

FROM FRUIT BIOWASTE TO FIELD-SCALE WATER SAVINGS: EVALUATING A NATURAL SUPERABSORBENT POLYMER FOR IMPROVED IRRIGATION PRACTICES AND WATER INPUTS

DES BIODÉCHETS FRUITIERS AUX ÉCONOMIES D'EAU À L'ÉCHELLE DE LA PARCELLE: ÉVALUATION D'UN POLYMÈRE SUPERABSORBANT NATUREL POUR AMÉLIORER LES PRATIQUES D'IRRIGATION ET LES APPORTS EN EAU

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ABSTRACT

Agriculture accounts for approximately 70% of global freshwater use, rising to over 80% in arid regions, where water scarcity endangers food production amid climate variability, depleting groundwater, and rising demands. Conventional irrigation methods in crops like wheat, tomato, and okra suffer from high losses via evaporation and percolation, reducing water use efficiency (WUE) and yields in semi-arid areas. Superabsorbent polymers (SAPs) offer a viable solution by enhancing soil water retention, but sustainable bio-based variants are needed to minimize environmental impacts. This study assessed Fasal Amrit, a bio-SAP from fruit waste, in field trials on wheat (Rabi 2022-23), tomato, and okra in India using randomized block designs. SAP doses ranged from 0-20 kg ha⁻¹, combined with varying irrigation regimes (IW/CPE 1.0-0.6 for tomato; 3–7-day intervals for okra; five irrigations for wheat and fertilizer levels of Recommended Dose of Fertilizer (RDF) at 100% or 85% RDF. Key metrics encompassed growth, yield, WUE, soil moisture, nutrient uptake, and economics, analyzed via ANOVA and Duncan's test ($p < 0.05$). In wheat, 20 kg ha⁻¹ SAP with RDF reduced water use by 19% (66.33 acre-inches vs. 81.66 in control), increased soil moisture to 23.73%, and raised grain yield to 42.86 q ha⁻¹ (12% gain), with net returns of Rs. 58,233 ha⁻¹ and B:C ratio of 1.83. Tomato at 20 kg ha⁻¹ and 0.6 IW/CPE achieved 21.66 t ha⁻¹, matching controls while saving 40% water. Okra with 20 kg ha⁻¹ extended intervals to 7 days, yielding 136.83 q ha⁻¹ (10% increase) and WUE of 304.07 kg ha⁻¹ cm⁻¹. Seedling tests delayed wilting by 15 days. A laboratory hygroscopic study with 1% EF Polymer in soil showed higher residual moisture over a 12-day drying period while sustaining viable bacterial populations, suggesting compatibility with soil microbial activity. Bio-SAPs improve water retention, yields, and profitability across crops, offering scalable solutions for water-scarce farming. Doses of 15-20 kg ha⁻¹ are recommended for rainfed and irrigated systems in arid zones.

Keywords: Superabsorbent polymer, Sustainability, Irrigation efficiency, Water use efficiency, Soil moisture retention, Nutrient uptake.

RÉSUMÉ

L'agriculture représente environ 70 % de l'utilisation mondiale d'eau douce, et cette proportion dépasse 80 % dans les régions arides, où la rareté de l'eau menace la production alimentaire dans un contexte de variabilité climatique, d'épuisement des eaux souterraines et de demande croissante. Les méthodes d'irrigation conventionnelles appliquées à des cultures telles que le blé, la tomate et le gombo subissent d'importantes pertes par évaporation et percolation, ce qui réduit l'efficacité d'utilisation de l'eau (WUE) et les rendements dans les zones semi-arides. Les polymères superabsorbants (SAP) offrent une solution viable en améliorant la rétention de l'eau dans le sol, mais des variantes biosourcées durables sont nécessaires pour réduire au minimum les impacts

