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Enhanced pearl millet yield stability, water use efficiency and soil microbial activity using superabsorbent polymers and crop residue recycling across diverse ecologies

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ABSTRACT

Under changing climate scenarios, developing sustainable adaptation strategies in agriculture will be obligatory. To understand the effect of carbohydrate-based superabsorbent polymer (SAP) and crop-residue mulch (CRM) on pearl millet productivity and water-use efficiency (WUE), field experiments were undertaken for three consecutive years at 11 different locations (representing ~30 % of the global pearl millet growing area). Eight treatments, namely, Control; CRM 5.0 t/ha; SAP 2.5 kg/ha; SAP 5.0 kg/ha; SAP 7.5 kg/ha; SAP 2.5 kg/ha + CRM 5.0 t/ha; SAP 5.0 kg/ha + CRM 5.0 t/ha and SAP 7.5 kg/ha + CRM 5.0 t/ha were evaluated. Co-application of CRM and SAP increased pearl millet grain and stover yield by up to ~45 % and ~36 %, respectively. Pearl millet responded significantly up to 2.5 kg/ha SAP application (with or without CRM) only. Further, soil microbial biomass carbon improved significantly with CRM (20 %) and SAP (10.9–12.1 %) individually and with simultaneous application of CRM and SAP (~30 %). Likewise, dehydrogenase, alkaline phosphatase, acid phosphatase, and urease activities also improved significantly due to the co-use of CRM and SAP. Positive effects of CRM, SAP, and their co-application were also witnessed on soil microbial (bacterial, fungal, actinobacteria) populations and water-use efficiency (WUE) across environments. Among the locations, New Delhi and Aurangabad were the most desirable and stable ecologies, whereas Bikaner and Vijayapur remained the least consistent. Hence, to tackle the moisture-stress problem under pearl millet production systems and to achieve stable productivity, greater WUE and better soil microbial activity, CRM 5 t/ha in conjunction with SAP 2.5 kg/ha may be recommended across diverse ecologies.

Abbreviations: CRM, crop residue mulch; SAP, Superabsorbent polymer; WUE, Water use efficiency; kg/ha, kilogram per hectare; mm, Millimeter; cm, Centimeter; AICRP-PM, All India Coordinated Research Project on Pearl Millet; ICAR, Indian Council of Agricultural Research; N, Nitrogen; P, Phosphorus; K, Potassium; DAS, days of sowing; t/ha, tons per hectare; eq, Equation; °C, Degree Celsius; mg, Milligram; μg, Microgram; ml, Milliliter; L, Liter; CFU, Colony forming units; MBC, Microbial biomass carbon; LSD, Least significant difference; *P*, Probability; PC, Principal component; *fb*, Followed by; BKR, Bikaner; DHL, Dhule; MDR, Mandor; JPR, Jaipur; JMR, Jamnagar; NDL, New Delhi; HSR, Hisar; KLI, Kalai; ABD, Aurangabad; VYP, Vijayapur; CBE, Coimbatore; D, Delhi; J, Jodhpur.

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1. Introduction

Escalation in extreme meteorological events, alarming water deficit, and severe malnourishment are set to jeopardize the global agri-food systems (FAO, 2021). Such adversities are presumed to deepen in coming decades with more incidences of extreme drought and heat-stress events and uncertainties in rainfall patterns (Ahmad et al., 2018; Rahman et al., 2018). Climate-crisis induced water shortages and droughts are envisaged to cause soil desertification and salinization (Emadodin et al., 2019). Therefore, it becomes obligatory to enhance water utilization efficiency in agriculture (Bana et al., 2018), introduce climate-resilient crops in the food systems and develop suitable, cleaner and perpetual adaptation strategies.

Across the arid and semi-arid ecologies of the globe, pearl millet [*Pennisetum glaucum* (L.) R. Br. Emend stuntz] crop is the kingpin of food, fodder, nutritional as well as income security, where it forms a vital part of the staple diet of > 90 million people below poverty (Bamboriya et al., 2017; Faiz et al., 2022; Kumar et al., 2021). Due to higher protein (10.5–14.5 %), fat (4.0–8.0 %), essential minerals (2.0–3.5 %), vitamins and amino acids content than other cereals, pearl millet has emerged as a primary nutritional source of food for millions in marginal agricultural areas (Faiz et al., 2022). Due to the C4 nature of the crop, it has high photosynthetic efficiency, resulting in better productivity even under adverse soil and climatic conditions (Choudhary et al., 2020). Owing to high resilience to hydrothermal stresses, pearl millet is well suited to water-scarce ecologies. It can be a strong diversification alternative to water-guzzling crops for many parts of the globe (Faiz et al., 2022).

Worldwide, the pearl millet covers ~31 million hectares of area, and India is the largest producer of the crop, both in terms of acreage (9.3 million hectares) and production (8.3 million tonnes) (ICARISAT, 2022). In India, pearl millet growing areas have been divided into three major zones, depending on soil, climate, and rainfall pattern. The zone-A1 is characterized by light and sandy soils with < 400 mm annual average rainfall covering regions of the Thar Desert. The zone-A covers the remaining parts of north India, characterized by > 400 mm annual rainfall and sandy loam soils. The southern states of India are categorized as zone-B with > 400 mm annual precipitation, heavy soils, and mild temperatures (AICRP pearl millet, 2022; Supplementary Fig. 1).

For water-efficient agriculture, smart moisture management protocols are needed to be developed while conserving soil moisture and augmenting soil water-holding capability (Kreye et al., 2009). There are several suggested pathways for in-situ soil moisture management that may have a stress-diminishing effect on pearl millet, such as organic mulching, aqua-fertilization sowing, and the application of synthetic polymers. The use of synthetic polymers, also known as Superabsorbent Polymers (SAP) or hydrogels, play a substantial part in water-use efficiency (WUE) enhancement in agriculture (Bana et al., 2018). SAPs, classified as cross-linked polymers, absorb water (400–600 times their weight) by bonding with water molecules in aqueous solutions (Bana et al., 2018). The SAPs favourably alter soil physical properties (El-Hady and Abo-Sedera, 2006) and reduce evaporation rates (Dar et al., 2017; Kumar et al., 2020). The use of SAPs for raising field crops, particularly under moisture stress ecologies, could be a viable option if they are applied in smaller quantities at shallow depths in rows beneath the seeds (Narjary and Aggarwal, 2014). However, despite the proven gains of SAPs, their adoption remained restricted to high-value crops and by fewer farmers (Kumar et al., 2021; Faiz et al., 2022).

Similarly, crop residue mulches (CRM) have demonstrated moisture conservation and soil temperature moderation advantages, besides weed menace reduction and soil health enrichment (Bamboriya et al., 2017; Bana et al., 2018). Moreover, CRM also facilitates the mobilization of nutrients in the soils, reduces environmental footprints and improves water-use efficiency (Sarkar et al., 2020). On the other hand, large-scale crop stubble burning has emerged as a severe environmental threat in recent decades in India, resulting in numerous health issues and policy challenges (Biswakarma et al., 2021; Kumar et al., 2021). Therefore, efficient crop residue management would have multiple advantages (Ankit et al., 2022; Yadav et al., 2018). Systematic information on the effect of SAPs on pearl millet growth and yield under diverse ecologies is not available. A knowledge gap also exists on WUE and soil microbial activities as affected by SAP application with or without organic mulching. In this context, the present work undertakes field studies in diverse pearl millet growing locations across India to test SAP under different ecological conditions of the country's various pearl millet growing zones. In addition, the study also provides insights into the interaction of SAP × CRM × environment × year on pearl millet yield, WUE, and soil microbial parameters.

2. Material and methods

2.1. Experiment sites, treatments and crop management

The field experiments aimed to understand the effect of carbohydrate-based SAP on nutri-cereal pearl millet were carried out at 11 different locations across India, representing 30 % of global pearl millet acreage, during the rainy seasons of 2017–18, 2018–19 and 2019–20. Research on pearl millet improvement in India is carried through the All India Coordinated Research Project on Pearl Millet (AICRP-PM), a continuing central plan project established in 1965 by the Indian Council of Agricultural Research (ICAR). The AICRP-PM has its centers across India representing specific pearl millet production ecologies based on soil typologies, climatic variability including rainfall pattern and geographical location (Supplementary Fig. 2). Details on experimental sites, rainfall, soil properties and other agronomic practices are presented in Table 1. The plough layer soil (0–15 cm depth) of experimental locations was analyzed for pH (1:2.5 soil-water ratio), $KMnO_4$ oxidizable N, $NaHCO_3$ extractable P (phosphorus) and NH_4OAc exchangeable K (potassium) before initiation of experimentation as per the standard methods, as described by Rana et al. (2014).

