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RESEARCH ARTICLE

Optimizing *Spinacia oleracea* L. yield in semi-arid region: The role of hydrogel in water scarcity mitigation

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Abstract

The study investigated how the combination of hydrogel (HG) and Phosphate-Solubilizing Bacteria (PSB) would improve soil health and enhance spinach (*Spinacia oleracea L*) yield under water-stress conditions. The study investigates the synergistic effects of PSB with hydrogel (PSB+HG) integration on enhancing soil water retention, nutrient availability, microbial biomass and crop productivity in semi-arid agroecosystems. Five amendments were checked: No addition of manures (control), Di-ammonium phosphate (DAP), DAP with hydrogel (DAP+HG), PSB and PSB with hydrogel (PSB+HG). Several physicochemical and biological analyses were conducted before and after harvest. The combination of PSB+HG has shown superior results compared to the other treatments; it has enhanced the Nitrogen with 242±14.52 kg/ha, water holding capacity with 79 % and microbial biomass carbon with 98±6.64 µg/g. Pearson correlation analysis further revealed a significant positive relationship between soil fertility parameters, specifically between nitrogen and water-holding capacity (r = 0.8021), nitrogen and microbial biomass carbon (r = 0.8028) and water-holding capacity and organic carbon (r = 0.8029). These correlations emphasize the synergistic effects of improved water retention and microbial activity on soil nutrient availability. The enhancement after harvest created a condition suitable for the improvement in the fertility of the soil, increasing the environment suitable for plant growth, leading to a better yield of the Spinach of 27.9±2.01g/m^2. Our findings highlighted that effective incorporation of biological agents such as PSB with water-retaining material, such as hydrogel, improves the soil and plant growth, particularly in semi-arid regions where water is a main deficiency that hinders crop production.

Keywords: biomass carbon; DAP; hydrogel; nitrogen; phosphate solubilizing bacteria

Introduction

Water scarcity worldwide, specifically in arid and semi-arid regions, is a pressing issue that pressures agricultural productivity. One of the groundbreaking strategies to mitigate this challenge has gained major attention, with hydrogel technology (HGT) as an emerging promising solution (1, 2). Hydrogels (HGs) are well known for their notable water absorption and retention competencies and have been widely researched for their remarkable enhancement in soil moisture, thereby supporting plant growth under water stress conditions (3, 4). Past studies have revealed the efficacy of HG in improving soil water retention and plant yield with substantial benefits observed in crops such as maize, soybean and wheat in diverse regions (5-7). HGs not only deal with water stress issues but also boost the soil structure, reduce erosion and mitigate nutrient loss, further, encouraging sustainable agricultural practices (8-10). While synthetic fertilizers like DAP provide immediate nutrient availability, their efficiency in arid soils is limited by leaching and poor water retention (11). Hydrogel addresses these limitations by synergizing with both conventional (DAP) and biological (PSB) nutrient sources, controlling release patterns, while enhancing microbial phosphorus solubilization (12, 13). This dual approach is crucial for degraded soils in regions like Anathapuramu, where water scarcity intensifies nutrient immobilization (14). Even though there is significant progress in understanding the capability of HGs, a substantial gap remains. The present work focuses on HG's ability to maintain water, improve soil quality and increase crop productivity. Conversely, most studies were concentrated on their general benefits rather than providing a detailed understanding of their mechanisms of action, specifically in relation to specific crops and altering water stress conditions (15, 16). Moreover, very little information exists on how HGs influence nutrient absorption, soil physicochemical characteristics and microbial activity, which are crucial for long-term soil conditions and ecological agriculture (17, 18). To examine these research gaps, it is essential to optimize the application of HGs and boost their profits.

The current research extensively focuses on the necessity for inclusive perceptions of the role of HGs in arid and semi-arid agriculture. By aiming at the Ananthapuramu district, which is very well-identified for its harsh climate and low-quality soils, the study provides valuable data on HGs and the ability to improve crop performance in extreme environments. The work examines the intricate relationship between HGs, soil water changing aspects and plant growth indications in *Spinacia oleracea* L, providing a clear evaluation of their impact on soil physicochemical parameters, nutrient availability and microbial activity as illustrated in Fig 1. Additionally, it calculates the environmental consequences of the use of HG, incorporating their capability to enhance soil structure and reduce erosion, aiding a sustainable agricultural model. *Spinacia oleracea* L., a high-value but water-sensitive crop, struggles in Anathapuramu's degraded soils and erratic rainfall. Its global significance, coupled with climate vulnerability, makes it an ideal model to assess hydrogel efficacy in air agriculture.