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environnementaux. Cette étude a évalué Fasal Amrit, un bio-SAP issu de déchets de fruits, lors d'essais au champ sur le blé (Rabi 2022-2023), la tomate et le gombo en Inde, selon des dispositifs en blocs randomisés. Des doses de SAP comprises entre 0 et 20 kg ha⁻¹ ont été associées à différents régimes d'irrigation (IW/CPE de 1,0 à 0,6 pour la tomate ; intervalles de 3 à 7 jours pour le gombo ; cinq irrigations pour le blé) et à des niveaux de fertilisation correspondant à 100 % ou 85 % de la dose d'engrais recommandée (RDF). Les principaux paramètres comprenaient la croissance, le rendement, la WUE, l'humidité du sol, l'absorption des éléments nutritifs et les résultats économiques ; ils ont été analysés par ANOVA et au moyen du test de Duncan ($p < 0,05$). Chez le blé, l'application de 20 kg ha⁻¹ de SAP avec la RDF a réduit l'utilisation d'eau de 19 % (66,33 acre-pouces contre 81,66 pour le témoin), porté l'humidité du sol à 23,73 % et accru le rendement en grains à 42,86 q ha⁻¹ (gain de 12 %), avec des recettes nettes de 58 233 Rs. ha⁻¹ et un rapport bénéfices/coûts (B:C) de 1,83. Pour la tomate, la combinaison de 20 kg ha⁻¹ et d'un rapport IW/CPE de 0,6 a permis d'obtenir 21,66 t ha⁻¹, soit un rendement équivalent à celui des témoins tout en économisant 40 % d'eau. Pour le gombo, 20 kg ha⁻¹ ont permis de porter l'intervalle d'irrigation à 7 jours, avec un rendement de 136,83 q ha⁻¹ (hausse de 10 %) et une WUE de 304,07 kg ha⁻¹ cm⁻¹. Les essais sur les plantules ont retardé le flétrissement de 15 jours. Une étude hygroscopique en laboratoire, réalisée avec 1 % d'EF Polymer dans le sol, a révélé une humidité résiduelle plus élevée pendant une période de séchage de 12 jours, tout en maintenant des populations bactériennes viables, ce qui suggère une compatibilité avec l'activité microbienne du sol. Les bio-SAP améliorent la rétention de l'eau, les rendements et la rentabilité de différentes cultures, et offrent ainsi des solutions transposables à grande échelle pour l'agriculture confrontée à la rareté de l'eau. Des doses de 15 à 20 kg ha⁻¹ sont recommandées pour les systèmes pluviaux et irrigués des zones arides.

Mots clés : Polymères superabsorbants; Durabilité; Efficacité de l'irrigation; Efficacité de l'utilisation de l'eau ; Rétention d'humidité du sol; Eléments nutritifs.

Introduction

Water scarcity poses a profound threat to global agriculture, which relies on irrigation for about 40% of food production yet consumes roughly 70% of available freshwater worldwide (FAO, 2021; Mancosu et al., 2015). In arid and semi-arid regions, this dependency intensifies as populations grow and climate change disrupts rainfall patterns, leading to aquifer depletion and salinization. Projections indicate that by 2050, over 5 billion people could face water shortages, with agricultural yields potentially declining by 10-20% without adaptive measures (Kummu et al., 2012). Staples like wheat, a cornerstone of diets in South Asia and the Middle East, demand consistent moisture during critical growth phases, yet conventional flood or furrow irrigation often results in 50-60% losses through evaporation and deep percolation, exacerbating inefficiencies (Kinzelbach et al., 2011).

For vegetable crops such as tomato and okra, the challenges are equally acute. These high-value horticultural plants, vital for nutritional security and income in developing economies, require frequent watering to support fruit development, but erratic supplies in rainfed systems lead to blossom-end rot in tomatoes or pod cracking in okra (Al-Omran et al., 2023). In India, where these crops occupy millions of hectares, traditional methods like surface irrigation waste up to 70% of applied water, particularly on sandy-loam soils prone to rapid drainage (Comas et al., 2019). Semi-arid zones like Rajasthan experience prolonged dry spells, compounding yield variability and forcing farmers to over-irrigate, which depletes groundwater and increases salinity-issues that could reduce tomato productivity by 25% under deficit conditions (Lu et al., 2019).

Superabsorbent polymers (SAPs) have emerged as innovative soil amendments to address these irrigation bottlenecks. These hydrophilic materials, capable of absorbing and retaining 100-1000 times their weight in water, form hydrogels that swell in moist soil and deswell gradually, supplying roots during dry periods (Bortolin et al., 2013). By increasing the soil's water-holding capacity, SAPs mitigate evaporation from surface layers and reduce leaching of nutrients beyond the root zone, potentially extending irrigation intervals by 20-50% (Bortolin et al., 2013). Their mechanisms involve osmotic retention, where absorbed water is held against gravitational forces, and vapor diffusion control, which

limits losses in the topsoil (Takahashi et al., 2023). In sandy soils, common in arid agriculture, SAPs can elevate available water by 30-40%, fostering root proliferation and drought tolerance without altering soil structure permanently (Banedjschafie & Durner, 2015).

