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RESEARCH ARTICLE

Evaluating hydrogel amendment rates as a climate-smart strategy for cowpea production under moderate drought in semi-arid Zimbabwe

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ABSTRACT

Superabsorbent hydrogels (SAPs) are three-dimensional polymer networks capable of absorbing and retaining hundreds of times their own weight in water, then releasing it gradually to plant roots as the soil dries. This property buffers soil moisture fluctuations, reduces deep percolation losses, and extends water availability between rainfall events, making SAPs a promising climate-smart soil amendment for mitigating drought stress in rain-fed agriculture. In semi-arid regions such as Zimbabwe, erratic rainfall and mid-season dry spells increasingly threaten crop productivity, and soil amendments that enhance water retention offer a practical strategy to buffer crops against these intermittent water deficits. This study evaluated the effect of soil incorporation of hydrogel (0, 0.1, 0.2, 0.3 and 0.4 g/kg soil) under two moisture regimes (soil moisture maintained at 75-85% as well-watered and 45-55% as moderate drought of field capacity) on phenology, reproductive traits and yield of cowpea in a pot experiment arranged in a randomized complete block design with three replicates. Increasing hydrogel rates progressively delayed days to 50% flowering (by up to 4.4 days) and physiological maturity (by up to 5.2 days). Seeds per pod increased from 10.4 (0 g) to 13.2 (0.4 g). Moderate drought increased 100-seed weight (19.80 g vs. 14.67 g), compensating for reduced seed number. Shelling percentage showed a significant hydrogel × moisture interaction ($p = 0.026$). Most importantly, total seed yield per plant increased by 41% with the highest hydrogel rate, and the main effect of moisture regime on yield was not significant ($p = 0.314$), indicating that hydrogel completely offset the yield penalty from moderate drought. Hydrogel × moisture interactions were non-significant for most traits, demonstrating additive benefits. Superabsorbent hydrogels at 0.4 g/kg soil therefore represent an effective, climate-smart amendment for enhancing cowpea productivity and buffering against moderate water deficits in semi-arid environments.

Keywords: Growth; Moisture stress; Phenology; Seed yield compensation; Superabsorbent polymer.

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INTRODUCTION

The rising frequency of mid-season dry spells and erratic rainfall, driven by climate change, is undermining rainfed agriculture across Sub-Saharan Africa (Zheng et al., 2023). In Zimbabwe, the majority of smallholder farmers rely on a short and unpredictable growing season; over recent decades, the region has experienced a marked increase in mid-season dry spells and a decline in annual precipitation (Poudel et al., 2025). These climatic shifts impose severe abiotic stress on staple dryland crops, particularly during phenologically sensitive stages such as flowering and pod filling, leading to substantial yield losses.

Cowpea (*Vigna unguiculata* (L.) Walp.) is a climate-resilient legume, valued for its excellent drought tolerance, nitrogen-fixing ability, and high nutritional content (Neetu et al., 2026). It is a key component of smallholder farming systems in Zimbabwe's semi-arid zones. However, even moderate water deficits during the reproductive stage can reduce seed yield by up to 46% by disrupting flower development, pod set, and seed filling (Poudel et al., 2025). To cope with terminal drought, cowpea often increases hundred-seed weight while reducing seed number, a compensatory shift in resource allocation (Poudel et al., 2025). Yet, these adaptive mechanisms are often insufficient to maintain productivity under prolonged or severe moisture deficits.

Superabsorbent polymer (SAP) hydrogels have emerged as a promising soil amendment for water-limited agriculture (Neetu et al., 2026). These three-dimensional polymeric networks can absorb and retain hundreds of times their own weight in water, gradually releasing it to plant roots, thereby buffering soil moisture and reducing irrigation frequency (Mamaghani et al., 2025). A recent meta-analysis confirms that SAPs improve soil water retention, reduce deep percolation losses, and consistently increase crop yield and water productivity across a wide range of climates and soil types (Zheng et al., 2023). In legume crops, SAP application has been shown to mitigate water stress effects, with field studies reporting yield increases of 23.6% in faba bean and 17.3% in pea at a rate of 20 kg/ha (Czopek and Staniak, 2025). Similarly, in cowpea, SAP at 150 kg/ha under full irrigation achieved grain yields of up to 2853 kg/ha, with the polymer attributed to enhancing water and nutrient availability during stress periods (Mombani and Marashi, 2023). Recent advances have moved beyond simple superabsorbent behavior toward multifunctional systems for controlled nutrient delivery and seed coating, and toward stimuli-responsive "smart" matrices that couple with precision irrigation (Mamaghani et al., 2025). Biopolymer-based hydrogels derived from cellulose, starch, chitosan/chitin, and alginate offer sustainable and environmentally friendly sourcing from agro-industrial waste, further enhancing their agricultural utility (Henn et al., 2025).

