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OPTIMIZING SOYBEAN PRODUCTIVITY IN RAINFED AGRICULTURE: SYNERGISTIC EFFECTS OF PUSA HYDROGEL AND FOLIAR NUTRIENT SPRAYS IN WATER-STRESSED ENVIRONMENTS

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ABSTRACT

Water scarcity, driven by climate change and rising demand, poses a critical challenge for agriculture globally. In India, where over 60% of agricultural land relies on rainfall, erratic weather patterns like delayed monsoon onset and early cessation worsen moisture stress, particularly in rainfed areas. Addressing this challenge requires the adoption of efficient soil-moisture conservation practices that enhance water retention and sustain crop productivity. This study explores the impact of Pusa hydrogel and foliar nutrient sprays on improving soybean productivity under rainfed conditions. The study evaluated the three levels of Pusa hydrogel and five levels of foliar nutrient spray. With the application of Pusa hydrogel, the results indicated a significant improvement in crop growth and yield. The application of Pusa hydrogel at 5.0 kg ha^{-1} recorded significantly higher plant height (115.4 cm), dry matter (55 q ha^{-1}) and LAI at 90 DAS (6.93) followed by application of Pusa hydrogel 2.5 kg ha $^{-1}$. A similar trend was observed in the yield attributes and yield with significantly higher number of pods plant^{-1} (22.11), number of seeds pod^{-1} (2.22), number of seeds plant^{-1} (46.7) seed yield (22.67 q ha^{-1}) and stover yield (42.28 q ha^{-1}) recorded under the application of Pusa hydrogel at 5.0 kg ha^{-1} followed by application of Pusa hydrogel 2.5 kg ha^{-1}. Among foliar nutrient sprays, application of thiourea (500 ppm) led to significantly higher plant height (120.9 cm), dry matter accumulation (59.9 q/ha) and LAI at 90 DAS (7.61) followed by application by vermiwash (1:10). Significantly higher seed yield of 24.68 q ha^{-1} was observed with the application of thiourea (500 ppm) followed by vermiwash (1:10) whereas higher stover yield of 43.05 q ha^{-1} was observed with the application of vermiwash (1:10) which was at par with thiourea. Using Pusa hydrogel at 5.0 kg ha^{-1} with thiourea (500 ppm) or vermiwash (1:10) considerably improves soybean growth and yield in rainfed settings. These findings show that hydrogel and foliar nutrition sprays can reduce water stress and boost agricultural yield in water-scarce areas. These interventions should be tested in long-term field experiments to determine their sustainability, farmer profitability, and application to other crops and agro-climatic zones. Exploring hydrogel's environmental impact and modifying foliar spray compositions could improve these methods for widespread implementation. Such innovations will help address global food security issues in shifting climates.

Keywords: Foliar nutrient sprays, Moisture conservation, Pusa hydrogel, Soybean, Thiourea, Vermiwash, Water deficits.

Introduction

Water shortage significantly constrains agricultural output worldwide, particularly in semi-arid and desert regions where soybean (*Glycine max* L.) is grown under rainfed conditions (Khatun *et al*., 2021). The rising frequency and severity of drought stress caused by climate change have required the implementation of novel soil moisture conservation methods. Hydrogels superabsorbent polymers that can retain substantial amounts of water are increasingly recognized for their potential to improve water use efficiency and crop output in conditions of low moisture availability (Zhu *et al*., 2024). Pusa hydrogel, a native formulation created by the Indian Agricultural Research Institute (IARI), has demonstrated effective results in enhancing soil water retention and alleviating the detrimental impacts of drought in legumes (IARI, 2012). Integrating this technology into traditional agronomic procedures can greatly enhance sustainable agriculture in at-risk habitats.

Pusa hydrogel, created by the Indian Agricultural Research Institute (IARI), is an environmentally sustainable polymer formulation that increases soil water retention, minimizes percolation losses, and enhances root activity in moisture-deficient environments (IARI, 2012). The application has demonstrated promising results in cereals such as wheat and sugarcane; however, its efficacy in legumes like soybean is less investigated, particularly under temperate Himalayan conditions. Simultaneously, foliar nutrient sprays including thiourea, urea, vermiwash, are under assessment as supplementary measures to alleviate drought impacts by enhancing photosynthetic efficiency and nitrogen metabolism (Premaradhya *et al*., 2018). Foliar applications offer essential nutritional support during key growth phases, improving plant resilience and productivity in response to abiotic stress.