Prior field trials underscore SAPs' potential for yield and WUE enhancements. In wheat, applications of 10-30 kg ha⁻¹ polyacrylamide-based SAPs have boosted grain yields by 15-25% and WUE by 30% under limited irrigation, as seen in Iranian semi-arid fields where water savings reached 25% (Du et al., 2025). Similarly, starch-g-polyacrylate variants improved tomato fruit set by 20% in deficit-irrigated plots in China, reducing evapotranspiration (ET) by 18% through sustained soil moisture (Toscano et al., 2023). For okra, Egyptian studies reported 12-18% pod yield increases with 15 kg ha⁻¹ SAPs, alongside 35% lower water inputs, attributing gains to decreased leaching and enhanced nutrient availability (El-Rehim et al., 2004). These benefits extend to economic viability, with benefit-cost ratios often exceeding 2:1 in resource-constrained settings (Mehrabi & Sepaskhah, 2020).

Despite these advances, significant limitations persist, particularly in arid and semi-arid regions. Synthetic SAPs, such as cross-linked polyacrylamides, degrade slowly and may release monomers toxic to soil microbes and crops, posing risks in edible produce (Neethu et al., 2018). Bio-based SAPs from renewable sources like cellulose or starch offer biodegradability but have been tested mainly in controlled environments, with scant data on long-term field performance across diverse soils and climates (Zohuriaan-Mehr et al., 2010).

Variability in SAP efficacy—dependent on soil texture, pH, and salinity—remains underexplored; for instance, performance drops in high-clay soils due to reduced swelling (Bisbis et al., 2019). Moreover, few studies integrate SAPs with reduced fertilizer applications or multi-crop rotations, overlooking synergies for smallholder farmers in India, where water and input costs dominate (Zhao et al., 2021). Gaps also exist in vegetable-specific trials, where hormonal responses to moisture stress interact uniquely with SAP-released water, and in assessing microbial impacts under variable rainfall (Damiri et al., 2023).

Addressing these voids requires expanded research on eco-friendly SAPs tailored to regional conditions, emphasizing mechanisms like reduced ET and leaching while evaluating climate dependencies. Such insights could guide scalable adoption, bridging the irrigation efficiency divide in water-stressed agroecosystems.

Materials and Methods

Field trials were conducted at two sites in India during 2022: the BAIF Development Research Foundation Central Research Station in Uruli Kanchan, Pune (18°30'N, 73°50'E; 600 m elevation), for wheat, and Maharana Pratap University of Agriculture and Technology (MPUAT) in Udaipur, Rajasthan (24°35'N, 73°42'E; 580 m elevation), for tomato and okra. Pune features a semi-arid climate with clay soils (pH 7.5, EC 0.4 dS m⁻¹, organic carbon 0.46%, available N 125 kg ha⁻¹, P 22 kg ha⁻¹, K 173 kg ha⁻¹), while Udaipur has loamy soils (pH 7.8-8.2, medium fertility). Rainfall was minimal (150-200 mm during trials), relying on supplemental irrigation from tube wells.

Measurements for all crops included: growth (plant height, tillers/spikelets at 50% flowering/maturity); yield (grain/fruit/pod weight at harvest, test weight); water use (V-notch weir for volume per irrigation, converted to acre-inches; 1 acre-inch = 102,790 L). Soil moisture (%) was gauged pre-irrigation and at harvest using a digital meter (0-10 cm depth). Nutrient uptake involved plant analysis (Kjeldahl for N, spectrophotometry for P/K) from maturity samples. Soil post-harvest samples (0-15 cm) assessed pH, EC, OC, and nutrients via standard lab methods (BAIF soil lab). Economics calculated gross returns (yield × market price: wheat Rs. 25,000 q⁻¹, tomato Rs. 1,000 t⁻¹, okra Rs. 9,000 q⁻¹), costs (inputs/labor), net returns, and B:C ratio. Seedling stress tests (wheat/maize) withheld water post-emergence, recording wilting days and height at 20 DAS.

