

HYDROGEL APPLICATION AS A WAY FORWARD FOR FOOD SECURITY IN THE RAIN FED AREAS OF PAKISTAN: A FOUR-YEAR FIELD EVALUATION OF SOIL MOISTURE RETENTION, WHEAT PRODUCTIVITY AND SOIL FERTILITY IN THE POTOHAR PLATEAU

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Abstract

Recurrent drought and highly variable rainfall constrain wheat productivity across the rain fed Potohar Plateau, where erratic soil moisture availability is the limit on cereal crop yields and leading cause of food security. Superabsorbent polymer can absorb and slowly release large volumes of water. This study evaluated a soil applied hydrogel at three rates (5.0, 7.5 and 10.0 kg ha⁻¹) against a control (without hydrogel) in a randomized complete block design with 3 replications for four consecutive rain-fed wheat seasons (2021 to 2024) on sandy loam texture soil at tehsil Jand district Attock of the Potohar Plateau, Pakistan. Soil moisture was monitored stage wise across five phenological phases, soil chemical properties (pH, electrical conductivity, available P₂O₅ and K₂O, and organic matter) were measured at two depths before sowing and after harvest. Crop growth, root behavior, grain and straw yield were recorded. Hydrogel consistently raised stage wise soil moisture relative to the control in every year, with the largest gains during the moisture sensitive flowering to maturity window. Mean grain yield increased by approximately 12.7 % at 5.0 kg ha⁻¹, 27.6 % at 7.5 kg ha⁻¹ and 26.4 % at 10.0 kg ha⁻¹ relative to the control. The relative yield advantage of hydrogel was greatest in the driest season (2024 averaged over years, depths

and sampling stages, hydrogel increased plant available phosphorus by 16.7 to 24.3 %, potassium by 20.5 to 23.0 % and leaving soil pH essentially unchanged. The 7.5 kg ha⁻¹ rate delivered the highest average productivity at a lower quantifiable and environmental cost than 10.0 kg ha⁻¹. We interpret hydrogel as a one component of integrated rainwater and soil fertility management for barani wheat. Therefore, this study suggests inclusion of hydrogels to store and retain water in rainfed areas which ultimately resulted in increase of yield and nutrients availability.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the staple food of Pakistan and the dominant crop of its rain fed (barani) tract where it fortifies both caloric supply and the livelihoods of a large resource constrained smallholder population. In these systems crop production is governed not by land availability but by the amount and temporal distribution of rainfall because no assured irrigation source exists to fulfill the gap period of dry spells. The Potohar Plateau of northern Punjab comprising the districts of Attock, Chakwal, Jhelum and Rawalpindi are the representative Pakistani barani region and wheat is its most drought sensitive staple crop. Rainfall in the region is not only limited but increasingly erratic and the frequency of agricultural and meteorological drought has risen since 2000 (Goheer et al., 2023). Under such conditions the obligatory constraint on cereal output is rarely not the availability of land. It is the availability of soil moisture at the crop stages when the plant needs it most. This is not merely a local concern meeting the food demand of a global population projected to approach nine to ten billion, while containing agriculture's environmental footprint is widely held to hinge on closing yield gaps through better nutrient and water management and on raising crop water productivity where water is scarce (Mueller et al., 2012), and rain fed drylands are simultaneously central to this task and disproportionately exposed to the climatic trends already depressing cereal production (Wheeler & von Braun, 2013).

Technologies that conserve soil moisture and buffer the crop against intra seasonal dry spells are therefore central to the productivity and resilience of barani wheat. Superabsorbent polymer

hydrogels three-dimensional hydrophilic polymer networks capable of absorbing water many times their own mass and releasing it slowly to the rhizosphere have attracted growing interest as one such amendment (Krasnopeeva et al., 2022). By retaining rainfall or early season moisture within the root zone and releasing it during subsequent dry periods. Hydrogels in principle can extend the plant available water, improve water use efficiency and stabilize yield in water limited environments (Ali et al., 2024).

The international and South Asian evidence base for hydrogels is expanding rapidly. Field studies in the Indo Gangetic Plains of India report improved crop and water productivity in soybean wheat systems (Adireddy et al., 2024), dryland trials in Central Asia demonstrate that localized, subsurface hydrogel placement can raise wheat yield while economizing on both polymer and fertilizer inputs (Manabaev et al., 2026); and in the Northwest Himalayan rain fed belt of India, Pusa Hydrogel applied at 2.5 kg ha⁻¹ raised rain fed wheat yield and productivity (Roy et al., 2019). Within Pakistan, however, peer reviewed field evidence is limited and concentrated on single season or single site studies and the domestic literature has more often examined hydrogels in irrigated horticulture than in rain fed cereals (Kausar et al., 2025). Findings generated in irrigated systems, in different soils or under different rainfall regimes cannot be transferred uncritically to the alkaline, calcareous, low organic matter soils and highly variable rainfall of the Potohar Plateau because hydrogel performance is strongly modulated by soil texture, salinity, temperature and the cations present in soil solution (Yu et al., 2012; Nascimento et al., 2021).

Pakistan's rain fed agriculture and food security

Rain fed agriculture occupies a large share of Pakistan's cultivated area and a still larger share of its most climate exposed farming households. In the Potohar Plateau the principal crops are wheat, alongside pulses, groundnut, millets and barley and the great majority of holdings are small resource constrained and dependent on a single winter cropping season fed by monsoon recharged soil moisture and limited winter rainfall (Goheer et al., 2023). Rain fed agriculture nonetheless remains pivotal to global food security and improving the productivity and resilience of "green water" rainfall stored in the root zone is recognized as one of the largest opportunities for closing the gap between current and attainable production in water limited regions (Rockström et al., 2009; Rosegrant & Cline, 2003).

Climate change intensifies this exposure. Analyses of the Potohar region document rising drought risk and increasingly variable rainfall, with wheat identified as the most drought-affected staple (Goheer et al., 2023). Studies of rain-fed Punjab more broadly show that farmers already perceive these shifts and adopt a range of adaptation measures, but that adaptation is constrained by resources, information and access to suitable technologies (Bakhsh & Kamran, 2019).

Hydrogels and soil water retention

Superabsorbent polymers used in agriculture are cross linked hydrophilic networks commonly based on polyacrylate/polyacrylamide chemistries or increasingly on biopolymers such as cellulose, starch, guar gum, alginate and lignin that swell on contact with water and release it as the surrounding matric potential falls (Krasnopeeva et al., 2022; Kaur et al., 2023). Their absorbency, mechanical stability and rewetting behavior can be tuned through crosslink density and through composite and nanocomposite formulations (Kabiri et al., 2011; Thombare et al., 2018). Incorporated into the root zone, they raise field capacity and plant available water and can slow evaporation and deep percolation (Singh et al., 2021; Oladosu et al., 2022; Agbna & Zaidi, 2025).