Soybean (*Glycine max* L. Merrill) is a globally important oilseed crop, widely recognized for its superior nutritional profile and economic significance, earning it the title of the "golden bean" (Chishi *et al*., 2022). It serves as one of the most affordable and accessible sources of high-quality protein and vegetable oil (Qin *et al*., 2022).It contains approximately 40-42% protein, 18-20% oil rich in Omega-3 and Omega-6 fatty acids, and a balance of essential amino acids, minerals, and carbohydrates (Chauhan *et al*., 2005). However, resource degradation, particularly water scarcity, poses significant challenges to crop production. Water is crucial for crop growth and yield, yet only 3% of the world's water is freshwater, and as many as 87 countries are projected to face water scarcity by 2050. Although India has 16% of the world's population, the country possesses only 4% of the worlds freshwater resource (Dhawan, 2020). Approximately 82% of the rural Indian population lives in rainfed portions of the country, and India ranks 41st out of 181 countries in terms of water stress (Fan and Hazzel., 2000). Given that agriculture accounts for 85% of freshwater use (Kalhapure *et al*., 2016), the need for water conservation and efficiency in farming is urgent. To address this, super-absorbent polymers (SAPs), which retain and release water slowly, have been developed (Schacht, 2004). Indian scientists, recognizing SAPs' potential, created Pusa hydrogel, a semi-synthetic polymer designed to retain soil moisture (IARI, 2012). Additionally, foliar nutrient sprays provide quick nutrient delivery to plants, helping manage issues like flower senescence and poor pod filling in soybean. (Jamal *et al*., 2006). Flower Senescence and poor pod filling are the major drawbacks in soybean, which can be managed through foliar application of nutrient (Kumar *et al*., 2013). Foliar nutrient sprays represent a strategic approach to mitigate abiotic stresses and improve yield in legumes. Thiourea, recognized as a plant growth regulator, has been shown to enhance photosynthetic efficiency and nitrogen metabolism during drought conditions, leading to increased biomass and grain yield in chickpea and lentil (Premaradhya *et al*., 2018). Vermiwash, a liquid bio-stimulant produced from earthworm activity, has shown notable enhancements in nutrient uptake, chlorophyll levels, and yield characteristics across various crops, such as ground nut and brinjal (George *et al*., 2007; Sundararasu & Jeyasankar, 2014). Foliar applications enhance soil-based interventions such as hydrogels by delivering essential nutrients at crucial growth phases, thus improving crop resilience in water-deficit conditions. This study seeks to assess the combined impacts of Pusa hydrogel and foliar fertilizer applications on soybean growth, yield characteristics, and economic returns in rainfed circumstances. We intend to establish a sustainable strategy for smallholder farmers confronting persistent water shortages in the north-western Himalayas by amalgamating these two methodologies.

Material and Methods

Experimental site description

The experiment was conducted at Agronomy farm of Sher-e-Kashmir University of Agricultural sciences and technology of Kashmir, Faculty of Agriculture, Wadura which is situated at a latitude of 34 ^{o} 21' N, longitude of 74^{o} 23' E and an altitude of 1590 m above mean sea level during *Kharif* 2022 under rainfed conditions. During the period of study relevant weather data was collected from Metrological observatory located at Shalimar. The data noted revealed that the weekly minimum and maximum temperature ranged from 19.34 °C to 32.64 °C, with 448 mm of recorded rainfall as shown in Figure 1. The soil was silty clay loam in texture having neutral pH. With respect to available NPK, the soil was found to be medium, as given in Table 1.