2.2. Experimental treatments and crop management

The test material, SAP, was synthesized using cellulose and acrylamide in the laboratory using a modified free radical polymerization technique. For hydrogel development, bio-degradable cellulolytic derivatives and clay, in conjunction with vinyl monomers, were blended with warm water. A free-radical initiator was added to the standardized mixture with constant stirring. After 6–12 h, the obtained polymer mass was washed and dried to result in bio-polymeric grafted and cross-linked polyacrylate SAP. For field application of the SAP, air-dried soil (of the same fields) was sieved and mixed with the SAP to make the bulk. The blend was then applied manually as per the treatment dose during seeding at 2–3 cm depth to ensure moisture availability in the immediate rhizosphere (Bana et al., 2018).

The eight treatments (as described in Table 2) were replicated three times in randomized block design (RBD). Chemical fertilizers (N, P, K) were applied as urea (46 % N), single superphosphate (16 % P_2O_5) and muriate of potash (60 % K_2O), respectively, as per the state recommendation in the respective zones. Nitrogen was applied in two splits, 50 % as basal dose (along with a full dose of P and K before sowing) and the remaining 50 % as a top dressing after 20–35 days, depending upon the availability of soil moisture. Gap filling and thinning were done as required within 15–20 days of sowing (DAS). Location-wise details on the variety used, previous crop and mulch, rainfall, fertilizer doze, etc. are included in Table 1 and dates of various operations carried out are given in Supplementary table 1.

2.3. Growth and yield attributes of pearl millet

Growth and yield attributes of pearl millet, i.e. test weight (weight of 1000 grains), number of total and effective tillers, plant height, ear head length and grain weight per ear head, were recorded from 10 randomly-designated plants from each treatment plot using standard procedures. From 5 randomly selected rows, number of effective tillers were counted from one meter row length in each treatment. Grain and stover yields were measured from the entire treatment plot and converted to t/ha at 14 % moisture content.

2.4. Water-use efficiency computation

Water-use efficiency (WUE) of various treatments was estimated by dividing the economic yield (kg/ha) by the quantum of irrigation water applied (mm) and effective precipitation (a rainfall of <6.25 mm in a 24 h period is known as ineffective) and it was multiplied with 0.65 to calculate the effective rainfall (https://www.fao.org/3/x5560e/x5560e03.htm; accessed on 16 July 2022) (Eq. 1).

$$WUE\ (\text{kg/ha-cm}) = Yg/(Wi + Re) \quad (1)$$

Where, WUE = Water-use efficiency (kg/ha-cm), Yg = Grain yield (kg/ha), Wi = Irrigation water applied, if any (cm), Re = Effective rainfall (cm).

2.5. Estimation of soil microbiological parameters

Considering the higher sensitivity of microbial activity to storage (sampling to analysis) period and resource constraints, two diverse agro-ecologically representative locations – Mandor (Jodhpur, Rajasthan) and New Delhi – were identified for maintaining greater precision of results (Mandor as typical of extremely arid desert climate and New Delhi representing semi-arid ecologies). To estimate microbial dynamism, soil samples from 0 to 15 cm depth were collected using a core sampler to assess the effect of SAP and CRM treatments on soil microbiological parameters at the flowering stage and stored at 4 °C. UV/VIS spectrophotometer (Thermo Fisher Scientific, USA, Evolution 300) was used for the estimation of enzyme activities using appropriate substrates and reaction conditions. Total culturable bacteria, fungi and actinobacteria in the soil were estimated by standard serial dilution and plating method (Rolf and Bakken, 1987). To assess the populations of cultivable bacteria, fungi and actinobacteria, the soil samples were serially diluted in 0.85 % saline and appropriate dilutions were spread on plate count agar (HiMedia) supplemented with sodium propionate (50 mg/L) to suppress fungal growth, Rose Bengal Agar (HiMedia) supplemented with streptomycin (50 mg/L) to suppress bacterial growth and KenKnight and Munaiers Agar (HiMedia) respectively. The plates were incubated at 28 ± 2 °C and the colony forming units (CFU) were counted and expressed as log10 CFU per gram dry weight soil.

Soil samples were analyzed for enzyme activities and microbial biomass carbon. Soil dehydrogenase was assayed by using 3 % triphenyl tetrazolium chloride (TTC) as substrate and reading the intensity of triphenyl formazan (TPF) using a spectrophotometer (Thermo Fisher

Table 2
Treatment details of the experiment.

Treatment no.	Treatment name	Description
T1	Control (no moisture management)	-
T2	Crop residue mulch (CRM) 5.0 t/ha	Residues from the previous crop were applied as surface cover (pearl millet in zone-A1, mustard in zone-A and chickpea in zone-B). Zone-wise, previous crops were identified based on acreage during the winter season in that particular zone, to maintain uniformity in the trials.
T3	Superabsorbant polymer (SAP) 2.5 kg/ha	Soil-blended SAP was mixed with seed thoroughly and applied in the seeding zone manually using a hand plow.
T4	SAP 5.0 kg/ha	Same as above except SAP dose
T5	SAP 7.5 kg/ha	Same as above except SAP dose
T6	SAP 2.5 kg/ha followed by (*fb*) CRM 5.0 t/ha	SAP was applied as per the procedure described above and after sowing of the crop the residues of previous season crop were applied as surface cover
T7	SAP 5.0 kg/ha *fb* CRM 5.0 t/ha	Higher dose of SAP *fb* surface residue cover
T8	SAP 7.5 kg/ha *fb* CRM 5.0 t/ha	Same as above except SAP dose

Table 1
Description of site, rainfall and soil properties (0–15 cm depth) before the commencement of the experiment and other agronomic details.

Location	Soil Status						Previous Crop	Mulch crop	Variety Used	Plot size (m^2)	Nutrient applied (kg/ha)			Rainfall (mm)		
	Type	pH	N (kg/ha)	P (kg/ha)	K (kg/ha)	Soil Depth (cm)					N	P_2O_5	K_2O	2017–18	2018–19	2019–20
Bikaner	LS	8.4	117	14.8	172	>90	Pearl Millet	Pearl millet	MPMH 17	16	40	20	40	293	300	236
Mandor	SL	8.7	154	15.5	281	>90	Pearl Millet	Pearl millet	MPMH 17	16	40	20	-	466	227	593
Jaipur	LS	7.8	171	25	240	>90	Mustard	Mustard	RHB 173	20	60	30	-	479	546	718
Jamnagar	CL	7.7	206	25.6	283	60	Sesame	Mustard	RHB 173	20	60	40	-	697	370	1311
New Delhi	SL	7.8	202	15.9	258	>90	Mustard	Mustard	RHB 173	20	60	40	40	855	929	559
Hisar	SL	8.7	126	13.0	248	>90	Mustard	Mustard	RHB 173	20	60	40	-	235	298	249
Kalai	SL	8.1	135	18.3	279	>90	Wheat	Mustard	RHB 173	20	60	40	30	605	553	628
Aurangabad	MDB	8.0	124	20.4	431	60	Wheat	Chickpea	GHB 558	16	60	30	-	662	478	659
Dhule	MB	8.1	187	17.4	528	60	Fallow	Chickpea	GHB 558	16	60	30	-	615	352	615
Vijayapur	MB	8.7	196	17.4	458	45 cm	Chick pea	Chickpea	GHB 558	16	60	30	-	703	472	301
Coimbatore	CL	8.1	289	12.6	496	>60 cm	Fallow	Chickpea	GHB 558	16	60	30	30	409	139	303

SL: Sandy loam; LS: Loamy sand; MB: Medium Black; CL: Clay Loam; MDB: Medium Deep Black

Scientific, USA, Evolution 300) as described previously (Tabatabai, 1994). The dehydrogenase activity was expressed as µg TPF/g soil/day. Alkaline phosphatase (Eivazi and Tabatabai, 1988) and acid phosphatase (Tabatabai and Bremner, 1969) were assayed by using *p*-nitrophenol phosphate as a substrate, at pH 11.0 and 6.0, respectively and expressed as µg/g soil/h. Soil urease activity was assayed by colorimetric determination of ammonium following indophenol method (Sinsabaugh et al., 2000) and expressed as µg ammonium/g soil/h. Soil microbial biomass carbon (MBC) was estimated by fumigation and extraction (K_2SO_4) followed by dichromate digestion and titration against ferrous ammonium sulphate and expressed as µg/g soil (Vance et al., 1987).

2.6. Statistical analysis

All the sample data obtained from the three-year pearl millet experiment were analyzed using the F-test (Gomez and Gomez, 1984). Least significant difference (LSD) values at $P = 0.05$ were used to determine the significance of the difference between treatment means. The methodology of Yan et al. (2000) and Yan and Kang (2003) was applied to the GGE biplot analysis. It was undertaken to reveal the main effects of moisture management treatments (T) and the interactive effects of treatments by environments (T × E) of the moisture management practices and locations. Similarly, crossover GGE biplots were developed using the R programming language to understand the interaction effects of treatment × location × year studies (R Core Team, 2021).