Crucially, their effect is soil dependent, retention and rewetting performance decline in saline and high cation soils and at high temperature, so the same product can perform very differently across environments (Yu et al., 2012; Nascimento et al., 2021). Reviews of bio based versus synthetic hydrogels similarly emphasize that gains in soil hydraulic properties are conditioned by dose, texture and the polymer's own degradation trajectory (Adjuik et al., 2022).

Effects on germination, growth, yield and water use efficiency

Across a wide range of crops and environments, hydrogel amendment has been associated with improved stand establishment, root development, water-use efficiency and yield under water stress (Nascimento et al., 2021; Ali et al., 2024; Oladosu et al., 2022). The most directly relevant analogue to the present work is a rain-fed field study in which superabsorbent polymers mitigated drought stress and raised yield in maize grown without irrigation (AbdAllah et al., 2021), complemented by controlled field evidence that hydrogel improves crop performance and water status under deficit irrigation (Satriani et al., 2018). At the establishment phase specifically, controlled studies show that hydrogel raises the water storage of sandy loam and loam soils and improves seedling growth of cereals including wheat, barley and chickpea (Akhter et al., 2004). In South Asian cropping systems, the evidence is increasingly quantitative: in the Indo-Gangetic Plains, biopolymeric superabsorbent hydrogels raised system yield and water productivity in a soybean-wheat rotation, with the largest relative gains under water-stressed conditions (Rajanna et al., 2022), and modified application methods (seed treatment and slurry placement) further improved germination, yield and profitability (Adireddy et al., 2024). Dryland wheat trials in Kazakhstan showed that localized subsurface co-application of hydrogel with reduced phosphorus and potassium raised yield by roughly a quarter while economizing on both hydrogel and fertilizer (Manabaev et al., 2026).

Effects on soil structure, nutrients and fertilizer use efficiency

Beyond water, hydrogels influence the movement and retention of nutrients. By holding water and solutes in the root zone they can reduce leaching of mobile nutrients and improve fertilizer-use efficiency, and some formulations are explicitly engineered as combined water reservoirs and slow-release nutrient carriers (Kaur et al., 2023; Ali et al., 2024; El Idrissi et al., 2024). Polysaccharide-based super absorbents are widely deployed as combined soil conditioners and nutrient carriers (Guilherme et al., 2015). Critically for the present context, bio-based super absorbents evaluated in alkaline, base-rich soils comparable to those of the barani tract have been shown to improve simultaneously the water- and nutrient-retention characteristics of the soil and to raise crop productivity (Zhao et al., 2022), indicating that the nutrient benefits observed in neutral soils are not automatically negated by high base status. In Pakistani conditions, a University of Agriculture Faisalabad study on potato reported that soil-applied hydrogel improved nutrient-uptake efficiency and, in combination with recommended fertilizer, substantially raised tuber yield (Faried et al., 2014). Such nutrient effects are directly relevant to the phosphorus- and potassium-limited, low-organic-matter soils typical of the Potohar Plateau.

Natural, synthetic, biodegradable nano-composite hydrogels and environmental considerations

The polymer chemistry of hydrogels carries important environmental concerns. Conventional acrylate/acrylamide super absorbents are highly effective and inexpensive but degrade slowly in soil, raising concern about long-term accumulation of polymer residues and their potential contribution to soil microplastic loads (Kaur et al., 2023). Bio-based and biodegradable alternatives mitigate persistence but can trade off durability of water-holding performance over repeated wetting-drying cycles (Adjuik et al., 2022). These considerations mean that the choice of hydrogel type, and the rate applied, is not only

an agronomic and economic decision but also a soil-health and environmental.

Pakistan specific and Potohar evidence

Pakistani field evidence on hydrogels in rain-fed cereals is still limited, though it is not absent. Early Pakistani work at the National Institute for Biotechnology and Genetic Engineering (NIAB), Faisalabad, established that locally prepared hydrogel increased the moisture retention of sandy loam and loam soils and improved seedling growth of barley, wheat and chickpea (Akhter et al., 2004), and horticultural trials confirmed nutrient-uptake and yield benefits under Faisalabad conditions (Faried et al., 2014). A recent Potohar study reported that hydrogel application improved relative soil moisture and wheat yield and raised available phosphorus, potassium and organic matter in a rain-fed system (Kausar et al., 2025), consistent with international mechanisms but based on a single agroclimatic pocket and without a resolved dose-response, water-use-efficiency computation or economic analysis. National reviews likewise identify superabsorbent polymers as a promising water-saving technology for drought-prone areas while noting the scarcity of local, multi-season, dose-resolved field data (Ashraf et al., 2021). The present study is designed to fill precisely this space.

Research gap

Synthesizing the literature, four gaps are evident for the Pakistani rain fed context. First, most domestic hydrogel evidence is single season and single site, leaving the year-to-year stability of the response the very property that matters most in a drought prone system undocumented. Second, dose response is rarely resolved. Most of the studies frequently compare a single hydrogel rate with a control, so the agronomically and economically optimal rate is unknown. Third, the mechanism linking moisture retention to yield is seldom traced through crop phenology, even though the timing of moisture availability relative to flowering and grain filling is decisive in wheat. Fourth, the co-evolution of soil chemical fertility under repeated hydrogel use has rarely been

measured in Pakistani barani soils. This study contributes original evidence on all four fronts by combining four consecutive rain fed seasons, three hydrogel rates, stage wise soil moisture and phenology data, and before and after harvest soil fertility measurements at two depths within a single experimental system.

Problem statement and objective

In the rain fed Potohar Plateau, wheat productivity and household food security are limited primarily by erratic soil moisture availability, yet the multi season, dose resolved performance of hydrogel amendment under local soil and climate conditions is not established.

The objectives of the study were to evaluate whether and at what rate soil applied hydrogel improves soil moisture retention, crop performance, yield and soil fertility in rain fed wheat across contrasting seasons.

The specific objectives were: (i) to quantify the effect of hydrogel rate on stage wise soil moisture retention across four seasons (ii) to determine the effect of hydrogel rate on crop phenology, growth and root development (iii) to quantify the effect on grain and straw yield and to test for a year × treatment interaction (iv) to assess changes in soil available phosphorus, potassium and organic matter (v) to identify the agronomically and economically preferable rate and (vi) to interpret the results for food security and environmental sustainability.

The present study addresses this gap with a four-year (2021 to 2024) rain fed field experiment evaluating three hydrogel application rates against a control on a representative Potohar soil. It links, within a single dataset, the effect of hydrogel dose on stage wise soil moisture retention, on crop phenology and root development, on grain and straw yield and on the evolution of soil chemical fertility. In doing so it aims to move beyond the common single season demonstration

Materials and methods

Study site and agro climatic conditions

The experiment was conducted over four consecutive rain fed wheat seasons (2021 to 2024) on sandy loam textured soil at tehsil Jand, district Attock with coordinates (33.496030° N, 72.171005° E) representative soil of the Potohar Plateau, northern Punjab, Pakistan.