Despite these promising results, knowledge gaps remain regarding the optimal application rates and mechanisms of action for SAPs in cowpea, particularly under moderate drought stress. Moreover, there is a scarcity of studies that have been conducted under controlled conditions, and field validation under the local context of Zimbabwe. Therefore, the present study aimed to evaluate the efficacy of SAP hydrogels as a climate-smart tool for enhancing cowpea productivity under moderate drought conditions. Specifically, the study investigated the effects of five hydrogel rates (0, 0.1, 0.2, 0.3, 0.4 g/kg soil) combined with two moisture regimes (well-watered and moderate drought) on phenology, growth, reproductive traits, and yield of cowpea.

MATERIALS AND METHODS

Study site description

The research was carried out at Midlands State University (Figure 1), located at 19°50' S latitude and 29°48' E longitude, at an altitude of 1457 m above sea level. The region experiences a mean annual precipitation ranging from 400 to 600 millimetres, with an average annual temperature of 25°C, as noted by Zimbabwe Worldplaces (2022).

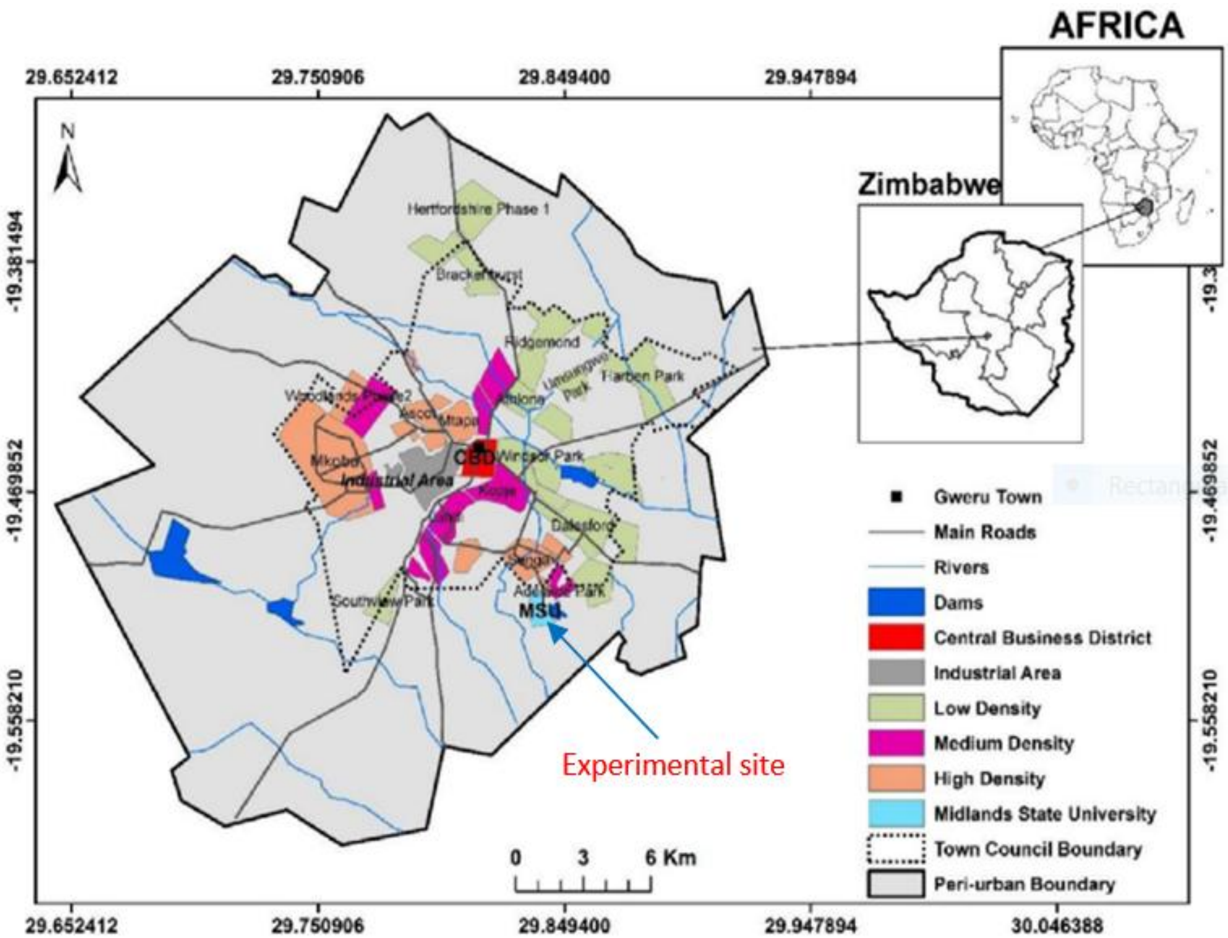

Figure 1. Experimental site, Midlands State University farm

Its soil consists of characteristic sandy loams derived from the fersialitic group, with kaolinite clay minerals being dominant. Soil analysis taken from the experimental site shows the soil to be slightly acidic with a pH (5.9), total soluble salts (74.00 ppm), nitrate nitrogen (6.23 ppm), organic carbon (1.54%) and N: C (0.25).