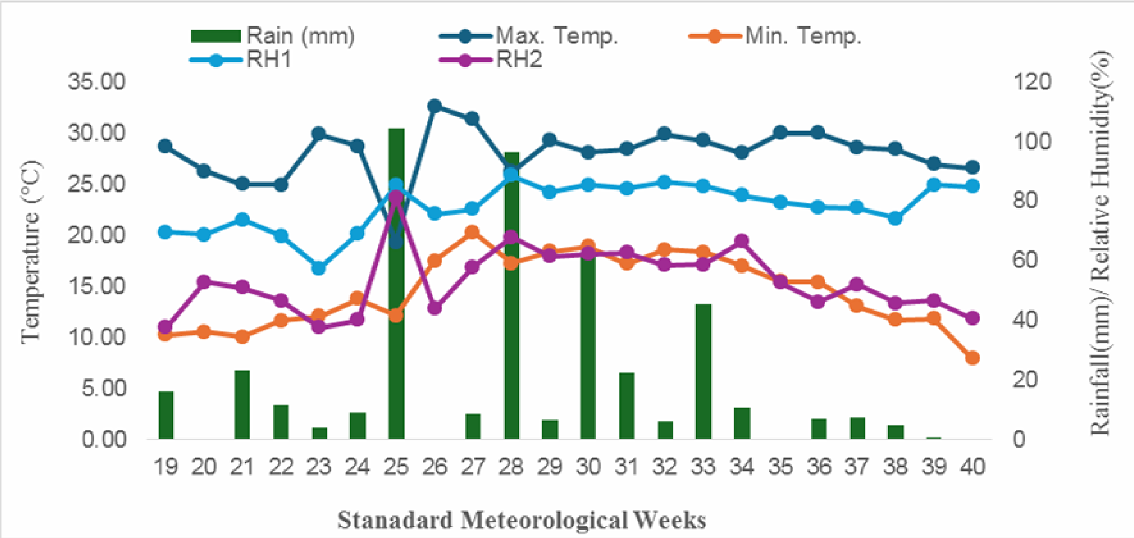

Fig. 1: Weekly meteorological observations during crop growing season of *Kharif* 2022

Table 1: Initial soil physicochemical properties of the experiment field

S. No	Parameter	Value	Remarks
1.	pH	6.7	Neutral
2.	Electric conductivity	0.25 Ds m^{-1}	Normal
3.	Organic carbon	0.75%	Medium
4.	Bulk density	1.32 g cm^{-1}	
5.	Texture	Silty clay loam	
6.	Available nitrogen	357 kg ha^{-1}	Medium
7.	Available phosphorous	17.2 kg ha^{-1}	Medium
8.	Available potassium	190 kg ha^{-1}	Medium

Experimental design:

The experiment consisted of two factors viz. Pusa hydrogel levels and foliar nutrient sprays with three levels of Pusa hydrogel (H_1: 0 kg ha^{-1}, H_2: 2.5 kg ha^{-1} and H_3: 5.0 kg ha^{-1}) and five levels of foliar nutrient sprays (F_1: control (no spray), F_2: water spray 500 l ha^{-1}, F_3: 2 % Urea, F_4: Thiourea 500 ppm and F_5: Vermiwash (1:10 ratio)). The experiment examined the effects of Pusa hydrogel and foliar fertilizer sprays on rainfed soybean (*Glycine max* L.) productivity using a factorial randomized block design (RBD) with three replications. These treatments produced 15 treatment combinations, reproduced three times, for 45 experimental plots. For each 4 m × 3 m plot, Shalimar Soybean-2 was employed, which thrives in the moderate climate of the north-western Himalayas. At sowing, Pusa hydrogel was completely mixed with the top 15 cm of soil for uniform distribution and moisture retention. Foliar sprays were used during flowering, when fertilizer demand is high and drought stress might reduce yield. To avoid confounding effects, all agronomic techniques, such as basal fertilizer application (20:60:40 kg $N:P_2O_5:K_2O$ ha^{-1}), weed management, and insect control, were uniform across all plots Plant height, dry matter accumulation, number of branches, leaf area index, pods per plant, seeds per pod, seed yield, stover production, and biological yield were recorded. Economics was used to calculate the cost-benefit ratio (BCR) of each treatment combination using input costs and market prices. This experimental arrangement examined Pusa hydrogel and foliar nutrition's main and interaction impacts, revealing their synergistic ability to boost soybean yield in moisture-limited settings.

Observations Recorded

Data collection was conducted methodically during the growing season to evaluate the effects of Pusa hydrogel and foliar fertilizer applications on the growth, yield, and physiological metrics of soybean (*Glycine max* L.). To achieve this objective, five plants were randomly chosen from each plot across all treatment combinations and replications. The plants were labelled and utilized for regular observations to guarantee consistency and precision in data collection. Observations were documented at consistent intervals (30-, 60-, 90-, and 120-days post-sowing) and at the time of harvest. The subsequent critical parameters were quantified: Plant height (cm), Number of branches per plant, Leaf area index (LAI), Dry matter accumulation (q ha^{-1}), Number of pods per plant, Number of seeds per pod, Seed index (weight of 100 seeds), seed yield, stover yield, and biological yield (kg ha^{-1}).