The region's rainfall is strongly seasonal, summer monsoon dominated and highly erratic between years and it is the temporal irregularity rather than the annual total alone that governs rain-fed wheat performance. Monthly rainfall over the four study years (Figure 1) illustrates the point. The winter wheat crop, sown in autumn and harvested the following spring is sustained largely by monsoon recharged stored soil moisture (July to August) supplemented by intermittent winter and spring showers. The intervening dry spells during tillering, flowering and grain filling are the critical gaps a moisture defending amendment is planned to bridge. The four seasons captured a wide and instructive moisture gradient. The 2021 season was comparatively dry in total (223 mm) but received useful spring rainfall in March 2022 (309 mm) combined a wet January with a strong July monsoon 2023 (397 mm) was the wettest and best distributed year with a pronounced August peak and good post monsoon recharge. The 2024 season is the most diagnostic despite the highest annual total (514 mm), its rainfall arrived in an agronomically unfavorable configuration a very dry early winter and intense March, April and an almost rainless May to June a distribution that coincided with the lowest observed yields (Section 6.3) and that therefore constitutes the severest natural test of treatment stability. This dissociating of annual total from crop outcome is a defining feature of barani systems and frames the justification for the present study.

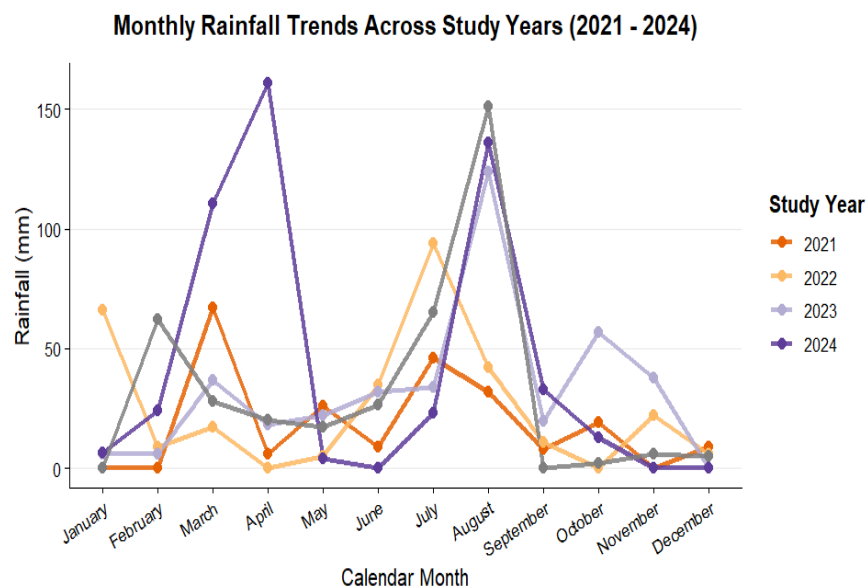


Figure 1. Monthly rainfall (mm) across the four study years (2021 to 2024) at the study site.

Experimental design and treatments

Treatments were arranged in a randomized complete block design (RCBD) with four replications and comprised four levels of soil applied hydrogel: control (0 kg ha⁻¹), hydrogel at 5.0, 7.5 and 10.0 kg ha⁻¹, was mixed into the soil followed by ploughing and planking at time of sowing. The same treatment structure was maintained across all four seasons allowing years to be treated as an environmental (random) factor and the year × treatment interaction to be examined explicitly. Standard agronomic management (variety, sowing window, seed rate and recommended basal fertilization) was held constant across treatments so that differences could be attributed to hydrogel rate. Wheat MA-21 cultivar was used in all study years. Recommended NPK @ 120,80,60 kg/ha was applied at time of sowing during the study season with the plot size 4m*5m.

Soil sampling and analysis

Composite soil samples were collected at two depths (0 to 15 cm and 15 to 30 cm) at two times in each season before sowing and after harvest for each treatment. Samples were analyzed for pH and electrical conductivity (EC_e, dS m⁻¹) in saturated

soil extracts, available phosphorus (reported as P₂O₅, mg kg⁻¹), extractable potassium (reported as K₂O, mg kg⁻¹) and organic matter (%). Soil moisture content (%) was recorded stage wise at five phenological phases emergence/early vegetative, tillering/booting, flowering/ heading, grain filling and maturity in every treatment and season, enabling the moisture response to be aligned with crop development rather than assessed only as a seasonal average. The soil reaction (pH) and electrical conductivity (EC_e) of soil were determined with the methods presented by McLean (1982) and Richards (1954) respectively, soil organic matter (Walkley, 1947), Exchangeable K (Rhodes, 1982), Available P (Watanabe and Olsen, 1965) and Mechanical Analysis of soil by Gee and Bauder (1986).

Crop measurements

Crop response was characterized across establishment, growth, root architecture, phenology and yield. Emergence percentage and plant height were recorded together with tiller number, spike length and spikelet number. Root traits included root length, depth, volume, surface area, fresh biomass, dry weight and number of lateral roots. Phenological development was

captured as days to key stages (emergence, first tiller, tillering, booting, heading/spike emergence, flowering, and maturity). Grain yield and straw yield (kg ha^{-1}) were determined at harvest.

Statistical analysis

Data was analyzed within the RCBD framework with treatment as a fixed factor and year (and its interaction with treatment) evaluated to test the stability of the response across seasons; a mixed model treatment of year as a random factor is appropriate for the four-season structure. Treatment means were separated and treatment effects are displayed with standard error bars in the interaction figures. The relationship between stage wise soil moisture and both phenology and yield were examined by linear regression, with the coefficient of determination (R^2) quantifying the share of variation explained. Percentage changes relative to the control were computed for soil fertility indices.

Results

Soil moisture retention across phenological stages

In every study year, hydrogel amended plots retained more soil moisture than the control at each phenological stage, and the advantage extended with application rate. The separation between treatments was consistently clearest during the flowering to maturity window the stages at which wheat is most sensitive to water deficit where the 7.5 and 10.0 kg ha^{-1} treatments maintained the highest moisture. Absolute moisture levels varied markedly among years reflecting rainfall values were highest in 2021 and lowest in the dry 2024 season, but the ranking of treatments ($\text{control} < 5.0 < 7.5 < 10.0 \text{ kg ha}^{-1}$) was preserved across this environmental gradient indicating a healthy moisture conservation effect rather than one confined to favorable years.