Experimental design and treatments

The study was established as a factorial pot experiment arranged in a Randomized Complete Block Design (RCBD) with three replications. Two factors were evaluated: two soil moisture regimes and five hydrogen levels give a total of 10 treatment combinations and 30 experimental units. Each pot served as an experimental unit.

Moisture regimes:

1. Well-watered control (WW): soil moisture maintained at 75-85% of field capacity (FC).
2. Moderate drought (MD): soil moisture maintained at 45-55% FC through restricted irrigation.

Hydrogel treatments:

1. 0 g/kg soil (0 g/pot; control)
2. 0.1 g/kg soil (0.5 g/pot)
3. 0.2 g/kg soil (1.0 g/pot)
4. 0.3 g/kg soil (1.5 g/pot)

5. 0.4 g/kg soil (2.0 g/pot)

Pot preparation and crop establishment

Plastic pots measuring 18 cm in diameter and 25 cm in height were used as experimental containers, with each pot filled with 5 kg of prepared soil. In treatments involving hydrogel (HiPro-Aqua, which is cellulose and starch-based SAP, purchased locally), the material was thoroughly blended into soil within the designated pots and left to homogenize for 7 days before seed placement. Conversely, hydrogel was purposefully excluded from the control treatment groups. Prior to sowing, seeds of a widely cultivated cowpea cultivar (cv. CBC1) known for its agronomic relevance and adaptability to Zimbabwean conditions were pre-germinated by soaking them in water for 16-hours. Five of these pre-germinated seeds were then carefully placed into each pot, subsequently thinned at the cotyledon stage to avoid competition and to achieve a final density of two plants per pot. All seeds were consistently sown at a maximum depth of 2 cm, with no rhizobium inoculant. Pots were maintained under well-watered conditions (75-85% FC) until the start of the drought treatments at 3 weeks from planting to ensure they started the experiment on an equal footing. At three weeks from planting, irrigation was done or withheld to achieve and maintain soil moisture at 75-85% FC and 45-55% FC, respectively.

To enable independent assessment of the moderate drought treatment, the soil used in the pot experiment was characterized for its water retention properties. Field capacity (FC) was determined gravimetrically by saturating representative pots and allowing free drainage for 24 h. The permanent wilting point (PWP) was estimated at approximately 30% of FC, consistent with published values for sandy loam soils (Nyamapfene, 1992). Based on this characterization, the moderate drought target range of 45–55% FC corresponded to an estimated soil matric potential of approximately -0.6 to -0.9 MPa. Previous studies on cowpea have demonstrated that this moisture range induces physiologically meaningful stress: it reduces seed number per pod by 20-30%, triggers compensatory increases in individual seed weight, and delays flowering without causing complete reproductive failure (Poudel et al., 2025; Sennhenn et al., 2017). Therefore, the 45-55% FC regime is classified as moderate drought – sufficient to elicit adaptive stress responses while maintaining plant survival and measurable yield. Throughout the experiment, treatment efficacy was monitored through phenological and morphological indicators of water stress (days to flowering, root: shoot ratio, and 100-seed weight), as described in Table 1. The results of these measurements are presented in the Results section.

At the time of planting, a full dose of N:P:K fertilizer (7:14:7) was incorporated into the soil at a rate of 600 kg ha^{-1} based on a plant population of 60,000 plants ha^{-1}. Nitrogen levels were further augmented with Ammonium Nitrate (34.5% N) at 300 kg ha^{-1}, administered in two equal split applications at 14 and 21 days after emergence.

Determination of field capacity and irrigation management

The experimental protocol began with characterizing the water-holding capacity of the potting medium. The FC was defined by watering representative pots to saturation, letting them drain unimpeded, and then measuring the resulting water content by weight (gravimetric). Field capacity (%) was calculated as:

$$FC (\%) = [(\text{Wet soil mass} - \text{Dry soil mass}) / \text{Dry soil mass}] \times 100 \quad \text{(i)}$$

Where wet soil mass is the mass of soil after free drainage, and dry soil mass is the mass after drying at 105°C until a constant weight is reached.