The experiment to evaluate the effect of 1% EF Polymer (EFP) on soil moisture retention and bacterial survival was conducted under controlled laboratory conditions. Two soil samples, each weighing 800 g and forming approximately 2 cm thick layers, were prepared in separate bowls. One sample was

amended with 8 g of agriculture-grade EF Polymer thoroughly mixed into the soil, while the other served as the untreated control. Both samples were saturated with water at the start of the experiment, and no additional water was added during the subsequent drying period. The soil samples were allowed to dry naturally in the laboratory environment over 12 days.

Soil moisture content was measured daily using a standard soil moisture meter at a depth consistent across samples. Live bacterial counts per gram of soil were determined every four days using the plate count method to assess microbial viability. Initial measurements for soil moisture and bacterial populations were recorded at the start of the experiment. All measurements were conducted in triplicate, and average values were calculated. Standard deviations were used to indicate variability among replicates.

Data were analyzed using ANOVA in SPSS (v.25); means separated by Duncan's multiple range test ($p < 0.05$). WUE was yield/water applied ($\text{kg ha}^{-1} \text{ cm}^{-1}$, assuming 1 acre-inch ≈ 6.45 cm effective depth). Lab moisture retention used 1% SAP in 800 g soil, dried 12 days, with bacterial counts via plate method every 4 days.

Crop-wise Experimental Details

Table 1. Wheat experimental details

Parameter	Description
Crop	Wheat (<i>Triticum aestivum</i> L., cv. Lokwan)
Sowing date	6 December 2022
Harvest date	14 March 2023
Crop duration	98 days
Design	RBD, 3 replications
Plot size	4 m $\times$ 3 m (net: 3.8 m $\times$ 2.5 m)
Row spacing	25 cm
Land configuration	Flat beds

Table 2. Wheat treatments details

Treatment	Description
T1	Control (RDF 120:60:40 kg N:P: K ha^{-1})
T2	100% RDF + SAP @ 12.5 kg ha^{-1}
T3	100% RDF + SAP @ 15 kg ha^{-1}
T4	100% RDF + SAP @ 20 kg ha^{-1}
T5	85% RDF + SAP @ 12.5 kg ha^{-1}
T6	85% RDF + SAP @ 15 kg ha^{-1}
T7	85% RDF + SAP @ 20 kg ha^{-1}

Table 3. Tomato experimental details

Parameter	Description
Crop	Tomato (<i>Solanum lycopersicum</i> L., local hybrid)
Transplanting	Late September 2022
Design	RBD, 3 replications
Plot size	3 m $\times$ 2 m
Spacing	60 cm $\times$ 30 cm
Irrigation method	Drip (based on CPE)

Table 4. Tomato treatments details

Treatment No.	IW/CPE Ratio	Fasal Amrit Dose (kg ha ⁻¹)
T1	0.6	0
T2	0.8	0
T3	1.0	0
T4	0.6	10
T5	0.8	10
T6	1.0	10
T7	0.6	15
T8	0.8	15
T9	1.0	15
T10	0.6	20
T11	0.8	20
T12	1.0	20

Table 5. Okra experimental details

Parameter	Description
Crop	Okra (<i>Abelmoschus esculentus</i> L.)
Cultivar	Arka Anamika
Experimental site	Maharana Pratap University of Agriculture & Technology (MPUAT)
Season/Year	Kharif 2022
Transplanting time	Mid-July 2022
Experimental design	Randomized Block Design (RBD)
Number of replications	3
Plot size	4 m × 3 m
Spacing	60 cm × 30 cm
Irrigation method	Furrow irrigation
Recommended fertilizer dose (RDF)	100:50:50 kg N:P: K ha ⁻¹

Table 6. Okra treatments details

Treatment No.	Irrigation Interval (days)	SAP Dose (kg ha ⁻¹)
T1	3	0
T2	5	0
T3	7	0
T4	3	10
T5	5	10
T6	7	10
T7	3	15
T8	5	15
T9	7	15
T10	3	20
T11	5	20
T12	7	20

Results

The bio-super absorbent polymer (bio-SAP) Fasal Amrit significantly influenced crop growth, yield attributes, water-use efficiency, nutrient dynamics, and economic returns under varying irrigation regimes. However, the magnitude of response varied among crops depending on dose, irrigation scheduling, and crop physiology.