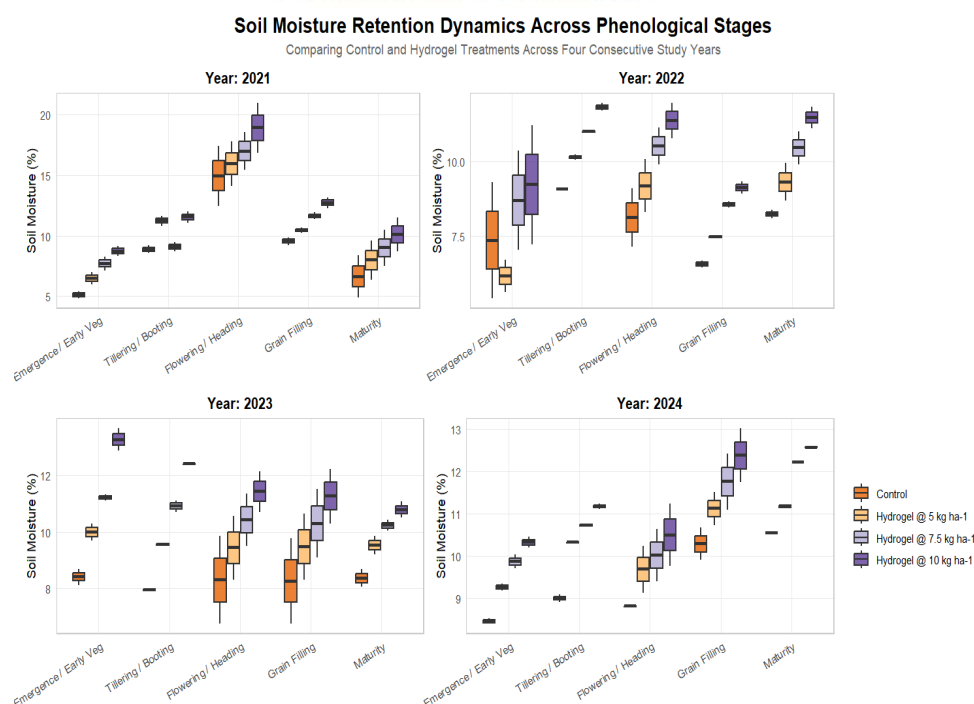


Figure 2. Soil moisture retention dynamics across five phenological stages, comparing the control and three hydrogel rates over the four study years (2021 to 2024). Hydrogel treatments retained more moisture than the control at each stage, with the widest separation during flowering to maturity.

Crop Phenology

Stage wise soil moisture was systematically related to crop phenology. Across the pooled dataset, higher mean seasonal soil moisture was associated with faster emergence but a substantial growth developmental period: days to first tiller, spike emergence, flowering and maturity all completed in their required complete days with proper moisture available. The relationship strengthened through the reproductive phase, with soil moisture

explaining an increasing share of the variation approximately 25 % for days to flowering and about 35 % for days to maturity. Because hydrogel raised retained moisture it correspondingly helped the crop to fulfil the flowering and grain filling period in it proper time hence crop maintained its maturity period, providing a credible physiological mechanism for the yield response reported below: a complete effective grain filling duration under sustained moisture supply (Figure 3).

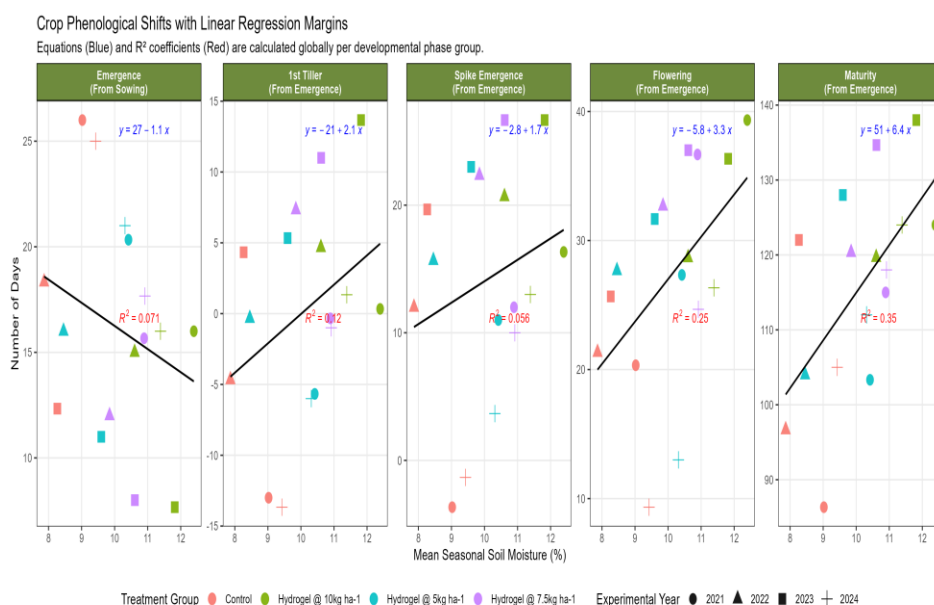


Figure 3. Crop phenological shifts against mean seasonal soil moisture, by treatment and year, with linear-regression fits and R^2 per developmental phase. Days to flowering and to maturity with soil moisture ($R^2 \approx 0.25$ and 0.35), indicating a complete required period for reproductive phase under higher retained moisture.

Grain and straw yield and the year $\times$ treatment interaction

Hydrogel raised grain yield at every rate and in every year. Averaged over the four seasons, grain yield increased from about 3,040 kg ha⁻¹ in the control to roughly 3,425 kg ha⁻¹ at 5.0 kg ha⁻¹ (+12.7 %), 3,878 kg ha⁻¹ at 7.5 kg ha⁻¹ (+27.6 %) and 3,843 kg ha⁻¹ at 10.0 kg ha⁻¹ (+26.4 %), so that the 7.5 and 10.0 kg ha⁻¹ rates were closely comparable and both clearly exceeded 5.0 kg ha⁻¹ and the control (Table 1). The objective that the yield increases with hydrogel rate relative to the

control is therefore supported with the response plateauing between 7.5 and 10.0 kg ha⁻¹.

The response was not uniform across seasons: a pronounced year $\times$ treatment interaction was evident (Figure 4). The absolute and relative advantage of hydrogel over the control was largest in the driest season (2024), when control yield fell to about 2,050 kg ha⁻¹ while the 10.0 kg ha⁻¹ treatment reached roughly 3,170 kg ha⁻¹ an increase of more than 50 %. In the more favorable seasons (2022 and 2023) the control yielded substantially more (around 3,590–3,650 kg ha⁻¹) and the proportional hydrogel benefit, while still

positive, was smaller. Notably, in the driest year the highest rate (10.0 kg ha⁻¹) out-performed 7.5 kg ha⁻¹, whereas in wetter years 7.5 kg ha⁻¹ was equal or superior. This pattern supports that the relative benefit of hydrogel is greater under greater moisture stress and identifies the highest rate as offering the strongest insurance value precisely when it is most needed. Average grain yield against

mean soil moisture at successive phenological stages. Yield rises with moisture availability at tillering, booting and grain filling. It was consistent with early to mid-season as the moisture being most limiting factor in the rain fed system. Straw yield followed the same qualitative pattern as grain yield.

Table 1: Mean wheat grain yield (kg ha⁻¹) by hydrogel rate and season, with change relative to the control
Year × treatment interaction was evident, with the largest relative benefit in the driest season (2024).