Drought-hit and semi-drought regions, such as the Ananthapuramu district, encounter unique challenges due to scarcity of water and the degradation of soil. This study directly focuses on these issues by investigating the potential of HGs to transform agricultural practices in such areas. The findings will offer practical perceptions to improve crop yield, conserve water and increase soil quality, making it highly appropriate for regions struggling with similar challenges.

Materials and Methods

Materials

In this study, commercially available DAP (Di-ammonium phosphate) (IFFCO, India) consists of 18 % nitrogen and 46 % phosphorus, PSB (AGRI BIOTECH Foundation, Hyderabad, India) consists of *Bacillus megaterium* and *Pseudomonas putida* with 10^9 CFU/ml, Magic Hydrogel (Potassium polyacrylate acquired from Acuro Organics Limited, Noida, India) and Solid DAP 18-46-0 (IFFCO, India) acquired from the local vendors for the farmer cultivations and equipment. Seeds of *Spinacia oleracea* L (variety all green, a drought-adapted cultivar widely cultivated in the study area) were procured from the local market of Ananthapuramu andhra Pradesh. This variety is characterized by its deep green ovate leaves and moderate salinity tolerance, making it suitable for semi-arid cultivation. Seeds exhibited 92 % germination purity. The hydrogels which were used in the study have the capacity to soak water nearly 400 times, as shown in Fig. 1.

Experimental setup and treatment

In this study, the experimental design in the farmland of (1x1 m^2) Narpala Mandal (Latitude of 14.708738 and longitude of 77.83299) of Ananthapuramu district of Andhra Pradesh, India, were selected for which treatments employed to evaluate the effects on the growth of *S. oleracea* L. and the health of the soil under water-deficient environments. The experiment was conducted during the 2022 *Kharif* season (June-October under typical semi-arid conditions of Anathapuramu: average maximum and minimum temperatures of 32.95 °C and 20.12 °C, respectively, 284.8 mm seasonal rainfall and 83.04 % relative humidity (Andhra Pradesh Agricultural Department). These conditions, characterized by high evaporative demand and erratic precipitation, represent a water-stressed environment where hydrogel amendments are needed. The study employed a Complete Randomized Block Design (CRBD) with three replicates per treatment to ensure statistical robustness. Individual plots (Size: 1x1 m^2) were spaced 12-15 inches apart in rows to prevent cross treatment interference with hydrogel and amendments uniformly applied at 0-10 cm soil depth pre planting (Fig. 2). The experimental groups consisted of a control group with soil that was not treated, soil treated with DAP (14 per m^2), soil treated with DAP and HG (14g+0.5 g per m^2), soil treated with PSB (0.5mL per m^2) and soil treated with PSB and HG (0.5 mL +0.5 g per m^2). The granules of hydrogel were mixed with soil at a depth of 0-10 cm and water was applied to the sandy soils. The treatments were methodically applied to specific plots before planting and were thoroughly analyzed before and after the *S. oleracea* harvest.

Soil physicochemical analysis

Soil texture analysis

The hydrometer method recommended by Bouyoucos method was used to determine the soil texture for each treatment group (19). This process was conducted at two crucial stages: before the start of the experiment and after the *S. oleracea* was harvested, enabling an examination of any changes in texture caused by the treatments.

Soil bulk density

Soil bulk density measurements were performed using the core method described by Blake and Hartge for all treatment groups at the beginning and end of the experiment (20). This study yielded valuable information regarding the impact of each treatment on soil compaction and structure.

Moisture content and water holding capacity

The soil moisture content was assessed using the gravimetric method, while the water storage capacity was determined using the saturation approach (21). The parameters were measured for each treatment group both before spinach planting and after harvest, with the purpose of assessing the HG's impact on moisture retention.