The two-dimensional GGE and the cross-over GGE polygons were generated by the first two principal components (PC), derived from subjecting the singular value data decomposition. For comparing 'between treatments' values, the data were kept environment-centred, and contrarily, the data were treatment-centred for comparing 'between environment' values. The symmetric scaling (f=0.5) was put in to generate "which won where/what" biplots. These polygons assist in the identification of the treatment combinations, which is relatively more stable and superior in the tested environments. The angles between environmental vectors defined the correlations (Yang et al., 2009; Yan et al., 2011). Similarly, various other GGE biplots like mean vs. stability, ranking treatment/genotypes, and ranking environments illustrate the most stable, best performer treatment combinations, relative treatments and environments of treatments, respectively under comparable or unlike mega-environments (Bana et al., 2020).

The following GGE biplot statistical model (Eq. 2) applied for the study:

$$Y_{ij} - B_j = \sum_{k=1}^{t} \lambda_k \alpha_{ik} \delta_{jk} + \varepsilon_{ij} \tag{2}$$

Where, Y_{ij} = Growth/ pearl millet yield/ WUE/ microbial enzymatic activity as affected by SAP and CRM i (i = 1,…., n) in environment (location × year) j (j = 1, …., p), B_j = mean growth/ pearl millet yield/ WUE/ microbial enzymatic activity in the j^{th} environment. The data matrix of Y_{ij} was disintegrated into k PC (1 to t with $t \le \min(p, n-1)$. The λ (1,…., t) are the singular values for the respective principal component with $\lambda1 \ge \lambda2 \ldots \ge \lambda t \ge 0$; α_{ik} (k = 1,…, t) are the eigenvectors for PC_1, PC_2, PC_3 …, PC_t respectively for entry i; δ_{jk} are the eigenvectors for PC_1, PC_2, PC_3…, PC_t respectively for tester j and ε_{ij} is the model residual.

Since the data were collected from various locations and multiple years, there were nearly 3 % missing values in the entire data set. Before analysing the observed data, the missing values are imputed using Artificial Neural Network (ANN)-based model (Godara and Toshniwal, 2022). The overall procedure of imputation can be divided into two parts i.e., first, an ANN-based model was trained to estimate the missing values using the values present in other variables. Later, the trained model was used to estimate the missing values of the dataset (Fig. 1). The ANN-based model consisted of a single layer of 8 neurons and was trained to minimize the loss function given by Eq. (3). Here, *y* represents the desired output value and $\hat{y}$ represents the model's output.

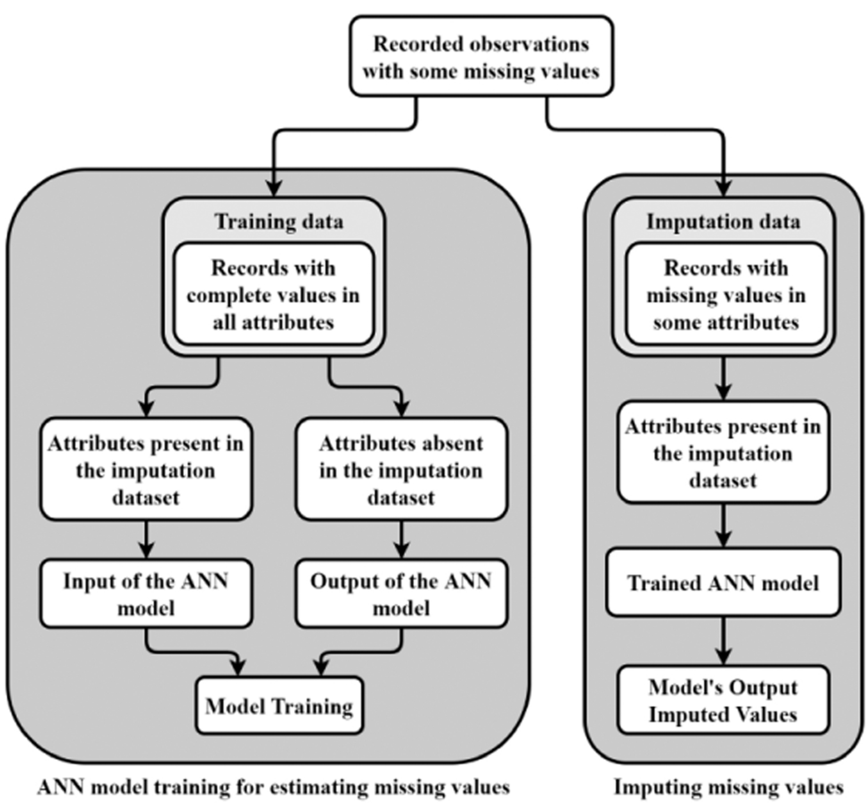

Fig. 1. Data imputation methodology used in the study.

$$Loss(y, \hat{y}) = \sum_{i=1}^{n} (y - \hat{y})^2 \quad (3)$$

3. Results

3.1. Growth and yield parameters

The main effects of pooled means (of 11 locations and three years) indicated that the plant height of pearl millet remained between 157 and 176 cm (Supplementary Fig. 3a). A difference of 12.1 % was noticed in the plant height, with the tallest plants under T8 treatment (highest level of SAP with CRM) and shortest under control (T1). Test weight (1000-grain weight) of pearl millet varied between 9.1 and 10.3 g (Supplementary Fig. 3b). The greatest value of test weight was obtained with the highest dose of SAP with CRM (T8) and the least with control treatment. Various levels of SAP had a similar effect on test weight as indicated by the non-significant differences between T3-T5 and T6-T8. Similarly, SAP application along with CRM enhanced tillering up to 42 % over control. The control plot had the lowest tillering (2.97), followed by T2, T4 and T3, whereas T8 and T7 had significantly ($p \leq 0.05$) the highest tillering (4.17). As depicted in Supplementary Fig. 3b, the effective tillers were slightly lower than the total tillers (2.97–4.17). Like total tillers, effective tillers were also highest with T8 and T7 (3.09) treatment and lowest with control (2.05). Compared to the control, other treatments had 18–50 % higher effective tillers. Treatments T2-T5 had a statistically similar effect on test weight, effective tillers, and total tillers, as the difference between them were statistically non-significant with each other.

3.2. Grain and stover yield

Application of SAP, CRM and their combinations in pearl millet significantly ($p \leq 0.05$) improved the mean (across years and locations) grain as well as stover yield (Fig. 2**)**. The highest grain yield was obtained with the maximum level of SAP along with CRM i.e. T8 (2.55 t/ha), which was at par with T7 (2.46 t/ha) and T6 (2.33 t/ha). Treatment T2-T6 were found to be statistically similar to each other with respect to pearl millet grain yield. Compared to the control, T8 increased the yield of pearl millet by 45 %. On average, in comparison to the control, yield gains of 0.36 t/ha were observed when SAP was applied at 2.5 kg/ha (T3). The next two incremental doses of SAP could result in only a nominal enhancement in productivity. In comparison to T3, the yield gains in T4 were merely 0.05 t/ha and there was only 0.02 t/ha increase in T5 relative to T4. In a similar manner, a comparative analysis of CRM (individual and in combination with SAP) treatment plots also exhibited that grain yield enhancements were 0.2, 0.13 and 0.09 t/ha under T2 & T6; T6 & T7 and T7 & T8 comparisons, respectively. This highlighted that pearl millet responded significantly up to 2.5 kg/ha SAP application and further enhancement in its doses was not beneficial in terms of relative yield increment. Therefore, SAP use beyond 2.5 kg/ha dose is not recommended.

Similarly, the application of SAP and CRM significantly influenced the stover yield of pearl millet (Fig. 2). Except for treatment T2 and T3, the rest of other treatments produced significantly higher stover yield (19–36 %) than the control. The maximum mass of stover was obtained under T7 (5.6 t/ha) and remained statistically at par with T4-T7.

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Superabsorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha.

3.3. GGE biplot analysis

To mine greater insights from the multi-year, multi-location experiments, the GGE biplot using principal component analysis (PCA) technology was used. The entire dataset on yield, yield components and WUE were subjected to PCA considering treatment × environment (location means across years) interactions. Whereas crossover GGE illustrates treatment × location × year interactions.