In wheat, plant height at maturity ranged from 64.63 cm in T2 to 69.34 cm in T4, although the differences were statistically non-significant (Table 7). Similarly, tillers per plant increased from 5.27 in T1 to 6.80 in T4, but high variability among treatments limited statistical significance. Spike length showed only marginal variation (7.77–8.32 cm), whereas spikelets per plant increased significantly from 12.93 in T1 to 14.20 in T4 and T7 (CD = 1.01). Grains per spike also improved, reaching 41.67 in T7 compared with 37.53 in T1. These improvements in reproductive attributes indicate that bio-SAP application enhanced moisture availability during critical growth stages, thereby sustaining assimilate partitioning and reproductive development under limited water conditions. Similar observations were reported by Mehrabi and Sepaskhah (2020), who documented enhanced spike development and grain formation in wheat due to improved soil moisture retention by hydrogel amendments.

Table 7: Effect of different treatments on growth parameters of wheat at maturity

Treatment	Plant height (cm)	No. of Tillers/plant	Spike length (cm)	No. of spikelets	No. of grain per spike
T1	64.92	5.27	7.84	12.93	37.53
T2	64.63	5.07	8.32	12.60	37.93
T3	65.74	5.40	8.08	13.33	40.13
T4	69.34	6.80	8.23	14.20	41.27
T5	65.67	5.87	7.79	13.40	40.00
T6	65.51	5.67	7.77	13.20	39.27
T7	67.95	6.20	8.17	14.20	41.67
SE(m)+	2.25	0.46	0.16	0.33	1.00
CD at 5 %	NS	NS	NS	1.01	NS
CV %	5.88	13.60	3.39	4.20	4.39

Grain yield increased significantly with SAP application, reaching a maximum of 42.86 q ha⁻¹ in T4, representing a 12% increase over the control (38.15 q ha⁻¹) (CD = 2.00; Table 8). Straw yield was highest in T3 (66.80 q ha⁻¹), although treatment effects remained non-significant. Test weight improved significantly from 4.71 g in T1 to 5.53 g in T7 (CD = 0.37), indicating improved grain filling under enhanced soil moisture conditions. The yield enhancement observed in the present study corroborates findings of Du et al. (2025), who reported improved wheat productivity and water-use efficiency under SAP-mediated moisture conservation. The comparatively lower dose requirement in the present investigation suggests greater efficiency of the bio-based SAP formulation under clay loam soils, possibly due to improved biodegradability and compatibility with soil microbial activity as also indicated by Neethu et al. (2018).

Application of Fasal Amrit substantially reduced irrigation water requirements. Total water applied declined from 81.66 acre-inches in the control to 66.33 acre-inches in T4 (Table 9), with marked reductions observed during successive irrigations. For instance, water applied during the fourth irrigation decreased from 17.99 acre-inches in T1 to 11.70 acre-inches in T4. Pre-irrigation soil moisture content remained consistently higher under SAP-treated plots, reaching 32.67% in T4 before the fourth irrigation, while average soil moisture increased from 19.48% in the control to 23.73% in T4 (Table 10). These findings confirm the water-buffering capacity of bio-SAPs, which absorb and gradually release water into the rhizosphere, thereby reducing evapotranspiration and maintaining soil moisture for longer durations. Similar reductions in irrigation demand and enhanced water-use

efficiency were reported by Zou et al. (2012), who attributed the effect to reduced deep percolation losses and improved soil water retention.

Table: 8 Effect of different treatments on yield and yield attributing parameter

Treatment	Grain yield (q ha ⁻¹)	Straw yield (q ha ⁻¹)	Test weight (g.)
T1	38.15	59.56	4.71
T2	40.40	59.14	5.12
T3	41.59	66.80	5.27
T4	42.86	60.37	5.10
T5	39.91	59.71	5.04
T6	41.07	65.85	5.26
T7	42.01	63.78	5.53
SE(m)±	0.64	3.03	0.12
CD at 5 %	2.00	NS	0.37
CV %	2.72	8.45	3.99

Table 9: Effect of different treatments on the total amount of water given to wheat

Treatment	First irrigation	Second irrigation	Third irrigation	Fourth irrigation	Fifth irrigation	Total
T1	19.74	15.90	11.09	17.99	16.95	81.66
T2	15.41	11.98	13.15	14.91	15.38	70.83
T3	12.08	17.21	11.95	16.27	15.76	73.26
T4	13.68	14.86	13.59	11.70	12.50	66.33
T5	12.16	15.42	14.83	15.38	16.47	74.26
T6	13.77	14.80	12.41	14.95	16.40	72.33
T7	14.56	14.29	12.45	13.40	14.77	69.48