Treatment	2021	2022	2023	2024	4 years mean	% inc over control
Control (without hydrogel)	2850	3650	3590	2050	3040	-
Hydrogel @ 5.0 kg ha ⁻¹	3420	4050	3720	2510	3425	+12.7 %
Hydrogel @ 7.5 kg ha ⁻¹	3880	4340	4420	2870	3878	+27.6 %
Hydrogel @ 10.0 kg ha ⁻¹	3730	4130	4340	3170	3843	+26.4 %

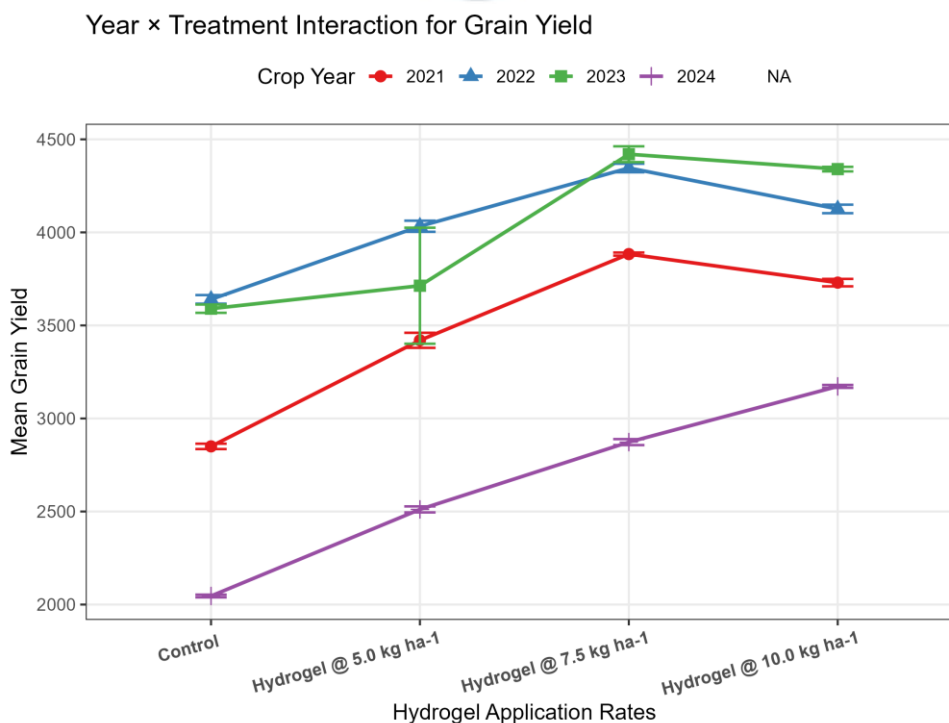


Figure 4. Year × treatment interaction for wheat grain yield (kg ha⁻¹). All hydrogel rates exceeded the control in every season; the absolute and relative advantage was largest in the driest year (2024), where the 10.0 kg ha⁻¹ rate raised yield by more than half over the control.

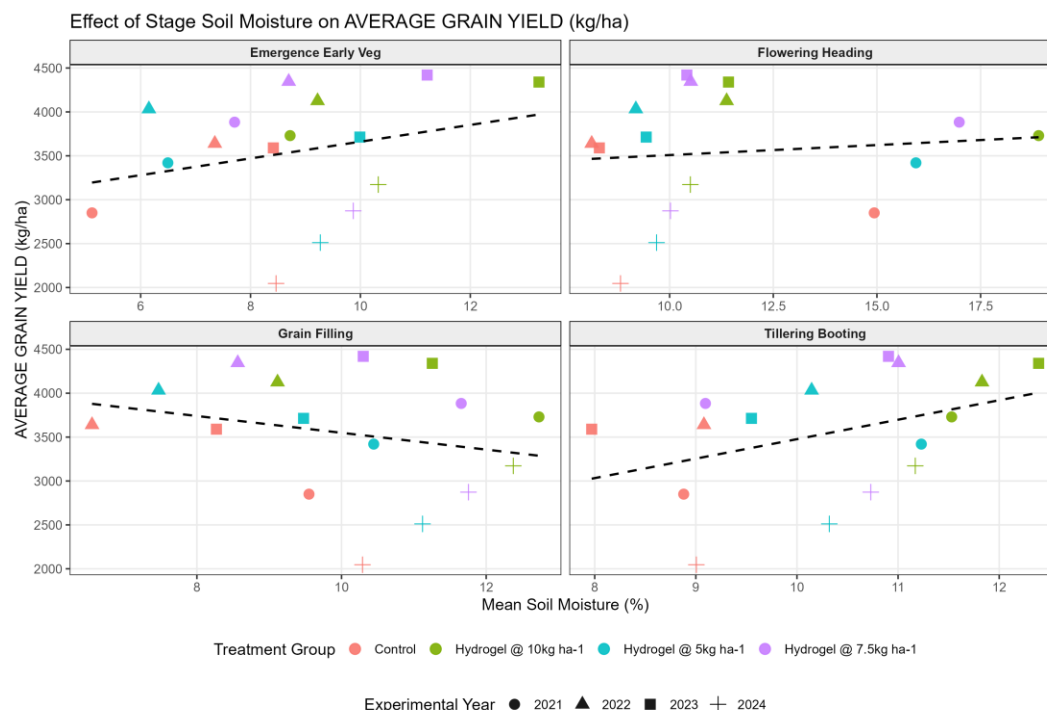


Figure 5. Average grain yield against mean soil moisture at successive phenological stages.

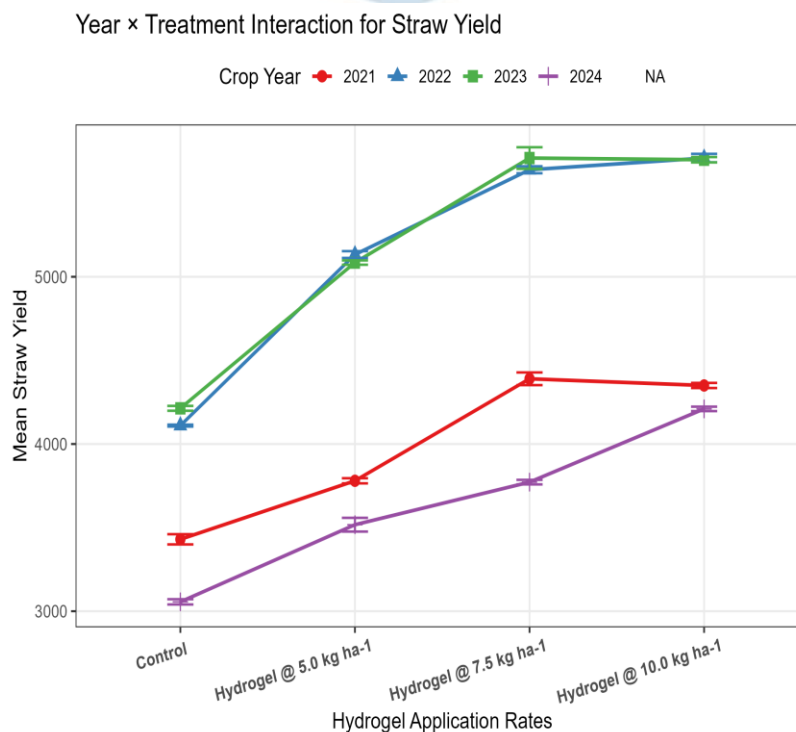


Figure 6. Year × treatment interaction for straw yield (kg ha⁻¹), following the same qualitative pattern as grain yield across rates and seasons.