3.3.1. Grain yield

For the GGE analysis of grain yield, the first two PCs explained 94.5 % of the cumulative variance (PC1 = 89.51 %, PC2 = 5.34 %) caused by treatment and location interactions. Thus, almost all of the information could be graphically depicted in the PC1 vs. PC2 polygons. The ‘which won where/what’ polygon showed the two-dimensional view of various moisture management practices and locations, illustrating the superior treatment across the diverse environments and their inter-relationship **(**Fig. 3**a).** The polygon highlighted that all the test environments (locations) had tumbled into the same broad-groups. Treatment 8 had the highest yield in this environment (all locations) followed by T7 and T6. In this group, T8 was the one farther away from the biplot origin, indicating its sensitivity to environments. This treatment also had the highest mean yield (2.54 t/ha) among all the treatments (Fig. 2**).** Treatment 5 is located near the origin, which means it was not responsive to environments and could have a similar ranking in all environments. No environment belonged to the same sectors where T1, T2, T3 and T4 were located; therefore, these treatments were the poorest in several or all environments.

Treatment with the highest yield across the test environments along with stable performance is considered ideal treatment (Yan et al., 2011). The ‘means vs. stability’ biplot indicated that T8 with the highest mean yield with higher stability, as it is situated adjacent to the AEC abscissa **(**Fig. 3**b).** The second highest yielding and most stable treatment was T7 followed by T6. In contrast, T1 T2 and T3 were the most unstable treatments, as they were falling away from the AEC abscissa. Across the

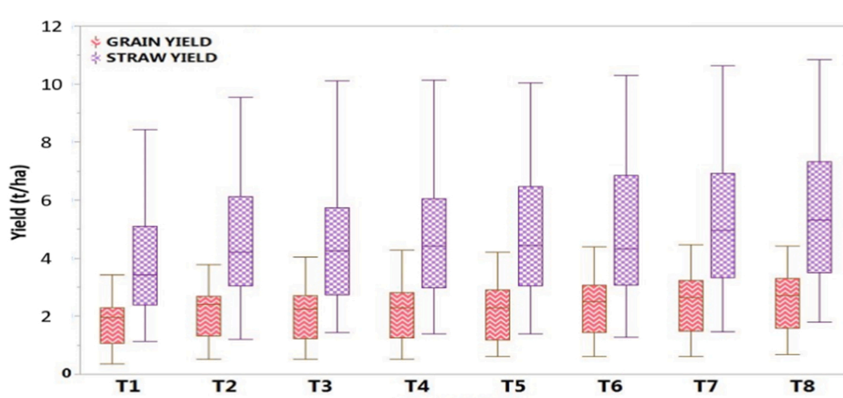

Fig. 2. Effect of moisture conservation practices on pearl millet grain and stover yields.

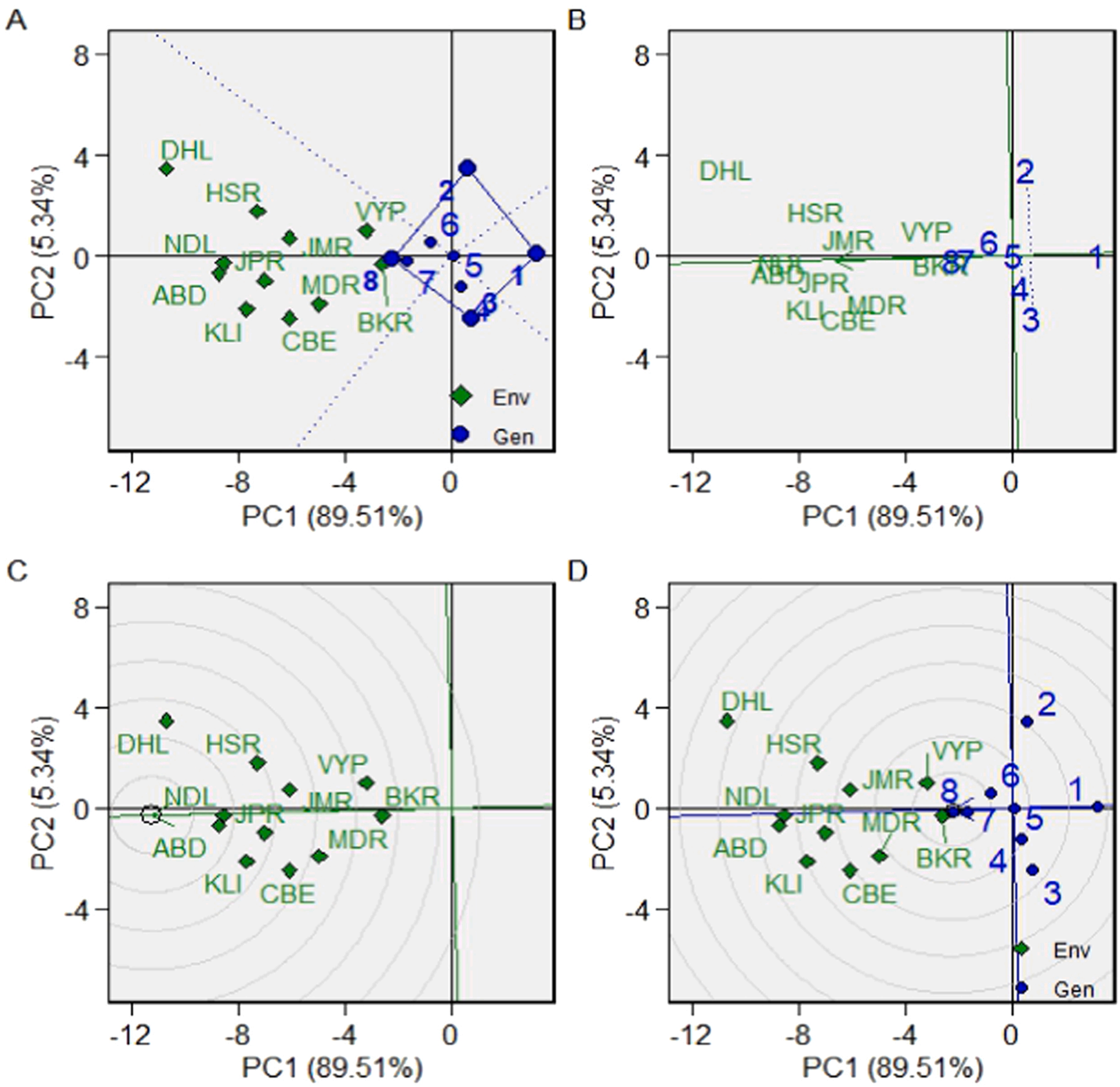

Fig. 3. GGE biplot for grain yield (a) 'which won where/what' polygon; (b) 'means vs stability' biplot; (c) Ranking environment polygon and (d) Ranking genotype polygon.

treatments, T5 was the most stable treatment as it was lying very close to AEC abscissa.

Polygons on 'Ranking environment' was used to provide the ranking based on distance from the 'ideal environment' (Bana et al., 2022a). An environment is more suitable if it is placed near the ideal environment, whereas environments positioned distantly from it have a poor ranking. The ideal environment is depicted by the central-most concentric circle (Yan, 2002). The ranking environment polygon (Fig. 3**c)** showed that NDL and ABD1 were the closest to the ideal environment; therefore, these two are the most desirable locations among all the 11 sites with the greatest level of consistency. In contrast, BKR and VYP were the least dependable locations. Ranking of the environments was NDL> ABD1 >DHL>HSR>JPR>KLI>JMR>CBE>MDR>VYP>BKR.

An ideal treatment is one that yields the highest across all the environments and bears good stability in its performance or possesses the highest ranking in all the environments. Treatment is more suitable if it is placed near the ideal treatment and vice versa (Bana et al., 2022b). Thus, placing the ideal treatment at the center, concentric rings were made to visualize the distance from the ideal treatment and to assign ranks to various treatments. Likewise, Fig. 3**d** showed that T8 and T7 was the closest treatment to the ideal one, followed by T6; therefore, they were most suitable across multi-environments. Treatment 1 had the poorest rank as it was positioned in the outer-most circles (farthest from ideal treatment). The ranking of treatments was in the order of T8 > T7 (in the inner orbit) followed by T6 > T5 > T4 > T3 = T2 > T1.

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Super-absorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha; BKR: Bikaner; DHL: Dhule; MDR: Mandor; JPR: Jaipur; JMR: Jamnagar; NDL: New Delhi; HSR: Hisar; KLI: Kalai; ABD: Aurangabad; VYP: Vijayapur; CBE: Coimbatore.