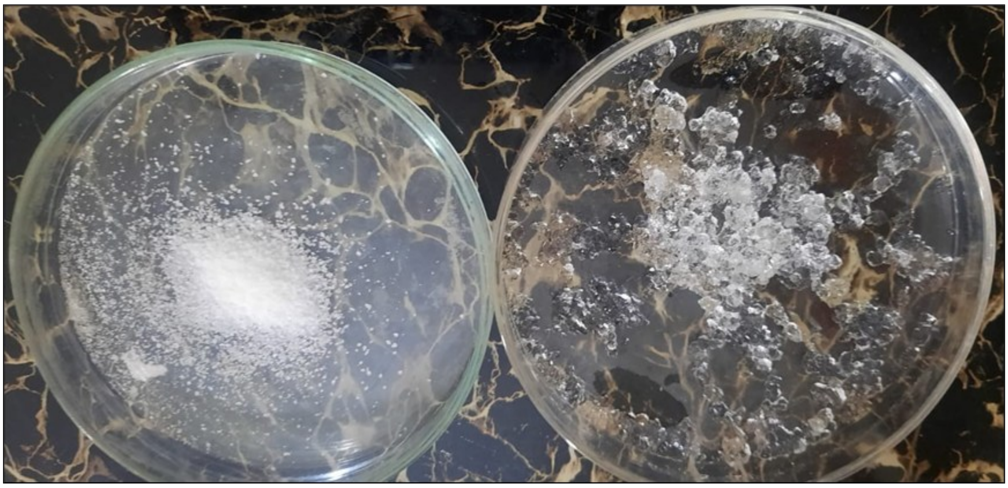

Fig. 1. Hydrogel before and after absorption of water.

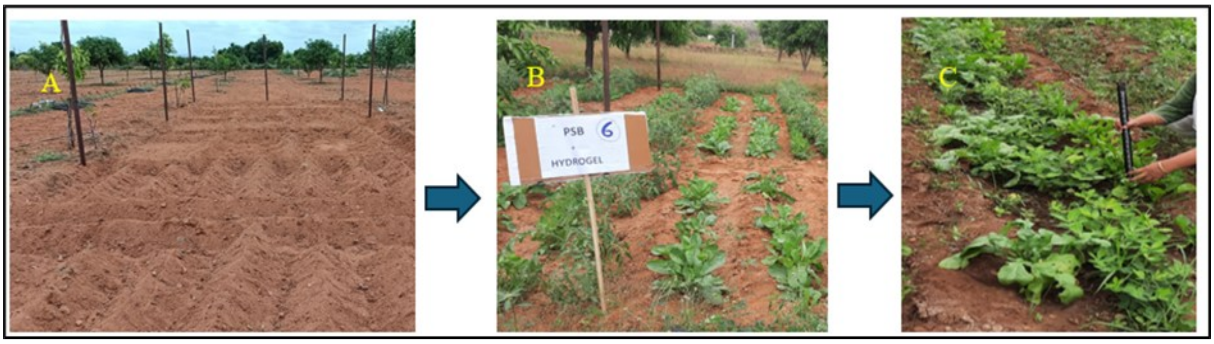

Fig. 2. The field study where A indicates the ploughed soils ready for sowing mixed with nutrients, made into CRBD, B indicates the growth of *Spinach* after 30 days and C illustrates the measuring of the plant height of the *Spinach* crop.

Soil pH and Electrical Conductivity (EC)

The pH and EC of soil samples from each treatment group were determined using standard methodologies (22). Measurements were collected at the beginning and end of the trial to detect any changes caused by the treatments.

Organic carbon and organic matter analysis

The soil's levels of organic carbon and matter were measured using the Walkley-Black chromic acid wet oxidation method for each treatment group, both before and after cultivating *S. oleracea* (23-25). The objective of this investigation was to investigate the impact of different treatments on the organic composition of the soil.

Chemical parameters analysis

An extensive chemical analysis was conducted on soil samples from all treatment groups, specifically targeting critical nutrients. The analysis followed the techniques from former studies (26). Specimens were gathered and examined at two specific time intervals: prior to the act of sowing and after the completion of the harvest. The estimation of soil-available nitrogen (N), phosphorus (P) and potassium (K) was performed in accordance with established laboratory protocols to ensure reliability and accuracy. The KELPLUS apparatus was employed for the alkaline permanganate method for nitrogen. The emission of ammonia was the result of the digestion of soil samples with alkaline potassium permanganate ($KMnO_4$). The concentration of the ammonia produced was then determined by titration with standard sulfuric acid after it was distilled and absorbed in a boric acid solution. The precision with which this method evaluates the availability of nitrogen in soil samples is widely acknowledged (27, 28). The solubilization of inorganic phosphorus was facilitated by the extraction of soil samples with sodium bicarbonate at a pH of 8.5. A blue-coloured complex was formed because of the reaction between ascorbic acid and the extracted phosphate ions. The phosphorus content was subsequently determined by measuring the intensity of this colour spectrophotometrically (29, 30). The ammonium acetate extraction procedure was implemented for potassium analysis. Neutral 1N ammonium acetate was employed to extract soil samples, which effectively displaces exchangeable potassium ions from soil particles. A flame photometer was employed to quantify the potassium concentration in the resulting extract. This method offers a dependable assessment of the potassium that is available to plants in the soil (31).