From this baseline, the precise target weights for two drought treatments were calculated. To enforce these moisture levels, a daily routine of weighing each pot on a digital scale (±1 g) and adding just enough water to return it to its designated target was followed. A greenhouse structure shielded the plants from any rainfall. For quality control, the watering method was cross-validated regularly with data from a soil moisture probe (either TDR or capacitive).

Data collection

Data collected from this study are explained in Table 1.

Table 1. Collected data variables during the investigation

Variable	Description / Measurement Method	Unit	Timing / Frequency
Days to 50% flowering	Number of days from sowing until 50% of plants in the experimental unit have at least one open flower. Recorded per plant.	days	Daily observation from emergence until flowering
Days to physiological maturity	Number of days from sowing until 90% of pods have turned brown/dry (characteristic mature colour). Recorded per plant.	days	Daily observation from start of pod filling until maturity
Root:shoot ratio per plant	After separating roots from shoots, dry both fractions in an oven at 65°C until constant weight. Calculated the: root dry mass / shoot dry mass.	ratio	At final harvest
Seeds per pod per plant	From a subsample of pods (10 random pods per plant), counted the total seeds and divided by number of pods.	count per pod	After threshing, at harvest
100-seed weight per plant	A random sample of 100 seeds were taken from the total harvest per treatment. Weighed using a precision balance.	grams (g)	After cleaning and drying seeds to constant moisture
Shelling percentage per plant	The ratio of seed weight to total unshelled pod weight, expressed as a percentage. (Seed weight / unshelled pod weight) × 100.	%	After threshing and drying
Total seed yield per plant	Total weight of all seeds harvested from a single plant after threshing and drying.	grams (g)	After cleaning and drying seeds

Data analysis

Data were subjected to two-factor analysis of variance (ANOVA) using GenStat 18th Edition following a randomized complete block design (RCBD) to account for greenhouse position. Normality and homogeneity of variance were confirmed prior to analysis using the Shapiro-Wilk test. The analysis evaluated the main effects and their interaction, separating significant means with a Fisher's protected Least Significant Difference (LSD) test at the 5% probability level ($p < 0.05$).

RESULTS

Days to 50% flowering

The ANOVA for days to 50% flowering revealed highly significant effects of both hydrogel application ($F_{4,18} = 19.36$, $p < 0.001$) and moisture regime ($F_{1,18} = 130.51$, $p < 0.001$), whereas the hydrogel × moisture interaction was non-significant ($F_{4,18} = 0.16$, $p = 0.957$) (Table 2). Increasing hydrogel rates progressively delayed flowering, from 58.3 days with plants receiving no hydrogel to 62.7 days at 0.4 g treatment. Moderate drought (MD) also delayed flowering (62.5 days) compared to well-watered (WW) conditions. Mean separation analysis grouped the 0.4 g (62.7 d) and 0.3 g (61.3 d) hydrogel treatments in the highest group; 0.2 g treatment (61.0 d) occupied an intermediate group; and 0.1 g (59.4 d) and control treatments (58.3 d) in the lowest statistical group. The delay induced by hydrogel suggests a prolonged vegetative phase due to improved soil moisture retention, while drought-induced delay reflects a classic stress response.

Table 2. Means for effect of hydrogel and moisture on days to 50% flowering, days to physiological maturity and number of seeds pod^{-1} of cowpeas

Treatment	Days to 50% flowering	Days to physiological maturity	Seeds pod^{-1}
Moisture			
Moderate Drought	62.53^{y}	87.63^{z}	10.53^{z}
Well-watered	58.53^{z}	93.40^{y}	12.87^{y}
P value	<0.001	<0.001	<0.001
$LSD_{0.05}$	0.736	1.137	1.059
Hydrogel			
0 g/kg soil	58.25^{c}	88.17^{c}	10.42^{b}
0.1 g/kg soil	59.42^{c}	88.67^{c}	10.92^{ab}
0.2 g/kg soil	61.00^{b}	90.58^{bc}	11.67^{ab}
0.3 g/kg soil	61.33^{ab}	91.83^{ab}	12.33^{ab}
0.4 g/kg soil	62.67^{a}	93.33^{a}	13.17^{a}
Mean	60.53	90.52	11.7
P value	<0.001	<0.001	0.021
CV%	1.6	1.6	11.8

Means in a column followed by the same letter are not significantly different at $p < 0.05$ (Fisher's LSD).

Days to Physiological maturity

Physiological maturity showed a similar pattern to that observed for days to 50% flowering. The ANOVA indicated highly significant effects of hydrogel application ($F_{4,18}$ = 12.72, $p < 0.001$) and moisture regimes ($F_{1,18}$ = 113.61, $p < 0.001$), while their interaction was not significant ($F_{4,18}$ = 0.38, p = 0.823). Mean maturity increased from 88.2 days in the control (0 g hydrogel) to 93.3 days at the highest hydrogel rate. WW-treated plants matured later (93.4 days) than those under moderate drought (87.6 days) (Table 2). The observed 5.8-day delay caused by well-watered conditions relative to drought stress is consistent with the known effect of water availability on crop duration. Hydrogel application extended the growing cycle by up to 5.2 days, which may be agronomically acceptable if it enhances yield.