3.3.2. Crossover yield and yield parameters

The first two PCs of 'which won where/what' of crossover GGE polygons for treatment × year × location polygon explained 90.97 %, 90.97 %, 93.64 %, 93.2 %, 89.94 %, 57.39 % and 76.81 % variability for grain yield, straw yield, effective tillers, total tillers, plant height and test weight, respectively (Fig. 4**a**-4**f)**. The polygon view of grain yield (Fig. 4**a)** showed that all the environments were divided into two mega-environments. The first broad group consisted of CBE1 and CBE2 environments (years 1 and 2 of Coimbatore location) and the rest other locations × years were placed in the second mega-environment. In contrast, MDR2 (Mandor, year 2) was located in between these two groups. In the first group, CBE2 had a higher yield than CBE1. Further,

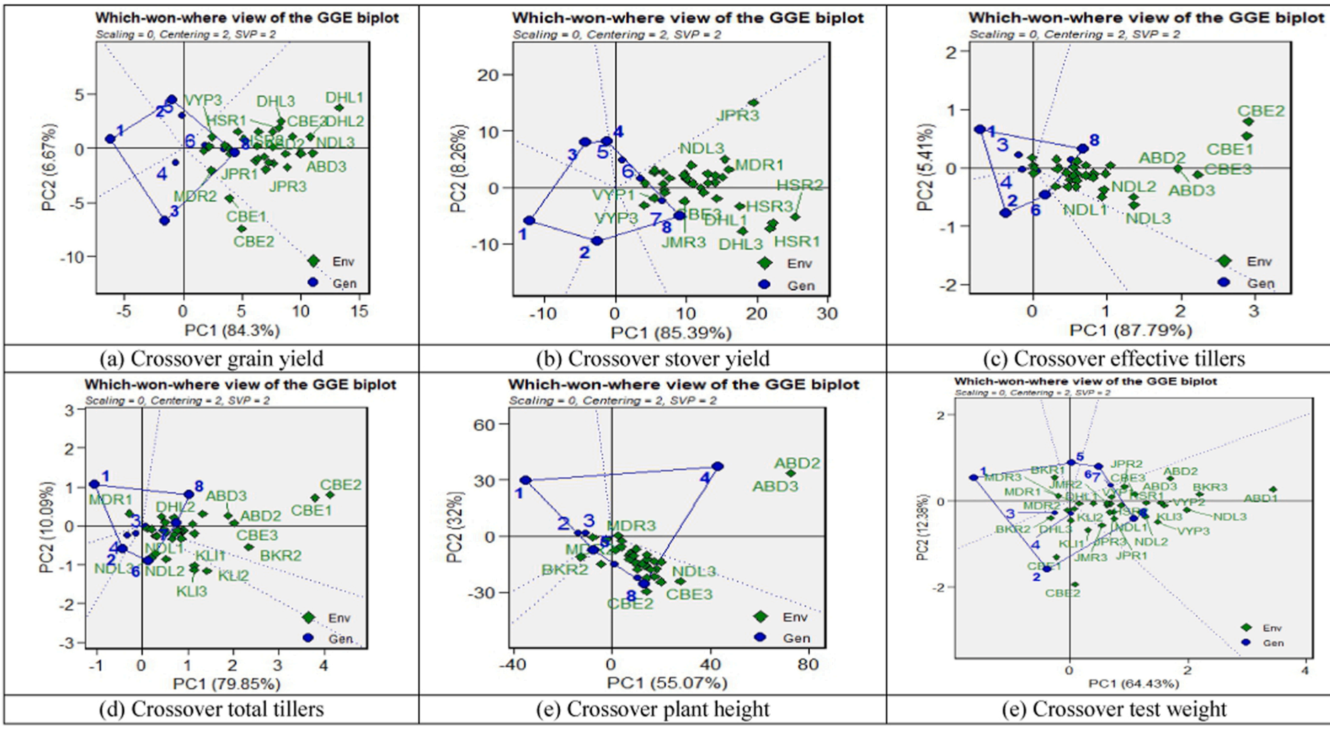

Fig. 4. Which won where/what crossover polygon for yield and yield attributes.

DHL1 was the highest-yielding environment in second group and it was most responsive as it was located furthest away from the biplot origin. In the case of stover yield and effective tillers all the environments had clustered in the same group (Fig. 4**b & 4c**). Regarding straw yield, HSR2 >HSR3 >HSR1 were the best environments, whereas CBE2 and CBE1 had the highest effective tillers. Interestingly, three groups were noticed for total tillers **(**Fig. 4**d)**. In group-I, MDR1 was located, whereas NDL1, NDL2, NDL3, KL1, KL2 and KL3 were situated in the second group and the rest other environments were bunched in the third group. In the second group, KLI2 and KLI3 had more tillers, whereas, in group III, CBE2 and CBE1 recorded the maximum tillers. From the plant-height perspective, there were four mega-environments; the first had BKR2; the second with MDR2; the third had ABD1 and ABD2 and rest environments were found in the fourth group. In the fourth group CBE2, CBE3 and NDL3 had maximum plant height (Fig. 4**e)**. Total of three groups were observed in the test weight crossover polygon **(**Fig. 4**f)**. In the first group, CBE2, CBE1, KLI1, DHL3, BKR2, MDH2 were located and among them CBE2 and CBE1 had the highest test weight. In contrast, in the second group only two environments were situated (MDR3 and BKR1). The rest of the other environments were located in the third group and among them, ABD11 and BKR3 had maximum test weights. The treatment ranking under GGE polygons and crossover biplots remained identical for different variables.

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Superabsorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha; BKR: Bikaner; DHL: Dhule; MDR: Mandor; JPR: Jaipur; JMR: Jamnagar; NDL: New Delhi; HSR: Hisar; KLI: Kalai; ABD: Aurangabad; VYP: Vijayapur; CBE: Coimbatore.

3.4. Water-use efficiency

Water-use efficiency (WUE) of pearl millet was 49 kg/ha-cm under control treatment, which increased by 22–58 % owing to the application of various moisture management treatments (Supplementary Fig. 4). Treatments 8 and 7 produces maximum yield (77 and 74 kg/ha, respectively) per cm of water use followed by T6 (68 kg/ha). The lowest WUE was recorded under control and T3 (lowest SAP dose) remained the second lowest treatment. This highlights that the combined application of CRM and SAP is a more effective strategy for achieving greater WUE than their sole applications.

3.4.1. GGE of water use efficiency

The first two PCs jointly explained 97.19 % (PC1 93 % and PC2 4.19 %) of the total variability, which means almost all information could be visually depicted by the biplots of these two PCs. The GGE biplot for the 'which-won-where/what' showed that all test environments (location and years) were featured in the same mega-group **(**Fig. 5**a)**. Among the treatments, T6, T7 and T8 were dropped in the same group. Among the three treatments, T8, closely followed by T7 remained superior with respect to WUE across the locations. Treatment 5 is located relatively closer to the origin; therefore, it is the least sensitive to environments and hence, can get a similar rank across the environments. No environments lay with T1, T2, T3, T4 and T5; therefore these treatments were poor performers in few or in all environments.

According to the mean vs. stability, GGE polygon T7 and T8 were the most stable treatments under multiple environments. The absolute length of AEC abscissa was greatest for T3 > T1 ≈ T4 ≈ T2 hence, these treatments were least stable in their performance across the environment **(**Fig. 5**b)**. Treatment 8 had the greatest yield as well as good stability; therefore, this treatment is best followed by T7. The ranking environments biplot **(**Fig. 5**c)** illustrated that the CBE environment was positioned closely inside the concentric ring (ideal environment); thus, it had the greatest ranking with more WUE. Contrarily, JPR and VYP environments remained located distantly from the concentric spheres therefore, they possessed the lowest ranking. The order of environments based on their ranking is CBE> HSR>JMR≈BKR>ABD1 ≈ DHL>MDR>VYP>JPR.

The ranking treatments polygon of the GGE biplot illustrated the order of the various treatments based on their efficiency **(**Fig. 5**d)**. Treatments 8 and 7 were situated close to the AEC axis inside the co-centred spheres of the 'ideal treatment'. Hence, they had a higher mean WUE and greater performance stability. Ranks assigned to different treatments were similar to that in the yield section i.e.,