Statistical analysis: Statistical analyses were conducted using the OPStat software, which is specifically designed for agricultural research

Results and Discussion

Growth parameters

Crop growth parameters marked a significant variation with the levels of Pusa hydrogel with maximum plant height of 115.4 cm at harvest recorded with the application of Pusa hydrogel @ 5.0 kg ha^{-1} which was at par with the application of Pusa hydrogel @ 2.5 kg ha^{-1} (Table 2). Maximum dry matter accumulation of 55 q ha^{-1} at harvest and LAI at 90 DAS of 6.93 was recorded with the application of Pusa hydrogel @ 5.0 kg ha^{-1} which was at par with the application of Pusa hydrogel @ 2.5 kg ha^{-1}). The application of Pusa hydrogel ensures adequate availability of moisture which might have helped the plant to maximize nutrient uptake which led to the significant difference in the crop growth parameters. Fidelis *et al.*, 2018) reported Pusa hydrogel a good water retention polymer as it retains a high amount of water when incorporated in soil and releases it slowly, more, or less matching plant requirements, leading to better growth of plant. Due to retention of moisture availability of plant nutrients increased which might increase the activity of cell division, cell expansion and cell elongation, ultimately leading to better performance of plant. Increased dry matter production due to Pusa hydrogel application might be due to the better utilization of resources and light interception. El-Salmawi (2007) demonstrated that increased dry matter was attributed to an increase in protein, carbohydrate, and amino acid, particularly when highly absorbent polymers were used. This increase in protein, carbohydrate and amino acids might be due to the adequate availability of nutrients particularly N, P and K. Nitrogen facilitate nutrient absorption, resulting in rapid foliage development, enhanced photosynthate accumulation, and ultimately improved plant growth. Phosphorus is an important component of ATP, the molecule that gives energy to plants for processes including photosynthesis, protein synthesis, nutrient translocation, nutrient uptake, and respiration (Oladosu *et al.*, 2022). Phosphorus is essential for plant growth because it promotes root development, tillering, and early flowering, among other things. Unlike nitrogen and phosphorus, potassium is not an essential component of plant constituents. It promotes increased cell division, elongation, and expansion as a result of proper enzymatic activity in plants that have a sufficient K concentration. This might be attributed to rapid meristematic cell division and cell elongation due to adequate soil moisture and nutrient availability(Dingley *et al.*, 2024). The availability of important nutrients such as nitrogen, phosphate, and potassium is increased by hydrogel. Similar results were confirmed by Agbna, and Zaidi, 2025, Yazdani *et al*. (2008) in soybean. Leaf area index (LAI) gives a fair estimate of photosynthetic capacity of a plant, whenever plant faces water stress leaf area declines. Keeping the water retaining ability of Pusa hydrogel into consideration, it shows positive correlation with the levels of Pusa hydrogel. Pusa hydrogel maintains sufficient amount of water inside the cell as per the crop need thus causing increase in leaf area (Abdelghafar *et al.*, 2024, Ali *et al.*, 2024, Yazdani *et al.*, 2007). A similar pattern was observed in number of branches with significantly higher number of branches (24.64) recorded with the application of Pusa hydrogel @ 5.0 kg ha^{-1} which was at par with the application of Pusa hydrogel @ 2.5 kg ha^{-1} with 23.22 number of branches.

Among the foliar nutrient sprays, the treatment F_4: thiourea 500 ppm recorded significantly higher plant height at harvest (120.9 cm) and dry matter accumulation of 59.9 q ha^{-1} at harvest which was at par with F_5 (vermiwash) 116.0 cm (Table 2). Application of thiourea increased plant height greatly due to the presence of two key elements, nitrogen and sulphur, which encourage plant vegetative development. Nitrogen, as a necessary component of genetic material and other key macromolecules, promotes plant growth. It also increases the synthesis of hormones such as auxin and cytokinin, which aid in cell development and division, resulting in a rise in plant height. Thiourea's sulphur content aided in protein production and influenced the growth of the treated plants. These findings endorse those of Meena *et al*., 2023 Fiaz *et al*., 2024, Amin *et al*. (2014), and Bangar *et al*. (2019) also observed similar trend. Plant dry matter accumulation correlates positively with plant height, hence the treatment effect that raised plant height must have an essential role in enhancing plant dry matter accumulation. Nitrogen application via thiourea increased chlorophyll content, and along with sulphur, nitrogen may have aided in increasing protein production, resulting in better plant growth and increased dry matter accumulation under the influence of foliar thiourea application (Bangar *et al*. (2019). Similar results were confirmed by Garg *et al*. (2006), Jagetiya *et al*. (2006), and Premaradhya *et al*. (2018).