Seeds per pod (per plant)

Seed number per pod was significantly increased by both hydrogel application ($F_{4,18}$ = 3.79, p = 0.021) and moisture regimes ($F_{1,18}$ = 21.44, $p < 0.001$), whereas their interaction was not significant ($F_{4,18}$ = 0.69, p = 0.609) (Table 2). Hydrogel application raised seed count from 10.4 (0 g) to 13.2 (0.4 g). WW-treated plants produced higher mean seed number (12.9) compared to those under moderate drought (10.5). The seed reduction of approximately 2.4 seeds per pod due to drought was alleviated by hydrogel application at 0.4 g, drought-stressed plants produced 12.7 seeds per pod, which was not significantly different from well-watered plants without hydrogel (12.2 seeds). This indicates that hydrogel application can effectively buffer ovule abortion and seed set failure caused by moderate water stress.

Root: shoot ratio

The root: shoot ratio (R:S) exhibited a distinct response to soil moisture ($F_{1,18}$ = 65.23, $p < 0.001$) (Table 3), but hydrogel application ($F_{4,18}$ = 0.40, p = 0.808), and the interaction effect was not significant ($F_{4,18}$ = 0.28, p = 0.888). Moderate drought increased the R:S ratio to 1.052 compared to 0.931 under WW conditions. Although hydrogel treatments showed minor variation (0.977–1.004), these differences were not statistically significant. The absence of a hydrogel effect indicates that the polymer does not alter biomass partitioning between roots and shoots. Instead, it promotes proportional growth of both organs, whereas drought alone shifts allocation toward roots, a classic adaptive strategy for water capture.

Table 3. Means for effect of moisture on root: shoot ratio and 100-seed weight of cowpeas

Treatment	R:S ratio	100-seed weight

Moderate Drought	1.0517[z]	19.80[z]
Well-watered	0.9306[y]	14.67[y]
Mean	0.9912	17.23
P value	<0.001	<0.001
CV%	4.1	7.9

Means in a column followed by the same letter are not significantly different at p < 0.05 (Fisher's LSD)

100-Seed weight

The ANOVA for 100-seed weight revealed a highly significant effect of moisture regime ($F_{1,18}$ = 105.67, p < 0.001), whereas hydrogel ($F_{4,18}$ = 1.05, p = 0.409) and the hydrogel × moisture interaction was not significant ($F_{4,18}$ = 1.14, p = 0.369). Interestingly, moderate drought (MD) resulted in higher 100-seed weight (19.80 g) compared with well-watered (WW) conditions (14.67 g), suggesting a compensatory response under moisture stress conditions.

Shelling percentage

Shelling percentage showed a significant moisture effect ($F_{1,18}$ = 93.50, p < 0.001) and, importantly, a significant hydrogel × moisture interaction ($F_{4,18}$ = 3.59, p = 0.026) was observed. However, the main effect of hydrogel was not significant ($F_{4,18}$ = 2.69, p = 0.065). Under well-watered conditions, shelling percentage was consistently high (grand mean 69.47%) and decreased with increasing hydrogel application rate from 74.33% (0 g) to 63.00% (0.4 g). Under moderate drought, shelling percentage was lower overall (grand mean 57.20%) and showed a less consistent pattern to hydrogel levels: 59.7% (0 g), 56.67% (0.1 g), 55.67% (0.2 g), 53.67% (0.3 g), and 60.33% (0.4 g) (Table 4). The significant interaction indicates that the effect of hydrogel on shelling percentage depended on the moisture regime. In well-watered plants, increasing hydrogel levels progressively reduced shelling percentage, possibly due to larger pod wall or seed coat development. In drought-stressed plants, the lowest shelling percentage occurred at 0.3 g hydrogel but showed a slight recovery at the highest application rate (0.4 g), suggesting a threshold response under water-limited conditions.

