^{g}	92.537 ± 1.362^{cd}	101.637 ± 1.410^{a}	88.910 ± 2.093^{a}
F_2	16.160 ± 0.386^{l}	17.428 ± 0.401^{i}	18.793 ± 0.417^{f}	20.542 ± 0.435^{b}	18.231 ± 0.390^{b}	74.673 ± 1.623^{jk}	82.782 ± 1.526^{h}	90.853 ± 1.420^{de}	98.967 ± 1.393^{b}	86.819 ± 2.012^{b}
F_3	15.575 ± 0.387^{m}	17.118 ± 0.418^{j}	18.557 ± 0.406^{f}	20.120 ± 0.421^{c}	17.843 ± 0.400^{c}	72.705 ± 2.173^{kl}	80.555 ± 1.294^{h}	88.773 ± 1.614^{ef}	97.095 ± 1.385^{b}	84.782 ± 2.048^{c}
F_4	15.170 ± 0.380^{n}	16.843 ± 0.394^{k}	18.302 ± 0.403^{g}	19.757 ± 0.417^{d}	17.518 ± 0.401^{d}	71.560 ± 1.570^{l}	77.608 ± 1.282^{i}	87.023 ± 1.822^{fg}	94.168 ± 1.615^{c}	82.590 ± 1.952^{d}
Mean	15.878 ±	17.304 ±	18.697 ±	20.316 ±		73.647 ±	81.691 ±	89.797 ±	97.967 ±	

Potassium Uptake										
	Seed					**Stover**				
Fertility	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**	**H_0**	**H_1**	**H_2**	**H_3**	**Mean**
	0.213^d	0.205^c	0.203^b	0.217^a		0.897^d	0.892^c	0.849^b	0.884^a	
	Hydrogel	**Fertility**	**Hx F**			**Hydrogel**	**Fertility**	**Hx F**		
SEm	0.044	0.044	0.088			0.409	0.409	0.818		
SEd	0.062	0.062	0.125			0.579	0.579	1.158		
CD (LSD) 5%	0.125	0.125	0.250			1.158	1.158	2.315		

3.4 Effect of Hydrogel and Fertiliser Levels on Post-harvest Soil Properties

Substantial variation in post-harvest soil nutrient status was observed due to hydrogel application and fertility management practices during both years and in the pooled analysis (Tables 4–8). Increasing hydrogel levels consistently improved residual available nitrogen, phosphorus and potassium in soil, with H_3 (hydrogel @ 10 kg ha^{-1}) registering the maximum pooled values of 221.54, 34.04 and 249.92 kg ha^{-1}, respectively. In contrast, the lowest residual nutrient availability was recorded under H_0. The enhanced nutrient retention under hydrogel-amended treatments may be associated with greater water-holding capacity and reduced nutrient movement beyond the root zone, thereby minimising nutrient depletion under rainfed conditions. An improved soil moisture environment under higher hydrogel levels likely facilitated sustained nutrient mineralisation and nutrient conservation within the soil system throughout the crop growth period.

Differences in fertility levels also exerted a pronounced effect on residual soil fertility following harvest. Application of F_1 (100% RDF) maintained the highest pooled available nitrogen (198.93 kg ha^{-1}), phosphorus (30.16 kg ha^{-1}) and potassium (229.31 kg ha^{-1}), remaining statistically comparable with F_2 in most observations (Table 5). Conversely, depletion in available nutrient status was more evident under reduced fertility levels. The maintenance of higher residual nutrient availability under F_1 and F_2 may be attributed to balanced nutrient replenishment, improved nutrient turnover and greater biomass contribution to soil. Integration of FYM with inorganic fertilisers likely improved nutrient buffering capacity and reduced nutrient exhaustion, thereby sustaining post-harvest soil fertility.

Marked improvement in soil organic carbon (SOC) was also evident under hydrogel and fertility treatments (Table 4). The pooled SOC content increased from 0.517% under H_0 to 0.597% under H_3, indicating a considerable enhancement in soil carbon status under higher hydrogel application. Among fertility levels, F_1 and F_2 recorded significantly greater SOC accumulation compared with F_3 and F_4. Improved SOC under hydrogel-treated plots may be linked with increased root biomass, greater residue deposition and reduced organic matter decomposition losses under favourable soil moisture conditions. Moreover, incorporation of FYM in integrated nutrient management treatments may have contributed additional carbon inputs and promoted stabilisation of organic matter through improved aggregation and microbial activity.