Table 10: Effect of different treatments on soil moisture of wheat

Treatment	1st irrigation	2nd irrigation	3rd irrigation	4th irrigation	5th irrigation	At harvest	AV.
T1	19.73	19.64	19.32	23.93	19.19	15.09	19.48
T2	20.21	19.76	20.98	26.69	21.65	15.48	20.80
T3	21.46	19.45	22.98	26.34	24.56	16.18	21.83
T4	21.99	22.35	22.19	32.67	25.93	17.26	23.73
T5	23.76	20.39	22.09	25.42	24.21	17.84	22.29
T6	24.81	21.74	23.22	27.89	22.98	17.93	23.09
T7	21.35	20.41	20.45	32.41	24.45	16.30	22.56

Nutrient uptake was also positively influenced by SAP application. Nitrogen uptake increased from 130.94 kg ha⁻¹ in T1 to 148.11 kg ha⁻¹ in T7, while phosphorus and potassium uptake reached 73.30 and 48.87 kg ha⁻¹, respectively, in T4 (Table 11). Post-harvest soil fertility status further indicated improved nutrient conservation, with available nitrogen increasing to 132 kg ha⁻¹ in T6 and potassium reaching 185 kg ha⁻¹ in T4 compared with the initial soil status (Table 12). Enhanced nutrient uptake under SAP treatments may be attributed to reduced nutrient leaching and prolonged nutrient availability within the root zone. Bortolin et al. (2013) similarly reported reduced nutrient losses and enhanced nutrient-use efficiency in SAP-amended soils. The present results also support observations by Zhao et al. (2021), who noted that SAP-mediated nutrient retention can sustain crop productivity even with reduced fertilizer application rates.

Table 11: Effect of different treatments on nutrient uptake by wheat

Treatments	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
T1	130.94	61.56	40.06
T2	133.51	64.70	43.13
T3	137.65	68.28	46.61
T4	143.26	73.30	48.87
T5	134.48	57.78	38.85
T6	141.13	63.08	42.77
T7	148.11	60.30	42.32

Table 12: Effect of different treatments on soil properties and soil fertility after harvest of wheat

Treatments	E.C. (μS/c)	pH	O.C. (%)	N (Kg ha ⁻¹)	P (Kg ha ⁻¹)	K (Kg ha ⁻¹)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Mn (ppm)
T1	435	7.39	0.42	130	25	177	0.39	2.26	1.26	3.30
T2	406	7.41	0.41	129	26	180	0.31	2.43	1.38	2.90
T3	461	7.44	0.40	131	24	182	0.33	2.33	1.49	3.30
T4	459	7.52	0.43	128	25	185	0.35	2.39	1.63	3.20
T5	501	7.39	0.41	128	24	180	0.38	2.11	1.55	3.30
T6	505	7.36	0.40	132	26	180	0.36	2.06	1.86	3.30
T7	436	7.45	0.42	127	24	175	0.36	1.73	1.56	3.60
Initial Sample	396	7.54	0.46	125	22	173	0.39	1.36	1.00	3.00

Economic analysis revealed higher profitability with SAP application. The maximum net return (Rs. 58,233 ha⁻¹) and benefit-cost ratio (1.83) were recorded in T4 compared with Rs. 50,123 ha⁻¹ in the control (Table 13). The improved economic performance resulted primarily from enhanced grain yield combined with reduced irrigation costs. Comparable economic benefits of SAP use in vegetable and field crops were also documented by (Bisbis et al., 2019) who reported improved profitability under water-limited conditions.