Table 4. Means for the interaction between hydrogel and moisture on shelling percentage of cowpeas

Hydrogel	Moderate Drought	Well-watered
0 g/kg soil	59.67[bc]	74.33[e]
0.1 g/kg soil	56.67[ab]	71.33[e]
0.2 g/kg soil	55.67[ab]	70.00[e]
0.3 g/kg soil	53.67[a]	68.67[de]
0.4 g/kg soil	60.33[bc]	63.00[cd]
Mean	63.33	
P value	0.026	
CV%	5.5	

Means followed by the same letter are not significantly different at p < 0.05 (Fisher's LSD)

Total seed weight per plant

Total seed weight per plant (g $plant^{-1}$) showed a significant effect of hydrogel ($F_{4,18}$ = 5.51, p = 0.004) but, importantly, no significant effect of moisture regime ($F_{1,18}$ = 1.07, p = 0.314) was observed. The interaction was also non-significant ($F_{4,18}$ = 1.66, p = 0.203). Hydrogel increased seed yield from 53.2 g (0 g) to 75.2 g (0.4 g). WW-treated plants yielded 64.5 g, while drought-stressed plants yielded 61.0 g, a difference of only 3.5 g that was not statistically significant. The lack of a moisture effect on total seed weight is remarkable and suggests that moderate drought during reproduction, when hydrogel is present, does not cause a net yield penalty. This is likely due to compensatory increases in individual seed mass that offset reductions in pod and seed numbers. Hydrogel at 0.4 g improved yield by 41% relative to the no-hydrogel (control), irrespective of moisture regime (Figure 2).

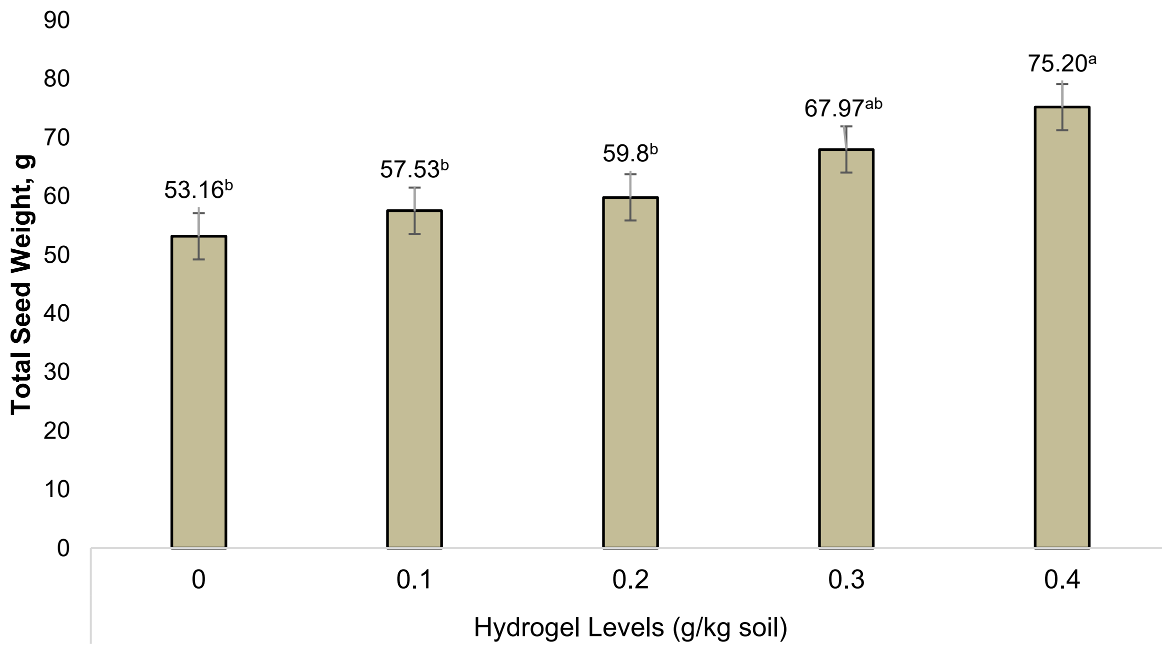

Figure 2. Means total seed weight (g) of cowpeas as influenced by hydrogel levels

DISCUSSION

The observed delays in days to 50% flowering (4.4 days between the 0 and 0.4 g hydrogel treatments) and days to physiological maturity (5.2 days) under increasing hydrogel rates, together with the drought-induced delays (4.0 days for flowering and 5.7 days for maturity), are consistent with the known function of superabsorbent polymers as water reservoirs that extend the soil moisture availability period. The observed delays in flowering (4.0 days), increased root:shoot ratio (from 0.93 to 1.05), and compensatory rise in 100-seed weight (from 14.7 g to 19.8 g) under the 45–55% FC regime (Tables 2–3) confirm that this moisture level imposed a physiologically meaningful moderate drought, consistent with previous characterisations of cowpea response to similar soil water deficits (Poudel et al., 2025). By maintaining a more favourable rhizosphere water potential, hydrogels allow plants to prolong vegetative growth before initiating reproduction, a phenomenon also reported in other legumes. For example, in a two-year field study on faba bean and pea, Czopek and Staniak (2025) found that superabsorbent polymer application significantly increased seed yield and, in pea, increased both pod number and seed number per plant under moisture-deficit conditions, suggesting that the extended moisture availability allowed more complete reproductive development. This is corroborated by Ostrand et al. (2020), who noted that SAPs improve and prolong soil water holding capacity and decrease drought stress by increasing the time between irrigation events.