Interaction effects between hydrogel and fertility levels remained non-significant for available nitrogen, potassium and SOC; however, available phosphorus after harvest responded significantly to combined treatment effects. The treatment combination $H_3 \times F_1$ recorded the highest pooled available phosphorus (35.88 kg ha^{-1}), whereas $H_0 \times F_4$ registered the minimum value (19.33 kg ha^{-1}). Numerically higher residual nitrogen, potassium and SOC were also associated with $H_3 \times F_1$, indicating the complementary influence of hydrogel-mediated moisture conservation and balanced nutrient supply on soil nutrient retention. These findings suggest that combined application of hydrogel and adequate fertility management not only improved crop nutrient acquisition but also contributed towards sustaining soil fertility and nutrient reserves under rainfed maize cultivation.

4. Discussion

NPK Content of Seed and Stover: The higher nitrogen content in seed and stover under increased hydrogel levels may be attributed to improved soil moisture retention, which enhanced nutrient solubility, root growth and nitrogen absorption by the crop. Sustained moisture availability under hydrogel application possibly reduced nitrogen losses through leaching and improved nitrogen use efficiency, resulting in greater accumulation of nitrogen in plant tissues. Similar findings were reported by Nascimento et al. (2019) in maize, where hydrogel application maintained grain protein content under moisture stress conditions. Yang et al. (2019), while working on wheat under superabsorbent polymer application, also observed improved nitrogen use efficiency and nutrient assimilation under limited moisture conditions. Furthermore, integrated nutrient management practices involving FYM and inorganic fertilisers may have enhanced microbial activity and nutrient mineralisation, thereby increasing nitrogen concentration in seed and stover. Similar observations were reported by Choudhary et al. (2022) in wheat and Wang et al. (2025) in sorghum, where combined application of RDF and organic manures significantly enhanced nutrient content and uptake. The increased phosphorus content in seed and stover under hydrogel treatments might be associated with enhanced soil moisture conditions, which improved phosphorus diffusion and its availability in the rhizosphere. Hydrogels possess the capacity to retain nutrients and release them gradually, thereby minimising fixation losses and ensuring continuous phosphorus supply to plants. Improved root proliferation under favourable moisture conditions may also have enhanced phosphorus acquisition and translocation within the plant system. Similar findings were reported by Saha et al. (2020), where superabsorbent hydrogel improved nutrient retention and gradual release of NPK fertilisers. Qin et al. (2025), working on soybean, also observed increased phosphorus concentration in seeds due to improved soil moisture conservation and nutrient availability under hydrogel application. Likewise, Wang et al. (2025), in maize, reported enhanced phosphorus concentration under balanced fertilisation combined with soil amendments, while Yang et al. (2019), in finger millet, observed improved nutrient uptake and crop performance with superabsorbent polymer application.

The higher potassium content in seed and stover with hydrogel application could be due to improved soil water availability, which enhanced potassium mobility and nutrient transport towards plant roots. Since potassium movement in soil mainly occurs through diffusion, sustained moisture conditions maintained by hydrogel may have facilitated continuous potassium uptake and translocation to reproductive and vegetative plant parts. Similar results were reported by Shivakumar et al. (2019) in maize, who recorded significantly higher potassium uptake under hydrogel-treated conditions. Integrated nutrient management practices might have further improved potassium concentration through balanced nutrient supply and improved soil physical properties.

NPK Uptake by Seed and Stover: The higher uptake of nitrogen, phosphorus and potassium by seed and stover under hydrogel application may be attributed to enhanced biomass production and improved nutrient availability under favourable soil moisture conditions. Hydrogels help maintain continuous moisture supply in the root zone, which improves nutrient dissolution, root growth and nutrient absorption efficiency while reducing nutrient losses from the soil. Increased nutrient mobility and sustained root activity under hydrogel-treated conditions possibly resulted in greater nutrient accumulation in crop tissues. Similar findings were reported by Islam et al. (2011) in tomato, who observed higher nitrogen uptake under hydrogel application due to improved soil moisture availability. Marques et al. (2024), while working on sugarcane under hydrogel-amended soils, further reported reduced nutrient leaching losses and improved nutrient retention. Karada et al. (2023), in custard apple, also observed enhanced phosphorus uptake owing to better nutrient mobility and root activity under polymer application, whereas Shivakumar et al. (2019), in maize, reported significantly higher potassium uptake due to improved soil moisture conditions and enhanced nutrient transport under hydrogel application.