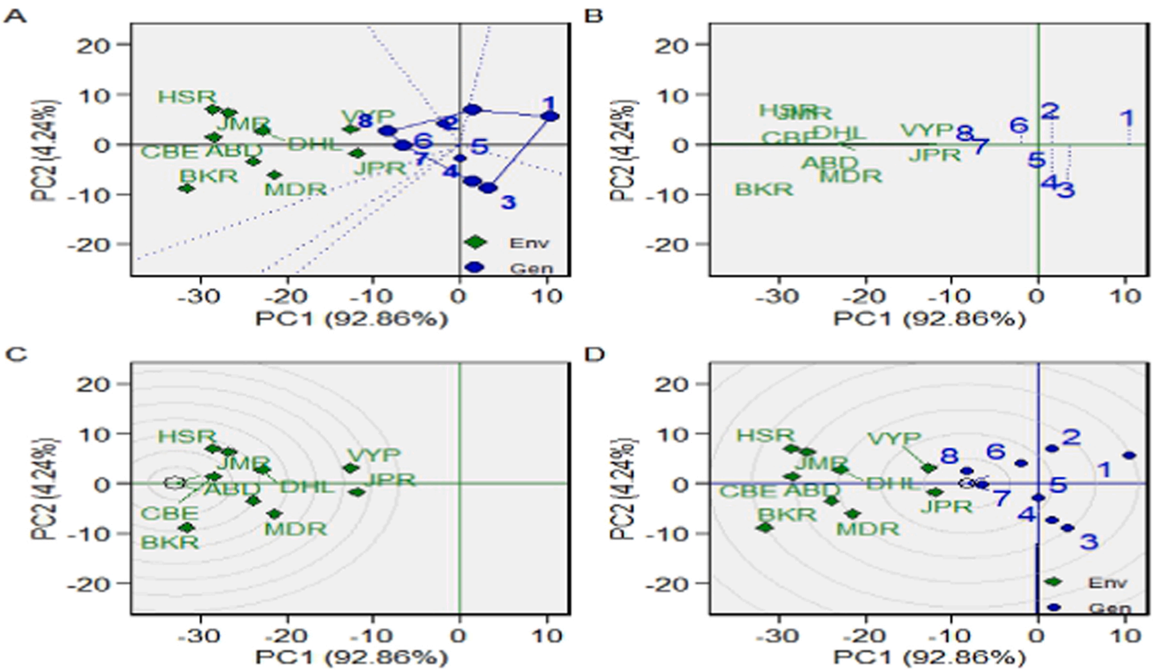

Fig. 5. GGE biplot for water use efficiency (a) 'which won where/what' polygon; (b) 'means vs stability' biplot; (c) Ranking environment polygon and (d) Ranking genotype polygon.

T8 > T7 > T6 > T5 > T2 > T4 > T3 > T1. Like grain yield, T1 also ranked poorest among all the treatments for WUE.

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Super-absorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha; BKR: Bikaner; DHL: Dhule; MDR: Mandor; JPR: Jaipur; JMR: Jamnagar; NDL: New Delhi; HSR: Hisar; KLI: Kalai; ABD: Aurangabad; VYP: Vijayapur; CBE: Coimbatore.

3.5. Soil microbial biomass carbon and enzyme activity

Significant variations were observed among different treatments with respect to soil microbial biomass carbon (MBC). Application of CRM showed (283 µg/g soil) significant improvement (20 %) in MBC over control (234.7 µg/g soil) treatment (Fig. 6). Application of sole SAP also showed a positive effect on soil MBC. However, the effect was significant at moderate (5 kg/ha) and high (7.5 kg/ha) SAP levels with 12.1 % and 10.9 % increase over control, respectively (Fig. 6**a**). Simultaneous application of mulch and SAP (T6-T8) showed further improvement over individual treatments, with T6 showing the highest improvement (32.6 %) followed by T7 (31 %) over the control treatment. Treatment T8 was at par with T2, T4 and T5.

The application of SAP and CRM significantly affected the activity of dehydrogenase enzyme in the soil profile. Dehydrogenase activity was considerably higher than control under CRM treatment (5.91 %) and under SAP treatments (1.6–8.76 %) (Fig. 6**a**). The current study found that the application of CRM in combination with SAP (low and medium levels) enhanced the dehydrogenase activity as observed under T6 and T7. Whilst the higher level of SAP in combination with CRM (T8) showed a slight reduction in dehydrogenase activity as compared to the control treatment. The highest dehydrogenase activity was found at T7 (7.58 µg TPF/g soil/day) and lowest at T8 (6.18 µg TPF/g soil/day).

All the treatments showed significant positive effects on soil alkaline phosphatase activity. It could be seen that CRM application (T2) improved alkaline phosphatase activity by 8.8 % when compared with control (Fig. 6**b**). Among the SAP treatments, moderate levels of SAP (T4) showed a maximum increase of 13 %. In contrast, low-level showed a least increase (3.5 %) in soil alkaline phosphatase activity as compared to control treatment. Further, co-use of CRM and SAP (2.5 and 5 kg/ha) showed 12.7 % and 14.3 % increases, respectively, over control treatment, indicating the positive effect of co-use of CRM and SAP. The treatment T8 (CRM + SAP 7.5 kg/ha) showed a nearly 5 % increase in alkaline phosphatase activity over the control treatment. However, the activity was significantly lower as compared to the T4 treatment (SAP @ 7.5 kg/ha). The highest alkaline phosphatase activity was observed in T7 (69.7 µg/g soil/h) followed by T4 (68.92 µg/g soil/h) and T6 (68.74 µg/g soil/h).

Acid phosphatase activity (Fig. 6**b**) was significantly higher in all the treatments than the control (22.82 µg/g soil/h). Application of CRM (T2) increased acid phosphatase activity by 13.6 % as compared to control and was at par with T3, T5, T6 and T8 treatments. The T4 (SAP 5 kg/ha), closely followed by T7 (CRM + SAP 5 kg/ha) showed maximum values (28.0 and 27.8 µg/g soil/h, respectively) for acid phosphatase activity.

The observations on urease activity revealed variation among treatments, with treatments T2, T3, T4 and T7 showing urease levels lower but at par with control (T1) (Fig. 6**b**). Treatment T6 (CRM + SAP 2.5 kg/ha), showed highest urease content as compared to control treatment with 13.4 % increase over control. Treatments T8 (CRM + SAP 7.5 kg/ha), and T5 (SAP 5 kg/ha) showed non-significant increases of 1.76 % and 1.61 %, respectively, over the control treatment.

3.6. Soil microbial population

Cultivation-dependent approach revealed the effect of different moisture conservation practices on soil bacterial, actinobacterial and fungal populations (Fig. 6**c**). All the individual and co-treatments showed significant (except T8) positive effects on the bacterial population as compared to the control treatment. Treatment T6 (6.909 log10 CFU/g soil) and T7 (6.906 log10 CFU/g soil) showed the highest values for bacterial population; however, were at par with other.

The positive effects of CRM, SAP and their co-application were observed on the fungal population. All the treatments showed significant improvement in the fungal population over the control treatment except T3 and T4 which showed positive but statistically non-significant effects on the fungal population. Application of CRM (T2) showed the highest

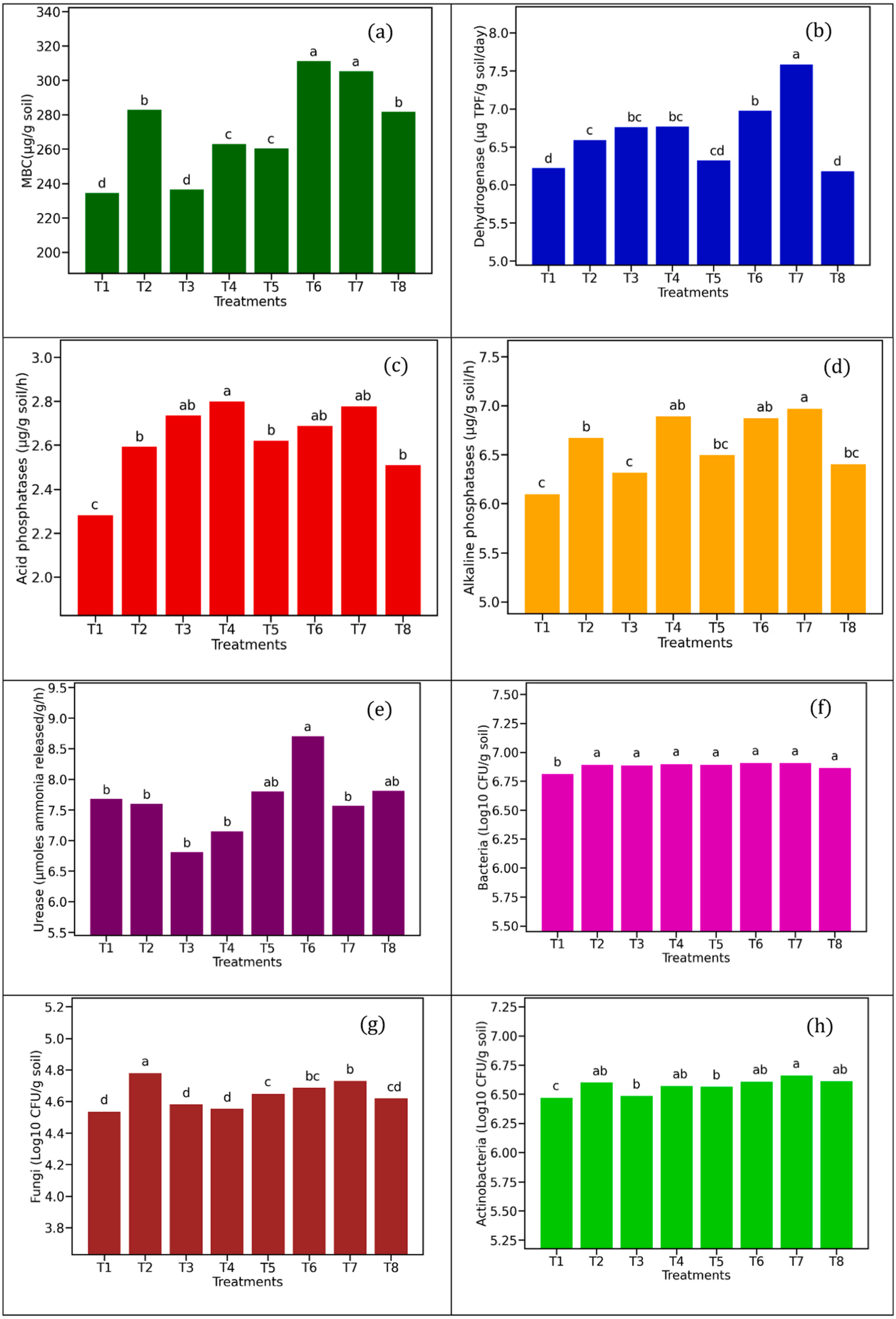

Fig. 6. Effect of moisture conservation practices on soil microbial properties (a) Microbial biomass carbon (MBC); (b) dehydrogenase activities; (c) acid phosphatase; (d) alkaline phosphatase; (e) urease activities; (f) Bacterial count; (g) fungal count and (h) actinobacteria count.