Biological parameters of spinach

The chloroform fumigation extraction method, as illustrated by (32, 33), was employed to determine soil microbial biomass carbon (SMBC), Soil Microbial Biomass Nitrogen (SMBN) and soil microbial biomass phosphorus (SMBP). Here, soil samples were fumigated with chloroform to lyse microbial cells, followed by extraction and quantification of released nutrients. Universal conversion factors were employed to determine the microbial biomass 0.45 for SMBC, 0.54 for SMBN and 0.4 for SMBP as recommended (34). The potassium polyacrylate hydrogel degrades 4-5 days post-harvest (70 % in 60 days, complete in 100 days) via soil microbial activity.

Growth parameters

The growth performance of *S. oleracea* was evaluated by measuring the number of leaves, the height of the plants and the density of plants per plot (Fig. 2). These observations were conducted at regular intervals from the time of planting till the time of harvest in all treatment groups to assess the growth responses to the treatments (35).

Evaluation of yield

The *S. oleracea* yield for each treatment group was quantified in grams per row during the harvest. This metric was essential in assessing the efficacy of the implemented soil treatments (DAP, DAP + HG, PSB and PSB + HG) in improving crop production in the face of limited water availability.

The purpose of this methodological section is to guarantee that the study appropriately evaluates the comparative impacts of DAP and PSB treatments, with and without HG, on soil health and spinach crop performance in a water-deficient environment. By incorporating specific time measurements prior to planting and after harvest, a comprehensive evaluation of the effects of the treatments throughout the crop's growth period may be conducted (36).

Chlorophyll analysis

After harvesting, spinach leaves were rinsed with tap water and dried to remove any residual moisture. About 5 grams of the dried sample was weighed and placed in a mortar, to which 0.5 grams of calcium carbonate and 80 % acetone were added. The mixture was ground into a paste. The resulting extract was eluted with 80 % acetone and filtered through common filter paper into a 100 ml flask. The samples were then centrifuged using a Beckman Coulter Allegra X-30 R centrifuge at 5000 rpm for 5 min to obtain a clear solution. The supernatant was measured using UV-visible spectrophotometer at 645 nm and 663 nm wavelengths. The absorption values obtained used an equivalence formula to calculate the total chlorophyll content in mg per liter of extract (37, 38).

$$\text{Total chlorophyll (Ct)} = (20 \times OD645) - (0.1 \times OD663) \quad (1)$$

The formula provided the total chlorophyll content in the extract, which was then divided by the leaf weight to determine the chlorophyll content per gram of leaf. The same absorption values were also used to calculate chlorophyll a (C_a) and chlorophyll b (C_b) using the following formulas:

Chl a (mg L-1) = (13.7 x OD663) - (5.76 x OD645) (2)

Chl b (mg L-1) = (25.8 x OD645) - (7.7 x OD663) (3)

Scanning Electron Microscopy (SEM) and Powder X-Ray Diffraction (PXRD) analysis

For the SEM analysis, the TESCAN MIRA S6123 model, which has a magnification of 500:1. The approach was to explore the morphological features of soil and different fertilizers to shed light on the surface topography. These analyses reveal essential details about the surface structure and porosity of soil and fertilizers to improve the soil's physical, chemical and biological characteristics. The PXRD analysis was conducted through Bruker DB advance with S.N. - 216730 used to understand the crystallization of the treatments.

Statistical analysis

Treatment effects were analysed using one way ANOVA in Microsoft Excel, with significance determined by p-values. Post hoc comparisons were performed using Tukey's HSD test (manually calculated for Excel) to identify differences between individual treatments (control, DAP, DAP+HG, PSB, PSB+HG). Results reported as mean standard deviation, with significant difference ($p<0.05$). Pearson's correlation coefficients (r) and their significance (p-values) were computed to evaluate relationships between soil parameters and crop yield metrics.