5. Conclusion

The study showed that hydrogel application and nutrient management significantly influenced nutrient uptake, grain protein content and post-harvest soil fertility in rainfed rabi maize. Increasing hydrogel levels improved nitrogen, phosphorus and potassium concentration and uptake in both grain and stover, with the highest values generally recorded under hydrogel application at 10 kg ha^{-1}. This response may be associated with improved soil moisture retention and better nutrient availability in the root zone under rainfed conditions. Among fertility treatments, 100% recommended dose of fertiliser produced the highest nutrient uptake and soil nutrient status, while 100% recommended dose of fertiliser combined with farmyard manure at 5 t ha^{-1} showed comparable performance for several parameters. Post-harvest soil available nitrogen, phosphorus, potassium and organic carbon were also improved under higher hydrogel application. The interaction between hydrogel and fertility levels was significant for selected parameters, particularly available phosphorus and grain nitrogen uptake, indicating a complementary effect of moisture conservation and nutrient supply. Based on the results, hydrogel application at 10 kg ha^{-1} with balanced fertiliser management may be considered a useful approach for improving nutrient use and maintaining soil fertility in rainfed rabi maize under the studied agro-climatic conditions.

6. Future Prospects

Future research should explore the long-term impacts of repeated hydrogel application on soil physical and biological properties across diverse agro-ecological zones. Investigations into economic feasibility, environmental safety and optimal integration with other conservation technologies are warranted. Additionally, studies assessing the interactive effects of hydrogel with advanced nutrient formulations and exploring its potential in other rainfed cropping systems could broaden the applicability of these findings. Addressing potential limitations, such as hydrogel persistence and cost-effectiveness at scale, will further inform sustainable intensification efforts in maize-based systems.

7. Limitations

The findings are based on a two-season field experiment conducted at a single location under the agro-climatic conditions of Dehradun, Uttarakhand. Therefore, the results may not fully represent the response of rabi maize to hydrogel and nutrient management under other soil types, rainfall patterns or agro-ecological regions. The study focused mainly on nutrient concentration, nutrient uptake, grain protein content and post-harvest soil fertility, while detailed observations on soil biological activity, root growth, water-use efficiency and economic returns were not included. Long-term effects of repeated hydrogel application on soil physical properties, polymer persistence and environmental safety were also not assessed. In addition, grain quality evaluation was limited to protein content. Further multi-location and long-term studies are required to confirm the stability, economic feasibility and environmental suitability of hydrogel-based nutrient management practices in rainfed maize systems.

Acknowledgement

The authors express sincere gratitude to the supporting institutions, technical staff and funding agencies whose resources and guidance made this research possible. Special thanks are extended to the field and laboratory teams for their meticulous assistance throughout the experimental period. Institutional support and constructive feedback from peer reviewers are also gratefully acknowledged.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment, 543*, 295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054

Campanile, A., Squillace, S., & Carbone, K. (2024). The role of superabsorbent polymers and hydrogels in sustainable agriculture. *Polymers, 16*(16), 2337. https://doi.org/10.3390/polym16162337

Choudhary, L., Singh, K. N., Gangwar, K., Sachan, R., & Pandey, H. P. (2022). Effect of FYM and inorganic fertilizers on nutrient content, uptake and quality traits of wheat (*Triticum aestivum* L.). *International Journal of Plant & Soil Science, 34*(19), 252–258. https://doi.org/10.9734/ijpss/2022/v34i1931109

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., Ihsan, M. Z., Alharby, H., Wu, C., Wang, D., & Huang, J. (2017). Crop production under drought and heat stress. *Frontiers in Plant Science, 8*, 1147. https://doi.org/10.3389/fpls.2017.01147

Guazzelli, E., Oliva, M., Pretti, C., Monni, G., Fahs, A., Bressy, C., & Martinelli, E. (2022). Polyethylene Glycol-b-poly (trialkylsilyl methacrylate-co-methyl methacrylate) hydrolyzable block copolymers for eco-friendly self-polishing marine coatings. *Polymers, 14*(21), 4589. https://doi.org/10.3390/polym14214589

Hashim, M., Dhar, S., Vyas, A. K., Pramesh, V., & Kumar, B. (2015). Integrated nutrient management in maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.) cropping system. *Indian Journal of Agronomy, 60*(3), 352–359. https://doi.org/10.59797/ija.v60i3.4484

Islam, M. R., Hu, Y., Mao, S., Mao, J., Eneji, A. E., & Xue, X. (2011). Effectiveness of a water-saving super-absorbent polymer in soil water conservation for corn (*Zea mays* L.) based on eco-physiological parameters. *Journal of the Science of Food and Agriculture, 91*(11), 1998–2005. https://doi.org/10.1002/jsfa.4408

Karada, M. S., Singh, Y., Mishra, R., Agnihotri, D., Patel, K. K., Yadav, N. K., & Singh, D. (2023). Enhancing nutrient content and uptake in chickpea through phosphorus and PSB inoculation in custard apple based agri-horti system. *International Journal of Environment and Climate Change, 13*(11), 2419–2428. https://doi.org/10.9734/ijecc/2023/v13i113408