Table 13: Effect of different treatments on crop economics of wheat

Treatments	Gross Monetary Returns (Rs ha ⁻¹)	Cost of cultivation (Rs ha ⁻¹)	Net Monetary Returns (Rs ha ⁻¹)	B:C Ratio
T1	114461.10	64338.25	50122.85	1.78
T2	121200.30	68088.25	53112.05	1.78
T3	124781.50	68838.25	55942.25	1.81
T4	128571.30	70338.25	58233.05	1.83
T5	119726.10	66364.50	53361.60	1.80
T6	123201.00	67114.50	56086.50	1.84
T7	126044.10	68614.50	57429.60	1.84

In tomato, application of 20 kg ha⁻¹ SAP under 0.6 IW/CPE produced a yield of 21.66 t ha⁻¹, which was statistically comparable to the fully irrigated control yield of 22.10 t ha⁻¹, whereas untreated plots under the same irrigation regime yielded only 18.54 t ha⁻¹. Likewise, 15 kg ha⁻¹ SAP at 0.8 IW/CPE also maintained yields at 21.66 t ha⁻¹. These results demonstrate that SAP application effectively compensated for deficit irrigation, enabling nearly 40% water savings without substantial yield reduction (Table 14). The ability of SAPs to minimize moisture stress under reduced irrigation regimes has also been demonstrated by Zou et al. (2012), who reported sustained tomato productivity through reduced percolation losses and improved root-zone moisture retention. Variations reported under

saline conditions by (Abd El-Mageed et al., 2017) suggest that soil electrical conductivity and texture strongly influence SAP performance.

Table 14. Effect of irrigation scheduling (IW/CPE ratios) and Fasal Amrit application rates on fruit yield and productivity.

Treatments Hydrogel dose (kg/ha)	Yield (t ha ⁻¹)			WUE (kg/ha-cm)		
	IW/CPE ratio			IW/CPE ratio		
	1.0	0.8	0.6	1.0	0.8	0.6
FA ₀ (Control)	20.47	19.88	18.54	292.38	361.52	463.54
FA ₁₀	21.44	21.17	20.47	306.31	384.85	511.67
FA ₁₅	21.74	21.67	21.27	310.60	393.94	531.67
FA ₂₀	22.10	22.00	21.67	315.71	400.00	541.67
	I st	II nd		I st	II nd	
SEm±	0.788	0.822		1.974	2.091	
C.D. at 0.05	0.2344	2.506		5.865	6.426	

In okra, application of 20 kg ha⁻¹ SAP under 7-day irrigation intervals produced 136.83 q ha⁻¹ yield, representing an 11% increase over the untreated control (105.63 q ha⁻¹), while water-use efficiency increased to 304.07 kg ha⁻¹ cm⁻¹, nearly 30% higher than the control (Table 15). Under 5-day irrigation intervals, yield further increased to 138.83 q ha⁻¹, which was approximately 18% higher than the untreated plots. The improved yield and WUE under extended irrigation intervals indicate that SAP application effectively reduced evaporative losses and prolonged water availability between irrigations. Similar improvements in pod yield and irrigation efficiency were reported by El-Rehim et al. (2004) in okra cultivated under arid environments. However, previous reports by Zohuriaan-Mehr et al. (2010) indicated comparatively lower responses in clay-dominated soils, emphasizing the role of soil texture in determining SAP swelling and water-release characteristics.

Table 15. Interaction effect of Fasal Amrit (Hydrogel) and Irrigation interval on yield of Okra and Water Use Efficiency

Treatments	Yield (q/ha-1)			WUE (kg/ha-cm)		
Hydrogel dose (kg/ha)	Irrigation interval (days)			Irrigation interval (days)		
	I3	I5	I7	I3	I5	I7
FA0 (Control)	123.63	117.63	105.63	123.63	180.97	234.73
FA10	133.43	130.43	124.83	133.43	200.66	277.4
FA15	136.43	135.43	132.83	136.43	208.35	295.18
FA20	140.03	138.83	136.83	140.03	213.58	304.07
Sem±	0.394	0.411		0.658	0.697	
C.D. @ 0.05%	1.172	1.253		1.955	2.142	

Seedling studies further confirmed the moisture-conserving ability of the bio-SAP. Under moisture stress conditions, wheat seedling height doubled to 21 cm at 20 DAS in SAP-treated media, while wilting was delayed from 8 days in untreated seedlings to 23 days with SAP application. These observations suggest that the bio-SAP not only improved soil water storage but also supported microbial activity by maintaining favorable moisture conditions. Similar enhancement in microbial compatibility and prolonged moisture retention has been reported for biodegradable SAPs derived from organic substrates (Bortolin et al., 2013). The incorporation of 1% EF Polymer into the soil significantly enhanced moisture retention over the 12day drying period compared to the control. The treated soil maintained higher water content consistently.

Water, thereby reducing moisture loss. This sustained moisture availability is critical for maintaining soil microbial activity and plant root hydration during dry intervals.