The drought-induced delay in flowering (4.0 days) and maturity (5.7 days) observed in the present study aligns with the classic stress-avoidance strategy in cowpea, whereby the plant slows down developmental progression to conserve resources. However, the finding that hydrogel further delayed phenology even under drought indicates that the polymer does not simply “rescue” the plant from drought-induced earliness; rather, it actively maintains a more favourable water status that permits extended vegetative growth even when water is limiting. A global meta-analysis by Zheng et al. (2023) on superabsorbent polymers across multiple crops concluded that SAPs consistently improve soil water retention and crop yield, with the magnitude of benefit depending on application rate and environmental conditions. The 4-5-day phenological delay observed here is within the range considered agronomically acceptable for most short-duration cowpea varieties in semi-arid Zimbabwe, especially when it translates into higher biomass and yield. These findings align with the broader perspective offered by Ashraf et al. (2021), who emphasised that systematic field studies under arid and semi-arid conditions are needed to develop appropriate doses and methods for hydrogel application to various crops. As reviewed by Neetu et al. (2026), hydrogels improve root architecture development, vegetative growth and photosynthetic stability under water-limited conditions, and the present study provides direct experimental confirmation of these principles in cowpea.

The root:shoot ratio was unaffected by hydrogel but strongly elevated by moderate drought (1.052 vs. 0.931). This classic response, increasing root investment relative to shoot growth under water deficit, is an adaptive strategy to enhance water capture, as also documented by Narimani et al. (2024), who observed that increasing the amount of superabsorbent polymer to 100 kg/ha increased the chickpea competition ratio and improved yield advantage in cereal-legume intercropping systems under semi-arid conditions. The lack of a hydrogel effect on the root:shoot ratio suggests that while hydrogel improves both root and shoot growth proportionally, it does not trigger the additional morphological shift toward root dominance that drought alone induces. In other words, hydrogel-treated plants under drought behave more like well-watered plants in terms of biomass partitioning, which may explain why their seed yield was not significantly different from well-watered controls. According to the review by Piccoli et al. (2024), hydrogels have been consistently shown to improve the performance of legume crops under moderate water deficit, primarily by increasing plant-available water rather than by altering biomass allocation. The present study thus confirms that hydrogel acts primarily by improving overall plant vigour rather than by altering carbon allocation patterns.

Seeds per pod were significantly increased by hydrogel (from 10.4 to 13.2) and by well-watered conditions (12.9 vs. 10.5 under drought), with no interaction. The 2.4-seed reduction due to drought was alleviated by hydrogel at 0.4 g, drought-stressed plants produced 12.7 seeds per pod, which was not significantly different from well-watered plants under control conditions (12.2 seeds). This indicates that hydrogel can effectively buffer ovule abortion and seed set failure caused by moderate water stress. These results align with multiple studies on cowpea. Lopes et al. (2019) found that hydrogel concentrations between 15 and 18 kg/ha resulted in higher number of pods per plant, number of grains per pod, one-hundred-grain mass, and grain yield under water stress. Similarly, a greenhouse study on cowpea ('Sempre-verde' cultivar) reported that the highest hydrogel concentration (6 g/pot) produced the highest number of pods and yield across all hydrogel types tested, with HyC and Polim-Agro yielding 7.4 and 7.0 pods/plant and 15.43 and 16.68 g/plant, respectively (Lopes et al., 2017). Benard et al. (2025) further demonstrated that treatments with SAP increased cowpea yield, biomass, water productivity and harvest index by up to 137%, 17%, 10% and 117%, respectively, with the AquaCrop model validating these improvements. The strong moisture effect, well-watered plants outperforming drought-stressed ones in seeds per pod, indicates that even with hydrogel, moderate drought still imposes a residual stress that cannot be eliminated at the rates tested. Nevertheless, the additive benefit of hydrogel was clear at every hydrogel level; well-watered plants outperformed drought-stressed ones, but both groups improved with increasing hydrogel. This pattern is consistent with the meta-analysis by Zheng et al. (2023), who concluded that SAPs increase crop yield and water productivity across a wide range of soil and climatic conditions, with the effect being additive rather than synergistic with irrigation level. Halagalimath and Rajkumara (2018) reported that in chickpea, irrigation scheduled at 0.4 IW/CPE + 2.5 kg/ha hydrogel recorded higher grain yield (2136 kg/ha), further confirming the effectiveness of hydrogel in improving reproductive outcomes in legumes under water-limited conditions.