Lindner, R. C. (1944). Rapid analytical methods for some of the more common inorganic constituents of plant tissues. *Plant Physiology, 19*(1), 76–89. https://doi.org/10.1104/pp.19.1.76

Mahmood, F., Khan, I., Ashraf, U., Shahzad, T., Hussain, S., Shahid, M., Abid, M., & Ullah, S. (2017). Effects of organic and inorganic manures on maize and their residual impact on soil physico-chemical properties. *Journal of Soil Science and Plant Nutrition, 17*(1), 22–32. https://doi.org/10.4067/S0718-95162017005000002

Marques, P. A. A., Mendonça, F. C., Marques, T. A., Silva, L. P. do P., Tiritan, C. S., Villa e Vila, V., & Mailapalli, D. R. (2024). Hydrogel polymer as a sustainable input for mitigating nutrient leaching and promoting plant growth in sugarcane crops. *Acta Scientiarum. Agronomy, 47*(1), e68642. https://doi.org/10.4025/actasciagron.v47i1.68642

Mozafari, S. H., Dass, A., Choudhary, A. K., Raihan, O., & Rajanna, G. A. (2020). Effect of moisture conservation and integrated nutrient management on summer maize (*Zea mays* L.) in Kandahar, Afghanistan. *Indian Journal of Agricultural Sciences, 90*(1), 236–239. https://doi.org/10.56093/ijas.v90i1.98693

Narjary, B., Aggarwal, P., Singh, A., Chakraborty, D., & Singh, R. (2012). Water availability in different soils in relation to hydrogel application. *Geoderma, 187–188*, 94–101. https://doi.org/10.1016/j.geoderma.2012.03.002

Nascimento, V. L., Rauber, W. A., Silva, G. S., Siebeneichler, S. C., & Fidelis, R. R. (2019). Hydrogel effects in biochemical composition of soybean grains cultivated under water deficit in Brazilian Cerrado. *Communications in Plant Sciences, 9*, 13–19. https://doi.org/10.26814/cps2019003

Panse, V. G., & Sukhatme, P. V. (1985). *Statistical methods for agricultural workers* (4th ed.). Indian Council of Agricultural Research.

Qin, C., Kan, X., Xu, D., Zhao, Y., Qi, Y., Wu, N., & Xu, W. (2025). Adjustable P(AM-co-NIPAM)/gelatin hydrogel soilless cultivation substrates for soybean seedling and root growth. *Industrial Crops and Products, 231*, 121189. https://doi.org/10.1016/j.indcrop.2025.121189

Rajeshkumar, A., Ramadass, S., Chandrasekaran, P., Rajasekar, M., Ashok, S., Saravanakumar, M., & Balasubramanian, P. (2025). Integrated nutrient management for enhanced maize yield and sustainability in Tamil Nadu, India. *Indian Journal of Agricultural Research, 59*(10), 1561–1569. https://doi.org/10.18805/IJARe.A-6247

Saha, A., Sekharan, S., & Manna, U. (2020). Superabsorbent hydrogel (SAH) as a soil amendment for drought management: A review. *Soil and Tillage Research, 204*, 104736. https://doi.org/10.1016/j.still.2020.104736

Shivakumar, R., Bridgit, T. K., & Ratheesh, P. K. (2019). Study on N, P, K uptake influenced by the application of hydrogel and mulching on maize (*Zea mays* L.) in sandy soil. *Journal of Pharmacognosy and Phytochemistry, 8*(2), 1524–1527. https://doi.org/10.22271/phyto.2019.v8.i2y.7880

Singh, V. (2020). Effect of integrated nutrient management on yield and uptake of nutrients in pearl millet (*Pennisetum glaucum*)–mustard (*Brassica juncea*) crop sequence. *Annals of Plant and Soil Research, 22*(4), 349–353. https://doi.org/10.47815/apsr.2020.10003

Wang, N., Zhang, T., Li, Y., Cong, A., Lian, J., & Feng, K. (2025). Integrated application of fertilization increased maize (*Zea mays* L.) yield by improving soil quality, particularly under limited water conditions in a semi-arid sandy area. *Agricultural Water Management, 309*, 109334. https://doi.org/10.1016/j.agwat.2025.109334

Yang, W., Guo, S., Li, P., Song, R., & Yu, J. (2019). Foliar antitranspirant and soil superabsorbent hydrogel affect photosynthetic gas exchange and water use efficiency of maize grown under low rainfall conditions. *Journal of the Science of Food and Agriculture, 99*(1), 350–359. https://doi.org/10.1002/jsfa.9195

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/160434