Soil chemical fertility

Repeated hydrogel use was associated with a consistent improvement in soil chemical fertility computed here directly from the primary dataset by combining both depths both sampling times and all four years (Table 2). Relative to the control available phosphorus (P_2O_5) increased by 16.7 %, 22.9 % and 24.3 % at 5.0, 7.5 and 10.0 kg ha⁻¹ respectively. Extractable potassium (K_2O) increased by 20.5 %, 21.9 % and 23.0 %. Electrical conductivity was marginally lower under

hydrogel (by roughly 3 to 4 %) consistent with reduced salt concentration in a better buffered moisture regime while soil pH was essentially unchanged (7.71 in the control versus 7.74 and 7.77 under hydrogel) as expected for a strongly buffered calcareous soil. The nutrient gains were somewhat larger in the after-harvest samples than in the before sowing samples for phosphorus, consistent with improved retention of applied and mineralized nutrients within the root zone over the season.

Table 2: Soil chemical properties by hydrogel treatment during the years 2021 to 2024, depths (0-15 and 15-30 cm)

Soil Properties	Control (without hydrogel)	Hydrogel @ 5 (kg/ha)	Hydrogel @7.5 (kg/ha)	Hydrogel @ 10 (kg/ha)
pH	7.71	7.74	7.77	7.76
EC _e (dS m ⁻¹)	0.78	0.77	0.78	0.79
P ₂ O ₅ (mg kg ⁻¹)	2.76	3.22 (+16.7%)	3.39 (+22.9%)	3.43 (+24.3%)
K ₂ O (mg kg ⁻¹)	59.3	71.4 (+20.5%)	72.3 (+21.9%)	72.9 (+23.0%)
Organic matter (%)	0.66	0.67 (+1.5 %)	0.68 (+3.0%)	0.67 (+1.5%)

Growth and root development

Growth and root traits were consistent with the moisture and yield results. Hydrogel amended treatments generally showed improved emergence, greater plant height, more tillers per plant, enhanced spike length and spikelet number relative to the control with the strongest expression at the 7.5 and 10.0 kg ha⁻¹ rates. Root development including root length, depth,

volume, surface area and biomass was likewise greater under hydrogel indicating that improved and more sustained root zone moisture supported a larger more exploratory root system capable of accessing water and nutrients over a longer period. These growth and root responses provide the developmental basis for the phenological, and yield effects described below (Figures 7 to 12).

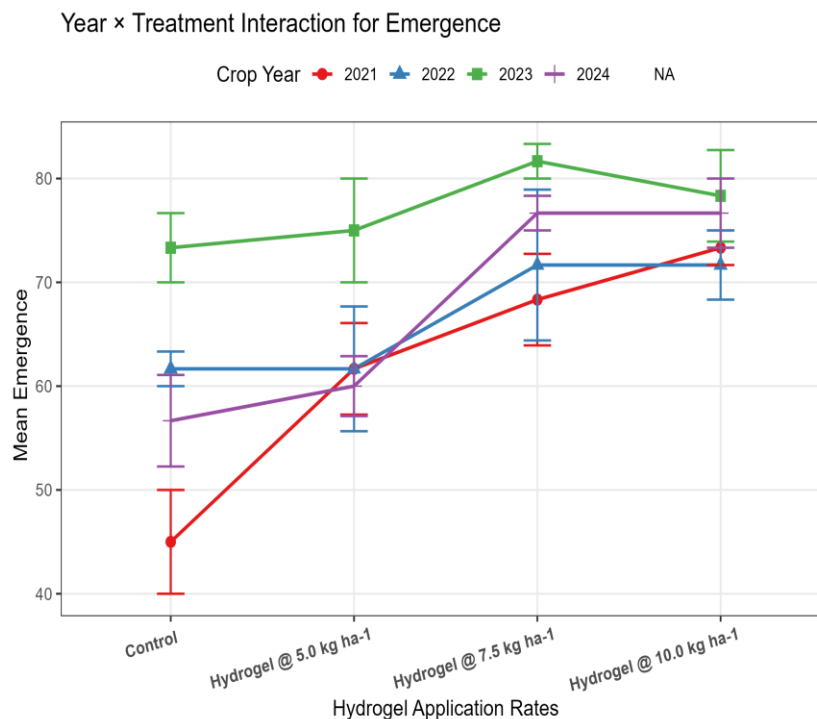


Figure 7. Year × treatment interaction for emergence (%). Hydrogel generally improved crop establishment relative to the control.

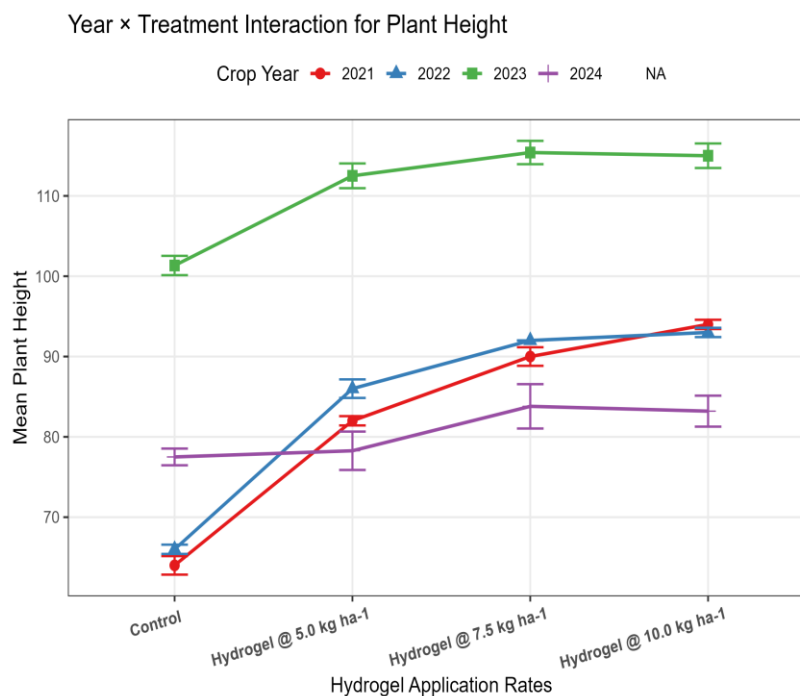


Figure 8. Year × treatment interaction for plant height. Hydrogel-amended plots were generally taller, with the strongest expression at 7.5 and 10.0 kg ha⁻¹.