The ANOVA for 100-seed weight revealed a highly significant effect of moisture regimes ($p < 0.001$), whereas hydrogel application had no significant effect ($p = 0.409$). Moderate drought increased 100-seed weight to 19.80 g, compared to 14.67 g under well-watered conditions. This strong moisture effect indicates that under moderate drought, cowpea plants produced heavier individual seeds, a classic compensatory mechanism that offsets reductions in seed number. Lopes et al. (2019) explicitly reported that hydrogel concentrations between 15 and 18 kg/ha increased one-hundred-grain mass along with pod number and grain number, indicating that heavier seeds can compensate for fewer seeds under stress. The absence of a hydrogel effect on 100-seed weight suggests that the polymer did not directly influence individual seed mass beyond its indirect effect through improved plant water status. As highlighted by Sennhenn et al. (2017), early phenology together with adapted canopy architecture allowed more optimal water use and greater partitioning of dry matter into seed (higher harvest index), and the present study confirms that this mechanism operates independently of hydrogel application. The 41% yield increase with the 0.4 g/kg hydrogel rate is comparable to the 23.6% and 17.3% increases reported for faba bean and pea, respectively, at a 20 kg/ha SAP rate by Czopek and Staniak (2025). The higher magnitude in the present study may reflect the more severe baseline stress in the pot environment and the relatively high application rate used.

The significant interaction indicates that the effect of hydrogel on shelling percentage depended on the moisture regime. In well-watered plants, increasing hydrogel progressively reduced shelling percentage, possibly due to larger pod wall or seed coat development. In drought-stressed plants, the lowest shelling percentage occurred at 0.3 g hydrogel, with a slight recovery at 0.4 g. According to the meta-analysis by Zheng et al. (2023), the effects of SAP on yield components can be highly dependent on application rate and environmental conditions, and the present study extends this understanding by demonstrating a rate-dependent interaction with moisture regime. The practical implication is that while hydrogel consistently improves total seed yield, farmers should be aware that very high rates under well-watered conditions may slightly reduce shelling percentage, though the overall economic benefit remains strongly positive.

The most striking result is that total seed weight per plant was significantly increased by hydrogel (a 41% increase from 0 to 0.4 g/kg) but was not significantly affected by moisture regime ($p = 0.314$). This means that, under the conditions of this experiment, moderate drought imposed during the reproductive phase did not cause a statistically detectable reduction in final seed yield when averaged across hydrogel levels. This finding appears to contradict the strong moisture effects observed on yield components such as seeds per pod. The resolution lies in the compensatory increase in 100-seed weight under drought, which offset the reduction in seed number. The 41% yield increase with the 0.4 g/kg hydrogel rate is consistent with the findings of Jahan and Nassiri Mahallati (2020), who concluded that superabsorbent polymers can improve dry matter yield and seed yield in arid regions by enhancing water retention and reducing the negative impacts of dehydration stress. From a practical standpoint, this result indicates that hydrogel application at 0.4 g/kg soil can increase cowpea seed yield by approximately 40% and can completely offset the yield penalty associated with moderate drought during reproduction, making it a highly promising climate-smart tool for rain fed cowpea production. Ashraf et al. (2021) highlighted that the soil application of superabsorbent polymers is found to be a promising methodology in drought-prone areas, and that products like 'Pusa hydrogel' have been developed to conserve water and enhance crop productivity.

CONCLUSION

This study demonstrates that superabsorbent hydrogel applied at 0.4 g/kg soil significantly enhances cowpea productivity under both well-watered and moderate drought conditions. Superabsorbent hydrogels therefore represent an effective, climate-smart soil amendment for rain fed cowpea production in semi-arid environments. Future research should focus on multi-season field validation, residual effects, economic analyses, and synergy with drought-tolerant cowpea varieties.

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AUTHORS' CONTRIBUTIONS

Moses Mutetwa: Conceptualization (lead), Writing original draft (lead), visualization. **Clapperton Mapwanyire**: Conceptualization (support), writing original draft, project administration, supervision. **Christopher Muchati**: Conceptualization (support), writing original draft, project administration. **Nomagugu Elizabeth Mazilawa:** Conceptualization (support), Writing-review and editing. **Malvin Mateveke:** Writing-review and editing, project administration, supervision. **Varaidzo Odatte Gwatidzo:** Writing-review and editing. **Rutendo Monicah Zishiri:** Conceptualization (support), Writing original draft (support), Writing-review and editing, visualization**. Wonder Ngezimana:** Conceptualization (support), Writing original draft (support), validation, project administration, supervision.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable.

CONSENT FOR PUBLICATION

Not Applicable

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AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

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