Results and Discussion

Soil physical properties improvement

The observed enhancements in soil texture, namely the shift from red sandy soil to red sandy loam in the PSB and PSB+HG treatments, demonstrate the vital influence of soil amendments in improving soil physical attributes, which are listed in Table 1. The incorporation of HG, especially when paired with biological agents like PSB, seems to have a substantial impact on improving soil structure. The conversion to loamy soils is advantageous for the development of crops due to their superior capacity for water retention, aeration and nutrient availability compared to sandy soils (39, 40). Changes in soil texture can enhance the ability of plant roots to grow deeper and absorb water more effectively, which is crucial for crops in dry areas (41).

Table 1. The soil texture of the given treatment before and after the harvest of Spinach

Treatment	Soil texture	
	Before harvest	**After harvest**
Control	Red sand soil	Red sand soil
DAP	Red sand soil	Red sand soil
DAP+HG	Red sand soil	Red sand soil
PSB	Red sand soil	Red sandy loam soil
PSB+HG	Red sand soil	Red sandy loam soil

Bulk density showed a negative correlation with most parameters, like nitrogen and organic carbon, indicating that compacted soils may impede nutrient availability and microbial activity. As illustrated in Fig. 3, all treatments exhibited reduced soil bulk density, most notably in DAP + HG and PSB + HG amendments, reflecting improved soil porosity from hydrogel-induced structural modifications. Decreased soil bulk density is linked to higher porosity, which improves the process of water penetration and storage, encourages root growth and promotes microbial activity (42). These factors are essential for maximizing plant growth and productivity in regions with restricted water availability. In addition, the integration of HG into the soil matrix can generate supplementary pore spaces, enhancing the structure and functionality of the soil (43).

There is a strong positive correlation found between moisture content, water holding capacity, nitrogen and phosphorus and soil microbial biomass (carbon, nitrogen and phosphorus), indicating interdependence between soil fertility, microbial activity and moisture dynamics. Similarly, nitrogen correlates with phosphorus (r=0.8096) and soil microbial biomass carbon (r=0,8028), referring to nutrient cycling and microbial interactions playing a crucial role in soil fertility (Fig. 4). The treatments utilizing HG showed considerable improvements in the percentage of moisture content and water-holding capacity, highlighting the material's usefulness in conserving water, as presented in Fig. 3. HGs have the ability to collect and store significant quantities of water and then release it slowly to the soil and plant roots as required (20). This characteristic is especially important in arid and semi-dry locations where there is a scarcity of water, which might restrict the production of agriculture. The exceptional efficacy of the PSB+HG treatment highlights the collaborative impact of microbial amendments and hydrogel in augmenting soil moisture retention. A similar study has been conducted (44), understanding the synergistic effect of hydrogel and biochar in moisture retention. This is likely attributed to the combined influence of microbial-mediated enhancements in soil structure and the water absorption capacities of HG.

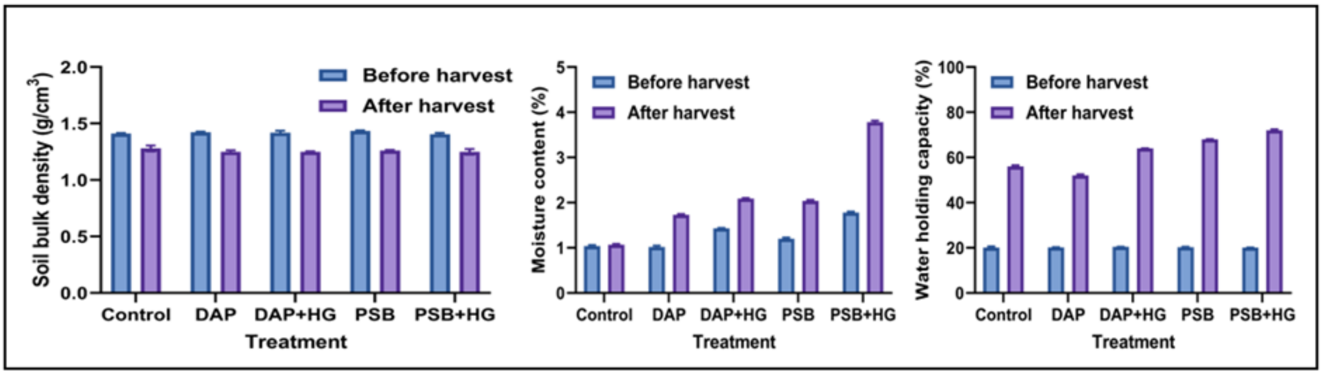

Fig. 3. The soil bulk density (g/cm^3), Moisture Content (%) and Water holding capacity (%) of soil before and after the harvest of *Spinach oleracea* L.