The application of F_4: thiourea 500 ppm had significantly increased the number of branches to 29.46 at harvest which were at par with vermiwash (26.24) followed F_3: 2% urea, F_2: water spray and F_1: control. The application of thiourea increases chlorophyll content, net rate of photosynthesis, starch, and reductase activity (Garg *et al*., 2006, Ahmad *et al*., 2024). Therefore, it could be due to the increased chlorophyll content which might lead to high production of photosynthates and eventually increased number of branches. Foliar nutrient sprays had a significant effect on LAI at 90 DAS with higher value of 7.61 recorded with treatment F_4: thiourea 500 ppm which was at par with F_5: vermiwash with a value of 7.12 followed by F_3: 2% urea, F_2: water spray and F_1: control (Table 2). The maximum leaf area due to the application of thiourea 500 ppm might be due to the presence of nitrogen which could help the plant to have substantial vegetative growth. This result is in conformity with the Zahid *et al*., 2024 and Solanki (2002).

Table 2: Effect of Pusa hydrogel and foliar nutrient spray on growth parameters of soybean.

Treatment	Plant height (cm)	Dry matter accumulation (q ha^{-1})	No. of branches	Leaf area index at 90 DAS
Pusa Hydrogel (kg ha^{-1})				
H1: 0	100.8	48.6	19.66	5.64
H2: 2.5	109.2	53.3	23.22	6.58
H3: 5.0	115.4	55.0	24.64	6.93
SEm±	1.7	1.08	0.83	0.20
CD (p≤0.05)	5.1	3.12	2.39	0.59
Foliar nutrient spray				
F_1: Control	97.7	44.5	15.21	5.40
F_2: Water	99.8	47.4	17.77	5.51
F_3: 2% Urea	107.8	52.2	22.26	6.30
F_4: Thiourea@500 ppm	120.9	59.9	29.46	7.61
F_5: Vermiwash	116.0	57.4	27.84	7.12
SEm±	2.3	1.39	1.07	0.26
CD (p≤0.05)	6.5	4.03	3.09	0.77

Yield Parameters

Table 3 presents the yield parameter data, showing that Pusa hydrogel significantly enhanced soybean yield attributes. With increase in the levels of Pusa hydrogel the yield parameters showed a positive trend. The number of pods plant^{-1}, seeds pod^{-1}, seeds plant^{-1} showed significant differences with the levels of Pusa hydrogel and all these parameters increase with increase in the levels of Pusa hydrogel. Significantly higher pods per plant was observed with treatment H_3: 5.0 kg ha^{-1} (22.11) per plant however it was at par with treatment H_2: 2.5 kg ha^{-1} (21.51). The results depict that there was 10.85% increase of pods per plant as compared to control plot. Among the foliar nutrients sprays treatment F_5 vermiwash (1:10) recorded significantly maximum number of pods plant^{-1} (24.37) followed by F_4: thiourea 500 ppm (22.69), F_3: 2% urea (20.88), F_2: water, F_1: control. Similarly, number of seeds pod^{-1} and seeds plant^{-1} recorded similar response with maximum seeds pod^{-1} (2.22) and seeds plant^{-1} (46.65) in treatment H_3: 5.0 kg ha^{-1}.

With respect to foliar nutrient sprays treatment F_5 @ vermiwash (1:10) recorded significantly highest seeds pod^{-1} (2.20) and seeds plant^{-1} (55.1) followed F_4: thiourea 500ppm, F_3: 2% urea, F_2: water and F_1: control. Seed index showed non-significant difference both with the levels of hydrogel and foliar nutrient sprays. This increase could be due to the sufficient availability of moisture and nutrients which invigorate the biomass per plant which eventually leads to increased growth and physiological parameters of plant. In addition to this sufficient availability of moisture and indirectly nutrients lead to better translocation of nutrients, water and photosynthates which increases yield attributing parameters. Similar results were recorded by Sivapalan (2006) in soybean, Yazdani *et al.*, (2007) in soybean and Mondal (2011) in pigeon pea. Increase in yield due to foliar application of vermiwash which contains major and micronutrients resulted in translocation of photosynthates towards the seeds and eventually lead to increase in yield and yield attributes. In addition to this vermiwash contain enzymes and growth regulators which enhance the yield of plant. Vermiwash contains micro and macro nutrients, hormones which promote plant growth and yield (Sharma *et al.*, 2005).

Table 3: Effect of Pusa hydrogel and foliar nutrient spray on yield attributes of soybean.