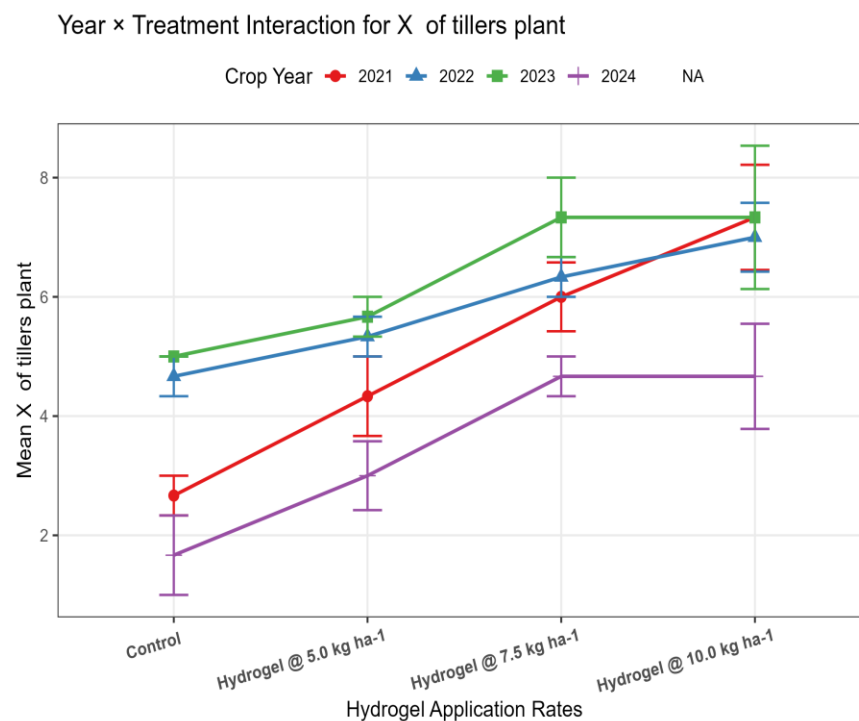


Figure 9. Year × treatment interaction for number of tillers per plant.

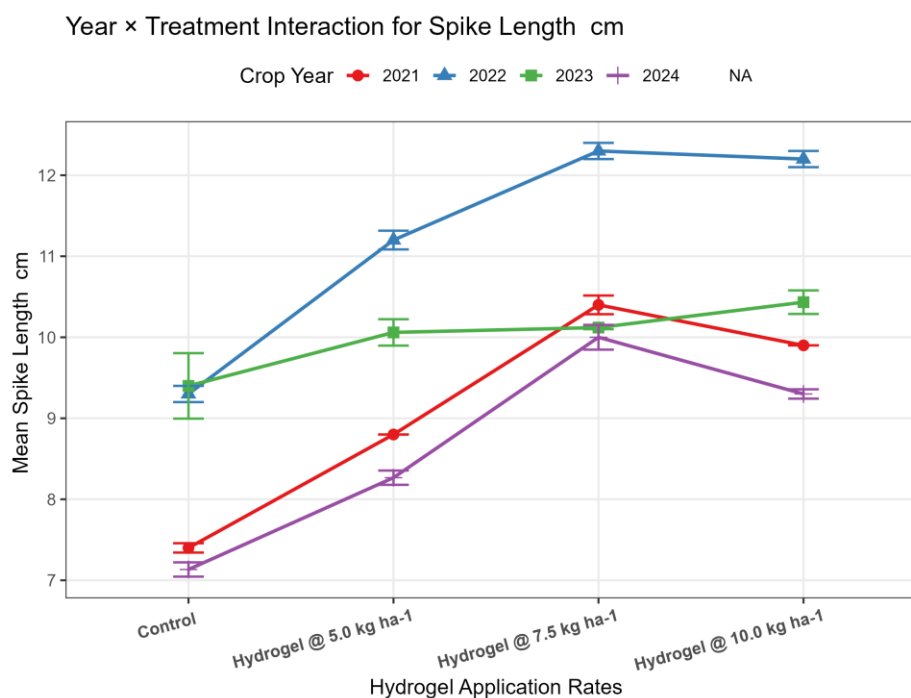


Figure 10. Year × treatment interaction for spike length (cm).

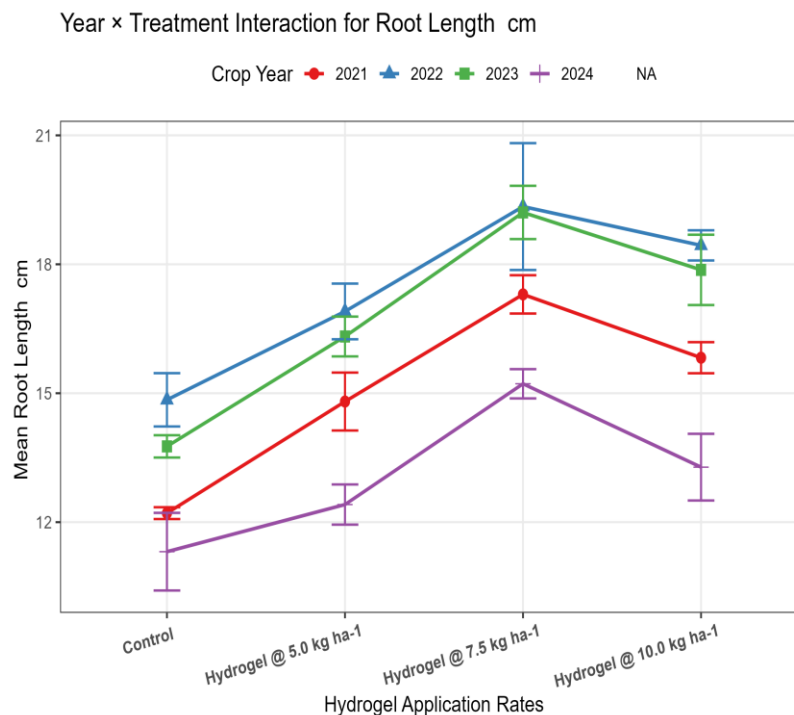


Figure 11. Year × treatment interaction for root length (cm), indicating a deeper, more exploratory root system under hydrogel.