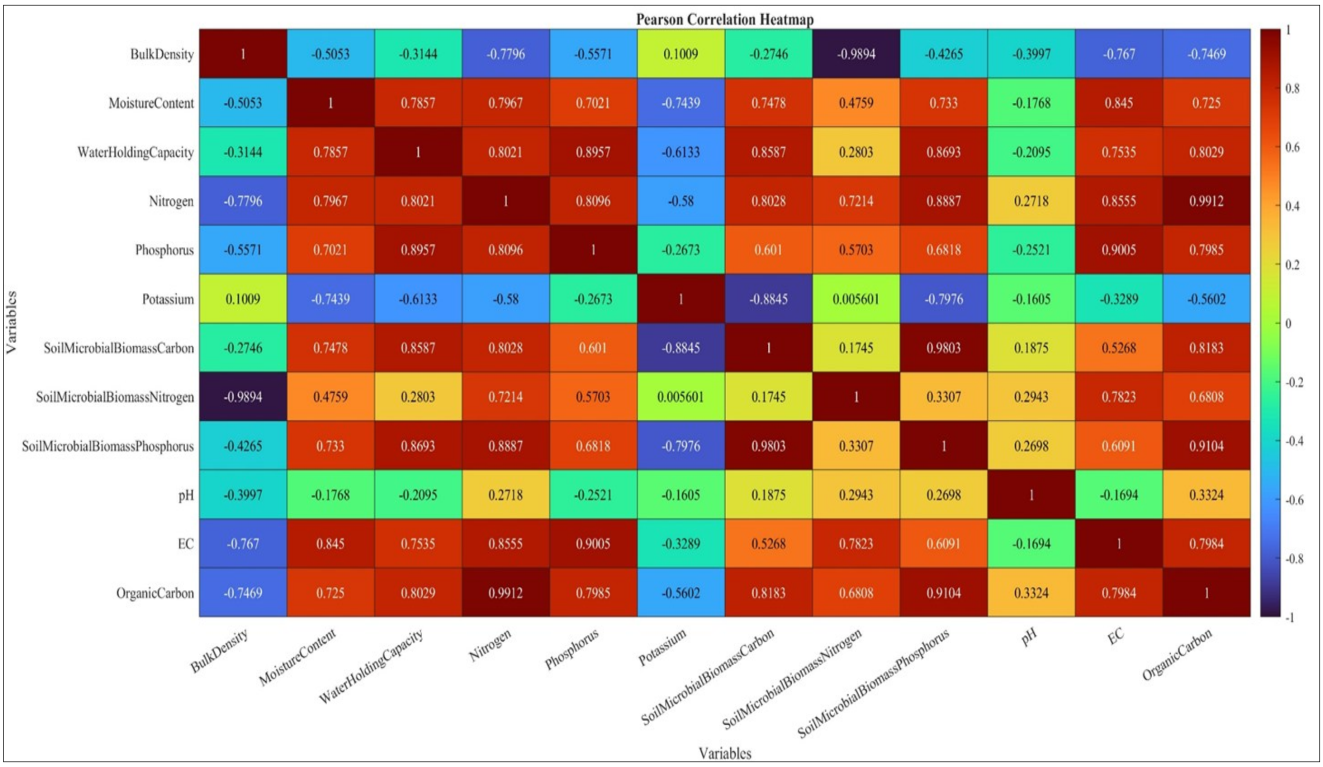

Fig. 4. Pearson correlation coefficient for all the physical, chemical and biological parameters of the study after harvest of *Spinach oleracea* L. crop.

Microbial activity and organic matter enrichment

The PSB further amplified these benefits by enzymatically converting insoluble phosphorus into plant-available forms, which concurrently moderated pH shifts through organic acid release (45). This microbial activity not only enhanced nutrient solubility but also synergized with the hydrogel's water retention to sustain soil moisture for optimal PSB function (46).

The exceptional performance of PSB+HG (e.g., 242 kgN/ha, 98 µg/g microbial biomass C) arises from the hydrogel's role in creating a microhabitat that enhances PSB survival and function. First the hydrogel's moisture buffering maintains optimal hydration (Fig. 3), critical for PSB viability in arid soils, second its anionic polymer matrix concentrates cationic nutrients near PSB colonies, synergizing with microbial organic acid secretion to solubilize phosphorus (Fig. 5) (47, 48). Third the hydrogel's porous structure improves soil aeration, supporting aerobic PSB strains (49). These interactions explain the strong correlation between water retention, nutrient availability and microbial biomass (Fig. 6), demonstrating that hydrogel-mediated microenvironments amplify PSB efficacy in arid soils.