fungal population among all the treatments, closely followed by T7 (CRM + SAP 5 kg/ha) and T6 (CRM + SAP 2.5 kg/ha).

The population of soil actinobacteria also showed improvement under various treatments, with all the treatments except T3 (SAP 2.5 kg/ha) showing significant positive effects over the control treatment. The treatment T7 showed highest actinobacterial populations (6.661 log10 CFU/g soil) followed by T8, T6, T2, (6.610, 6.613, 6.601 log10 CFU/g soil respectively).

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Super-absorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha.

3.6.1. *GGE analysis of microbial activities*

The "which-won-where" polygon view of the biplot (Fig. 7) presents moisture conservation practices and location × year (environment)**.** The first two PCs explained 86.0 %, 88.9 %, 77.2 %, 63.5 %, 92.1 %, 82.5 % and 77.9 % of the cumulative variance caused by treatment and environmental interactions in MBC, dehydrogenase, acid phosphatase, alkaline phosphatase, ureas, bacterial count, fungal count and actinobacteria count, respectively. The polygon view of the MBC biplot had two sectors as mega-environment (Fig. 7**a**). The first mega-environment sector had treatment 7 as vertex treatment (best treatment) and J1, J2, D2 and D3 environments. The second mega-environment sector included T2 as vertex and J3 and D1 environments. No environment fell in the sector where T1, T3, T4 and T5 were located, demonstrating that these treatments were the lowest with respect to MBC. Likewise, in Fig. 7**b** also, two mega-environments were identified; one with vertex as T7 and D1, D2, J2 and J3 environments and the second one with T4 vertex along with D3 and J1 environments.

In acid phosphatase GGE biplots, three mega-environments were found. Treatment 5 was the winner for J1, J2 and D3 environments; T3 for D2 and J3 and T4 for J3 environment (Fig. 7**c**). Polygon view of Fig. 7**d** indicated that among the three mega-environments; T6 was the best for J1 and J3; T5 for J2 and D3 and T7 for D1 and D2. The "which-won-where" biplot for urease activity had divided the biplot into three broad environments, where environments J1 and J3 were in the same group with T6 as the vertex; D1, D2 and J2 were in the second group with T3 vertex and D3 alone were in a separate group with T1 as vertex treatment (Fig. 7**e**).

GGE biplot for bacterial count also had three broad environments (Fig. 7**f**). The first mega-environment sector included treatment T7 as the winner treatment with J1 and J3 environments. The second mega-environment sector included T1 as vertex along with J2 and D3 location × year while the third mega-environment comprised of D1 and D2 environments with T4 as outperformer treatment. A total of four broad-environments were identified for fungal count (Fig. 7**g**)**,** one having D1 and J1 environment with T2 as best treatment; the second one containing D2 and D3 environments with T3 as vertex; the third having T5 winner treatment and J2 environment and the fourth group included J3 environment with T7 vertex. In the actinobacteria count GGE biplot, two mega-environments were found. Treatment 7 was the outperformer for J1, J2, J3 and D1 environments; while T8 for D2 and D3 environment (Fig. 7**h**).

T1: Control; T2: Crop residue mulch 5.0 t/ha (CRM); T3: Super-absorbant polymer (SAP) 2.5 kg/ha; T4: SAP 5.0 kg/ha; T5: SAP 7.5 kg/ha; T6: CRM + SAP 2.5 kg/ha; T7: CRM + SAP 5.0 kg/ha; T8: CRM + SAP 7.5 kg/ha; D1: Delhi 1st year; D2: Delhi 2nd year; D3: Delhi 3rd year; J1: Jodhpur (Mandor) 1st year; J2: Jodhpur 2nd year; J3: Jodhpur 3rd year.

The means vs. stability biplot indicated that treatment T7 had the greatest parameter mean value, as well as good stability; therefore, this treatment is best with respect to MBC, dehydrogenase and actinomycetes count (Supplementary Fig. 5). Treatment T4 and T2 were the best performers for acid phosphatase as they have higher mean value and stability whereas T6 was found superior in performance and stability for alkaline phosphatase, urease and bacterial count. In the case of the fungal count, T2 had the highest mean value whilst less stability. Therefore, T7 and T6 exibiting good performance and stability, were identified as the best treatments for this parameter.

4. Discussion

In this study, SAP application along with CRM enhanced tillering up to 42 % over control (Fig. 2**b**), grain yield up to 45 % (Fig. 3) and stover yield up to 36 % (Fig. 3). This improvement in crop growth and

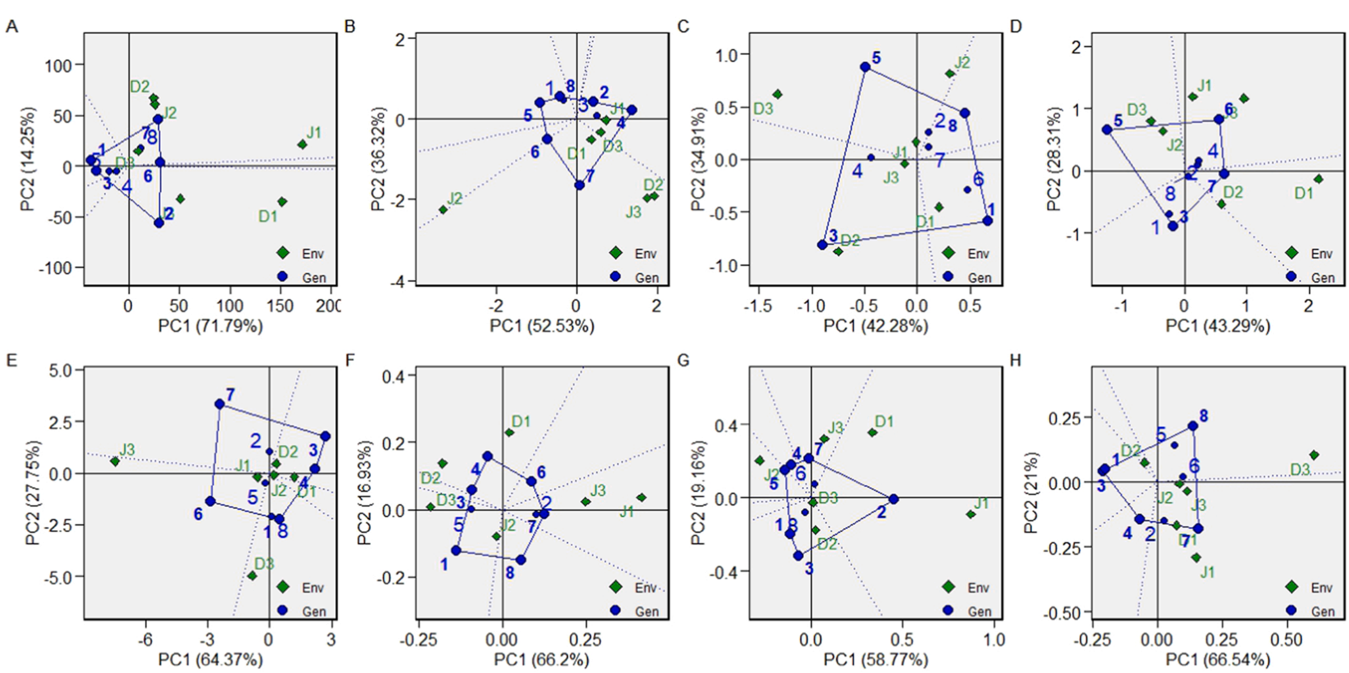

Fig. 7. GGE biplot (Which won where/what polygon) for soil microbial enzymatic activities and microbial populations (a) Microbial biomass carbon (MBC); (b) dehydrogenase activities; (c) acid phosphatase; (d) alkaline phosphatase; (e) urease activities; (f) Bacterial count; (g) fungal count and (h) actinobacteria count.

productivity may be attributed to favorable effects of surface residues retention on soil physico-chemical and biological properties (Bana et al., 2018), especially soil moisture retention (Kumar et al., 2021), soil organic carbon enrichment (Kumar et al., 2021, 2020), nutrient bio-availability (Singh et al., 2018) and temperature moderation. Furthermore, adequate supply of moisture enhanced the growth and biomass production of respective crops directly and indirectly by increasing the bio-availability and utilization of applied and native nutrients (Tetarwal and Rana, 2006; Choudhary et al., 2020). Also, better soil surface covering under CRM resulted in reduced weeds and water losses, besides promoting better root anchorage with higher crop yields (Bana et al., 2018; Singh et al., 2018). Application of SAP also played a key role in enhanced soil moisture retention and its availability, which could have favorably enhanced plant growth and yield under SAP applied treatments (El-Hady and Abo-Sedera, 2006; Narjary and Aggarwal, 2014).