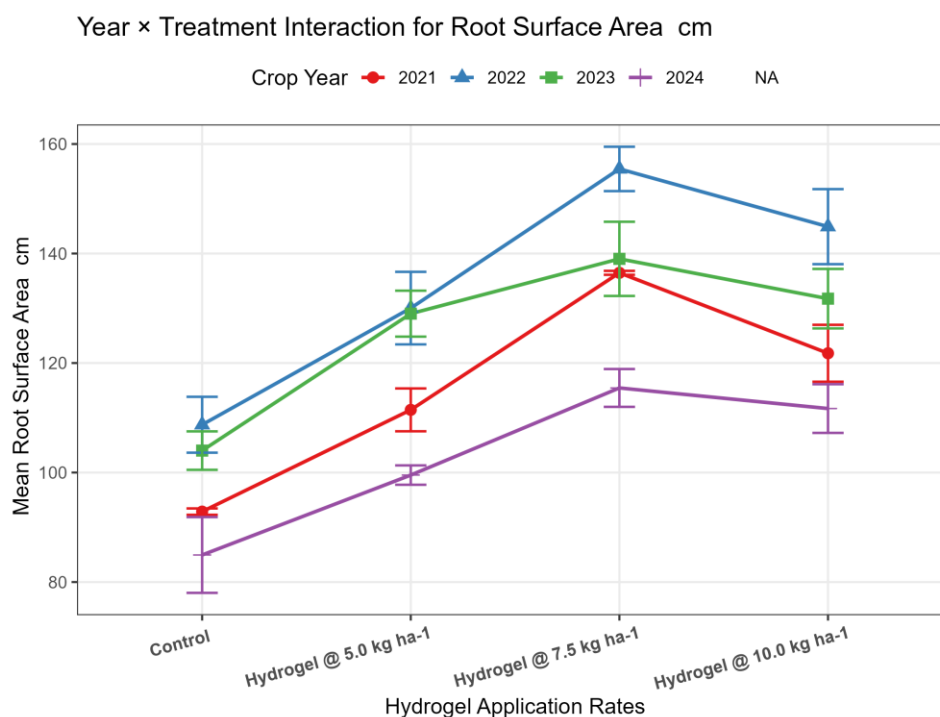


Figure 12. Year × treatment interaction for root surface area (cm²), consistent with enhanced water- and nutrient-capture capacity under sustained root-zone moisture.

Discussion

The critical finding that soil applied hydrogel raises retained soil moisture, crop completed its all phases in time and increases rain fed wheat yield with the largest relative benefit in the driest season is coherent internally, consistent and is comparative with literature. The moisture retention effect aligns with the established understanding of superabsorbent polymers as root zone water reservoirs (Saha et al., 2020; Krasnopeevea et al., 2022) and the finding that the effect persists across a four-year moisture gradient strengthens the findings. The magnitude of the yield response roughly 27 to 28 % at the better performing rates, averaged over four years fits within the range reported for South Asian systems being broadly comparable to the yield and water productivity gains documented in the Indo Gangetic Plains (Adireddy et al., 2024) and to the roughly one quarter yield increase reported for localized hydrogel use in Central Asian drylands (Manabaev et al., 2026). It is directionally consistent with the earlier Potohar study that reported improved soil moisture, yield and fertility under hydrogel (Kausar et al., 2025). The soil fertility gains higher available phosphorus and potassium and modestly higher organic matter under hydrogel are consistent with improved retention of water soluble nutrients within a better buffered root zone and with reduced leaching losses (Kaur et al., 2023; Ali et al., 2024). The nutrient uptake efficiency benefit reported for Pakistani hydrogel use in horticulture (Faried et al., 2014) and align with the simultaneous water and nutrient retention gains documented for bio-based super absorbents in alkaline soils elsewhere (Zhao et al., 2022). That pH remained unchanged is expected for a strongly buffered calcareous soil and indicates that hydrogel does not, over four seasons materially alter soil reaction. The dependence of the optimal rate on season 7.5 kg ha⁻¹ best on average but 10.0 kg ha⁻¹ superior in the driest year reflects the soil and climate contingency emphasized in the literature (Yu et al., 2012; Nascimento et al., 2021).

Economic, environmental and adoption considerations

Whether these agronomic gains translate into farmer benefit depends on economics. Hydrogel is a purchased input, and its cost effectiveness turns on whether the value of the additional grain (and any saving in re-sowing or supplementary inputs) exceeds the cost of the polymer and its application. International dryland studies report favorable benefit cost ratios for hydrogel for example, values of 2.6 and 2.1 for guar gum hydrogel in sugarcane at 2.5 and 5.0 kg ha⁻¹ respectively (Songara & Patel, 2023) but such ratios are crop price specific and cannot be transferred directly. For barani wheat the calculation is finely balanced because the crop's value per hectare is modest, the high cost of quality hydrogel is repeatedly identified as the principal barrier to adoption in developing country contexts (Kaur et al., 2023). A formal benefit cost and sensitivity analysis using local hydrogel and wheat prices and accounting for the multi-season persistence of a single application is a priority. On present evidence the plateau between 7.5 and 10.0 kg ha⁻¹ suggests that 7.5 kg ha⁻¹ is likely to be the more economically efficient rate in average years with the higher rate justified mainly where drought risk is high.

Environmental sustainability is the second qualifier. If the hydrogel used is a conventional acrylate/acrylamide polymer, its slow degradation raises legitimate concern about long term accumulation of polymer residues in soil and possible contribution to soil microplastic loads under repeated application (Adjuik et al., 2022; Kaur et al., 2023). Biodegradable and bio-based hydrogels reduce this risk but may lose water holding performance more quickly over wetting drying cycles (Saha et al., 2020). The soil health implications therefore depend on polymer chemistry and dose and is the reason for using the lowest rate consistent with the agronomic goal where their performance is adequate and for monitoring soil over successive seasons. These considerations reinforce the framing of hydrogel as one carefully managed component of soil and water management rather than an input to be maximized. Adoption finally depends on more

than price and product. Farmer awareness of correct placement, rate and availability of quality product through input channels and extension support are all necessary for the experimental benefit to be realized in farmers' fields (Bakhsh & Kamran, 2019). The relative simplicity of soil incorporation at sowing is an advantage but misapplication wrong rate, poor incorporation and use of low-quality product could dissipate the benefit.

New Contribution

The present study's distinct contributions are three. First, it resolves a dose response and shows a plateau between 7.5 and 10.0 kg ha⁻¹, which single rate studies cannot reveal. Second, it demonstrates a year × treatment interaction in which the benefit is greatest under stress an assurance property of direct relevance to drought prone systems. Third, it traces the moisture to yield link explicitly through phenology, showing that due to sustained moisture flowering and grain filling was completed on time.

Conclusion and recommendations

Across four rain fed wheat seasons on an alkaline, calcareous, low organic matter soil of the Potohar Plateau, soil applied hydrogel consistently improved root zone moisture retention, crop completed its all stages of growth in time, enhanced growth and root development and raised grain yield by approximately 27 to 28 % at the better performing rates with the largest relative benefit in the driest season. It also improved soil available phosphorus and potassium and modestly raised organic matter, while leaving pH unchanged. The agronomically preferable rate on average was 7.5 kg ha⁻¹, with 10.0 kg ha⁻¹ offering additional insurance value under severe drought and 5.0 kg ha⁻¹ giving a smaller but still positive return. We therefore recommend that hydrogel be promoted for rain fed wheat in the Potohar and comparable barani zones as one component of integrated rainwater and soil fertility management, prioritized for drought prone areas and drought years where its stabilizing value is greatest; that 7.5 kg ha⁻¹ be adopted as the default rate with 10.0 kg ha⁻¹ reserved for high drought risk situations. The

degradable formulations and the lowest effective rate be favored to protect soil health.

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