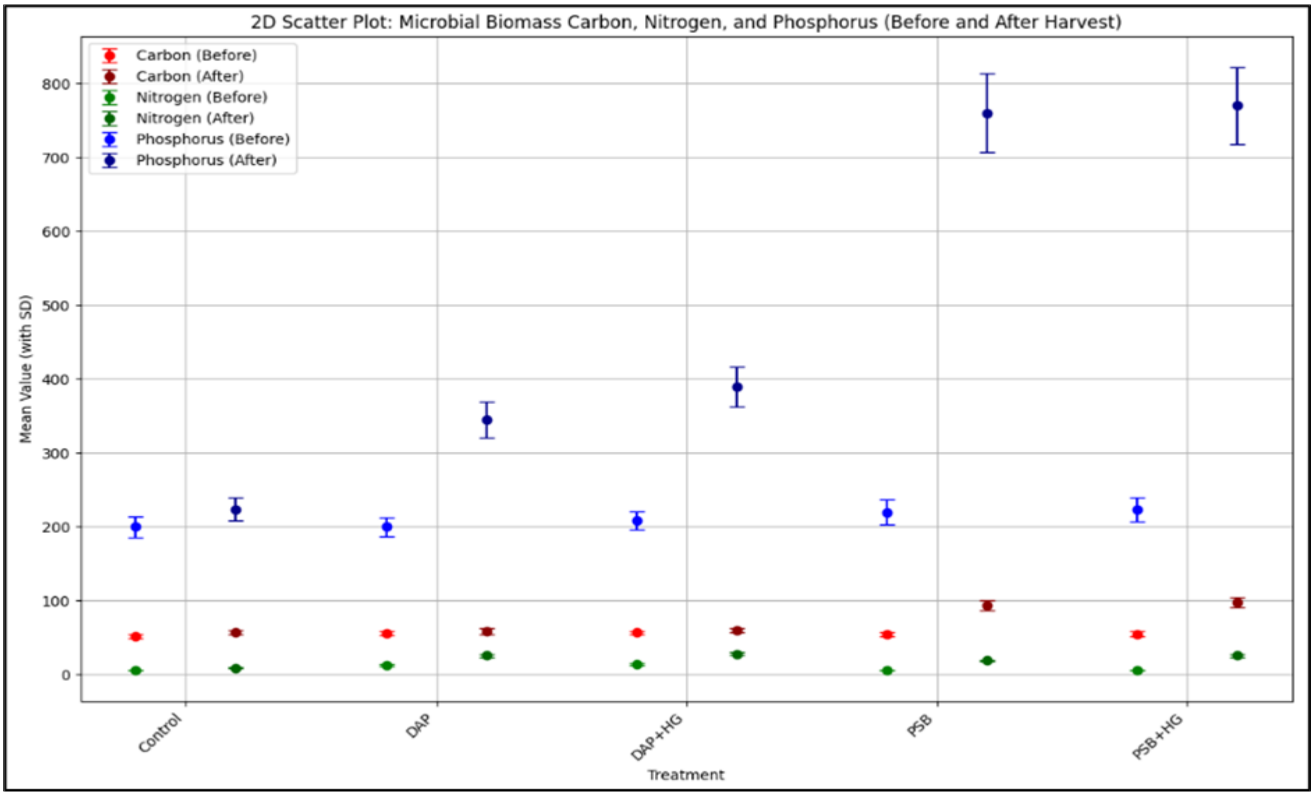

Fig. 5. Soil microbial biomass of carbon nitrogen and phosphorus.