Treatment	Pods plant^{-1}	Seeds pod^{-1}	Seeds plant^{-1}	Seed index
Pusa Hydrogel (kg ha^{-1})				
H_1: 0	19.71	1.48	33.6	20.44
H_2: 2.5	21.51	2.03	43.1	21.96
H_3: 5.0	22.11	2.22	46.7	22.17
SEm±	0.41	0.07	1.91	0.52
CD (p≤0.05)	1.19	0.22	5.53	NS
Foliar nutrient spray				
F_1: Control	18.64	1.61	30.8	20.62
F_2: Water	18.98	1.65	31.9	20.52
F_3: 2% Urea	20.88	2.01	39.9	21.64
F_4: Thiourea@ 500 ppm	22.69	2.09	47.9	22.21
F_5: Vermiwash	24.37	2.20	55.1	22.64
SEm±	0.53	0.10	2.47	0.68
CD (p≤0.05)	1.53	0.28	7.14	NS

Yield

The yield showed positive results with respect to the levels of Pusa hydrogel and significantly maximum seed yield, stover yield and biological yield was observed with treatment H_3: 5.0 kg ha^{-1} (22.67 q ha^{-1}), (42.28 q ha^{-1}), (64.95 q ha^{-1}) respectively which was at par with H_2: 2.5 kg ha^{-1} significantly varying from control. Among the foliar nutrient sprays' treatment F_5: vermiwash (1:10) recorded maximum seed yield of (24.68 q ha^{-1}), which was at par with F_4: thiourea 500ppm (23.07 q ha^{-1}) followed by F_3: 2 % urea while the application of water spray was at par with control. However, with respect to stover and biological yield treatment F_4 thiourea 500 ppm recorded highest stover and biological yield (44.68q ha^{-1}), (67.75 q ha^{-1}) respectively (Table 4). This increase might be due to excessive vegetative growth. It has been observed that thiourea application increases chlorophyll content of leaves hence net rate of photosynthesis, starch synthesis and eventually the growth of plant (Garg *et al.*, 2006, *Nahar et al.*, 2024).

Table 4: Effect of Pusa hydrogel and foliar nutrient spray on yield of soybean.

Treatment	Seed yield (q ha^{-1})	Stover yield (q ha^{-1})	Biological yield (q ha^{-1})
Pusa hydrogel (kg ha^{-1})			
H_1: 0	19.81	36.44	56.25
H_2: 2.5	21.76	40.99	62.75
H_3: 5.0	22.67	42.28	64.95
SEm±	0.40	1.00	1.17
CD (p≤0.05)	1.16	2.89	3.40
Foliar nutrient sprays			
F_1: Control	18.80	35.03	53.82
F_2: Water	19.25	36.45	55.70
F_3: 2% Urea	21.28	40.30	61.58
F_4: Thiourea@ 500 ppm	23.07	44.68	67.75
F_5: Vermiwash	24.68	43.05	67.73
SEm±	0.52	1.29	1.52
CD (p≤0.05)	1.49	3.73	4.39

Conclusion

This study's results indicate that the incorporation of Pusa hydrogel and foliar nutrient sprays markedly improves soybean development, growth, yield and yield attributes in rainfed circumstances of the north-western Himalayan region. The maximum tested dose of Pusa hydrogel (5.0 kg ha^{-1}) consistently surpassed smaller doses in enhancing plant height, dry matter accumulation, branch count per plant, and leaf area index (LAI). These enhancements result from improved soil moisture retention and nutrient accessibility, which facilitate root growth and photosynthetic efficacy during the growing season. Among foliar fertilizer treatments, thiourea at 500 ppm exhibited the most pronounced favourable effect on growth metrics, succeeded by vermiwash at a 1:10 dilution. Thiourea's efficacy is probably attributed to its function in augmenting chlorophyll synthesis and nitrogen metabolism, leading to enhanced biomass output and improved physiological performance. Vermiwash has also had a beneficial impact, perhaps attributable to its abundant presence of plant growth regulators, including auxins and cytokinin. The combination of H_3 (5.0 kg ha^{-1} Pusa hydrogel) and F_5 (vermiwash 1:10) produced the maximum seed production, stover yield, and biological yield demonstrating a synergistic effect of soil moisture conservation and foliar nutrition. These outcomes carry important implications for strengthening climate-resilient farming systems in the north-western Himalayas.

Conflicts of interest: The authors declare that they have no conflict of interest.

Authors' contributions

SAB, and FAB: conceived and designed the project; SAB, FAB, WR, FW, KR, SQ, , BJ, BN, MG: analyzed, wrote, revised and proofread the manuscript. All authors contributed to the article and read and approved the final manuscript.

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