Though the greatest growth and yields were observed in the combined application of CRM and SAP, SAP alone – even at the lowest dose – resulted in yield gains of 0.36 t/ha (Fig. 3). The SAP application increases the soil porosity, which again resulted in improved root growth due to enhanced oxygen/air availability, nutrient bio-availability and moisture availability in the root zone (Dar et al., 2017; Bana et al., 2018). The SAP also had favorable effects on bulk density and infiltration rate of soil (Dar et al., 2017) and improved the soil nutrient status indirectly either by lowering the soil pH and nutrient bio-availability, and also through enhanced SOC due to better plant growth and biomass accumulation (El-Saied et al., 2016; Gunes et al., 2016). In a previous study, the application of SAP at the rate of 5 kg/ha significantly improved plant population, the number of effective tillers, plant height, and grain yield in rainfed wheat (Roy et al., 2019) and co-application of SAP (5 kg/ha) and farm yard manure (FYM) significantly improved the hydrological properties like field capacity, plant available water content and hydraulic conductivity in an alluvial sandy loam soil (El-Hady and Abo-Sedera, 2006). The GGE analysis highlighted that the co-use of CRM and SAP produced the most stable results across pearl millet growing agro-ecologies. Among the environments, New Delhi (NDL) was the ideal location for pearl millet cultivation (Fig. 6**c**). It was probably due to the fact that NDL falls in semi-arid conditions, and faces less water stress – both low and high water stress – in comparison to other ecologies. Bikaner (BKR) and Vijayapur (VYP) were the least desirable locations. As the BKR is situated in the heart of the Thar Desert, it faces adverse soil and weather conditions; and the VYP is located in the dry tract of the *Deccan* plateau with the rain shadow effect of the Nilgiri Hills resulting in intermittent stress to the crops. Likewise, the year one and two at Coimbatore (CBE) locations, environments behaved differently than others (Fig. 7**a**). The reason may be clay loam soils and tropical conditions in South India and the application of irrigation during two out of three years as the region falls under the rain-shadow zone of the mighty hill series of western-ghats during southwest monsoons (coinciding with the pearl millet growing season). The rest of the locations were placed in a single mega-environment, as all other locations receive monsoon rains during crop periods. Among the experimental years and locations, the first year at location Dhule (DHL1) was the highest yielding and most responsive environment due to an equitable temporal distribution of rains in good amount (615 mm).

The presence of organic (crop residues) mulch over the land surface improved the WHC and soil structure, thus leading to minimized evaporation and enhanced soil water content compared to the control. In the present study, the combined application of CRM and SAP enhanced the water use efficiency (WUE) of pearl millet up to 58 % (Fig. 4). A higher increase in pearl millet yield was observed under the combined application of CRM and SAP compared to the other treatments. Further, better growth (Fig. 2**a**) and increased microbial activity (Fig. 5**a,b,c**) lead to the proliferation of the root system due to greater translocation of photosynthates to roots under reduced stress scenarios resulting in the extraction of more moisture from deeper soil profile (Tetarwal and Rana, 2006; Faiz et al., 2022) could be another cause for greater WUE.

Soil microbial biomass plays an important role in the biogeochemical cycling of nutrients in the soil through the production of various enzymes involved in mineralization and immobilization processes, thus it is crucial in maintaining soil health. The soil environment and cultivation practices influence soil microbial health (Lal et al., 2019). Several indicators can be applied to gauge the effect of agronomic management on the soil microbial biomass, including, MBC, enzymatic activity, and the status of the microbial population. In our present study, the application of CRM had a stimulatory effect on soil MBC, microbial populations, and soil enzymatic activities at both locations. Better microbial status in Delhi soils may have been attributed by better rainfall and soil physico-chemical properties of Delhi soils as compared to Jodhpur soils. Better moisture regime and soil properties help improve plant growth and root development, thus increasing root exudates' availability for microbial proliferation (Grover et al., 2021). In our study, it was observed that the application of CRM improved soil microbiological parameters over control treatment, which may be owing to the improved soil moisture and soil condition. This resulted in increased plant biomass and had a positive effect on the rhizosphere (Jabran, 2019; Tang et al., 2020). The application of CRM along with SAP further improved the soil microbiological parameters indicating the interactive effect of mulch and SAP. Šarapatka et al. (2006) reported improvement in studied soil biological and biochemical parameters under the application of hydro-absorbents, TerraCottema. As many of the soil microorganisms can degrade cellulose, the added SAP might provide additional nutritional support for the growth of the microorganisms. However, studies need to be conducted on the biodegradation of added SAP in the soil environment. Treatment with CRM and moderate SAP (5 kg/ha) was found to be the best and most stable in terms of the majority of the soil microbiological parameters. Higher levels of SAP applied either individually or in combination with CRM resulted in reduced expression of microbiological health parameters as compared to that under lower doses of SAP, indicating the inhibitory effect of a higher dose.

In the present study, observations on depth-wise soil moisture and nutrient contents and microbial activity at different crop growth stages (temporal variations) remained a major limitation. The study provided some leads on the effects of various interventions on the population of only cultivable, heterotrophic soil microbial groups which is a limitation associated with the classical approach used. The use of biochemical markers based profiling and/or metagenomic tools can help in studying the influence of SAP treatments on soil microbial community structure and functions in depth. Further, the influence of soil load on SAPs water retention i.e., absorbency under load (AUL), has not been examined in the present work. In the future scope, the authors intend to overcome the abovementioned limitations by incorporating the left-out factors and delivering other uncovered perspectives of the present study.

5. Conclusion

Climate-resilient crops like pearl millet possess the potential to contribute considerably to the nutritional security in the drought-prone food systems of the globe. For tackling moisture- and thermal-stress effects on crop plants, the application of superabsorbent polymers (SAP), either alone or coupled with crop-residue mulches (CRM), are prospective technologies, among other adaptation strategies. From the multi-location field trials, representing almost the entire pearl millet cultivation domains of India, we have demonstrated that simultaneous application of CRM and SAP resulted in stable and substantially greater pearl millet grain yields and enhanced water use efficiency (WUE) across the environments (location × year). In addition, the co-use of polymers (2.5–5.0 kg/ha) and organic mulches also improved soil enzymatic activities and microbial populations. From the present experiments, to overcome the moisture-stress problem and to achieve stable and greater productivity, WUE and soil microbial activity gains, we recommend the simultaneous application of CRM 5 t/ha and SAP 2.5 kg/ha across diverse pearl millet production systems. Future research is required to understand how to improve crop and water productivity and economic feasibility in other fields and horticultural crops and to standardize appropriate management recommendations for SAP use in agriculture under long-term trials. Furthermore, mathematical cropping system models can be calibrated and validated to analyze the long-term SAP use effects under various representative concentration pathways of futuristic climate.

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CRediT authorship contribution statement

R.S. Bana: Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Minakshi Grover:** Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Shanti D. Bamboriya:** Data curation, Formal analysis, Writing – review & editing. **Samarth Godara:** Data curation, Formal analysis. **Manoj Kumar:** Conceptualization, Investigation. **Anil Kumar:** Conceptualization, Investigation. **Seema Sharma:** Investigation. **P.S. Shekhawat:** Investigation. **Dinesh Lomte:** Investigation. **H.M. Bhuva:** Investigation. **Sadhana R. Babar:** Investigation. **Ravindra T. Suryawanshi:** Investigation. **V. Vasuki:** Investigation. **Nirupama Singh:** Formal analysis. **Vikas Khandelwal:** Funding acquisition. **Anil Kumar:** Data curation. **Anupama Singh:** Conceptualization. **C. Tara Satyavathi:** Funding acquisition, Project administration. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126876.

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