Bacterial survival was markedly improved in the EF Polymer-amended soil. Live bacterial counts showed a slower decline over time compared to the control, indicating that the polymer-created microenvironment supported microbial viability by preserving favorable moisture conditions. This finding aligns with previous research highlighting biodegradable superabsorbent polymers' role in fostering soil microbial communities by mitigating desiccation stress (Bortolin et al., 2012; Fauconnier et al., 2021).

The improved moisture retention and microbial survival suggest that EF Polymer not only functions as a water reservoir but also contributes to maintaining soil health, which is essential for nutrient cycling and plant growth. These results corroborate field trial observations where bio-SAPs enhanced soil moisture and crop performance (Yang et al., 2014; Gaur et al., 2022). The laboratory findings provide mechanistic support for the polymer's role in sustaining soil moisture and microbial ecosystems under water-limited conditions, reinforcing its potential utility in semi-arid agricultural systems.

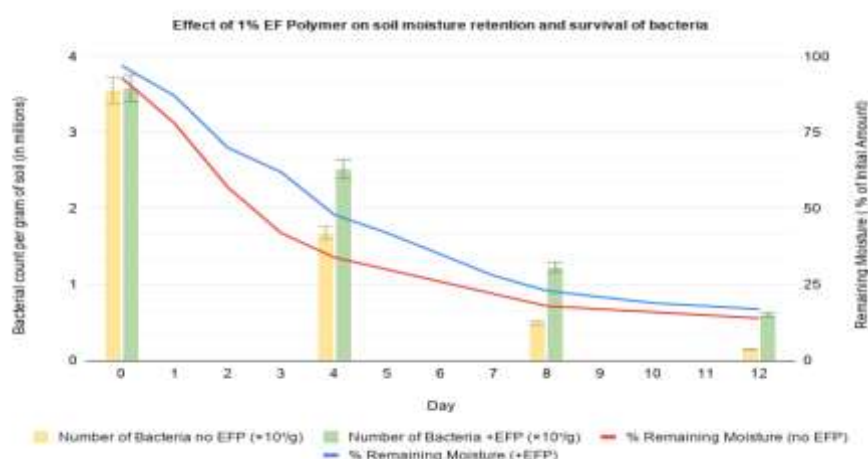


Figure 1 Effect of 1% EF Polymer on soil moisture retention and survival of bacteria.

Overall, the differential responses observed among wheat, tomato, and okra indicate that SAP performance is strongly influenced by crop physiology and irrigation strategy. Cereals benefited primarily through improved tillering and grain filling under stabilized moisture conditions, whereas vegetable crops exhibited greater responsiveness under deficit irrigation due to their higher evapotranspirational demand. Despite the promising outcomes, SAP efficiency may vary under highly saline or heavy clay soils, where swelling capacity and aeration can be restricted. Therefore, integration of bio-SAPs with precision irrigation systems, mulching, and site-specific nutrient management may further enhance their effectiveness under semi-arid agroecosystems.

Conclusions

This multi-crop evaluation of Fasal Amrit bio-SAP demonstrates its efficacy in curbing irrigation demands while elevating yields and economic viability in wheat, tomato, and okra. Key findings reveal 15-20% water savings in wheat (down to 66 acre-inches), with 12% yield boosts (42.86 q ha^{-1}) and superior B:C ratios (1.84), alongside enhanced nutrient uptake and soil moisture (23.73%). Tomato maintained 21.66 t ha^{-1} under 40% deficit, and okra extended intervals to 7 days for 136.83 q ha^{-1} and 30% WUE gains, with seedling stress tolerance doubled. These outcomes, consistent across sites, affirm SAPs' buffering against scarcity, particularly when paired with 85% RDF for cost efficiencies.

Practically, farmers in semi-arid India should apply $15\text{-}20 \text{ kg ha}^{-1}$ pre-sowing for cereals and vegetables, potentially saving 1-2 irrigations per season and adding Rs. 5,000-8,000 ha^{-1} net. Extension services could prioritize demos in Rajasthan-Maharashtra belts, integrating with drip for

hybrids. Future work might explore longevity (2-3 seasons) and scaling to pulses, aiding sustainable water governance. Overall, bio-SAPs like Fasal Amrit offer a simple, green lever for resilient farming amid escalating droughts.

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