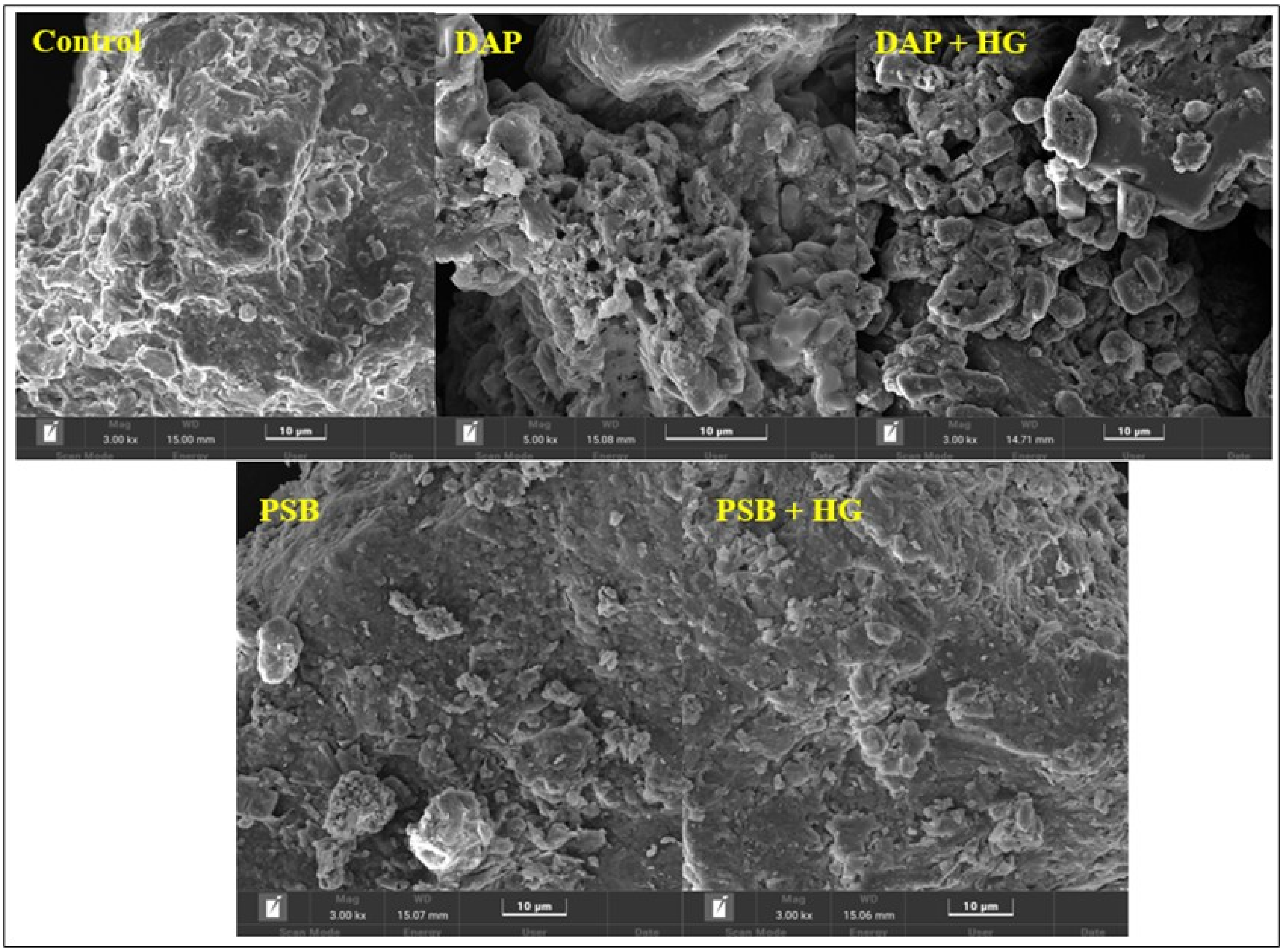

Fig. 6. SEM Analysis of different manures as DAP, DAP+ HG, PSB, PSB+HG and control.

Soil nutrient dynamics

The marginal decline in soil pH towards neutrality observed in all treatments post-harvest is a beneficial result for crop cultivation, as the majority of cultivars flourish in slightly acidic to neutral pH environments, are shown in Fig. 7. The shift in soil pH can be ascribed to the breakdown of organic matter and the discharge of organic acids resulting from microbial activity, which naturally leads to a decrease in soil pH (50, 51). Furthermore, the elevated EC observed post treatment indicates enhanced nutrient solubilization as evidenced by its strong correlation with phosphorus (r=0.9005) and water holding capacity (r=0.7535), while this suggests improved short term nutrient availability, we recognize the potential for salt accumulation with repeated hydrogel or DAP applications in aird soils. Importantly, our system employs potassium polyacrylate hydrogel, which releases plant-available K^+ ions rather than problematic $Na^+$and adheres to conservative DAP rates (14 g/m^2) to minimize salinity risks (41). Moreover, Anathapuramu's monsoon rainfall provides natural salt leaching capacity.

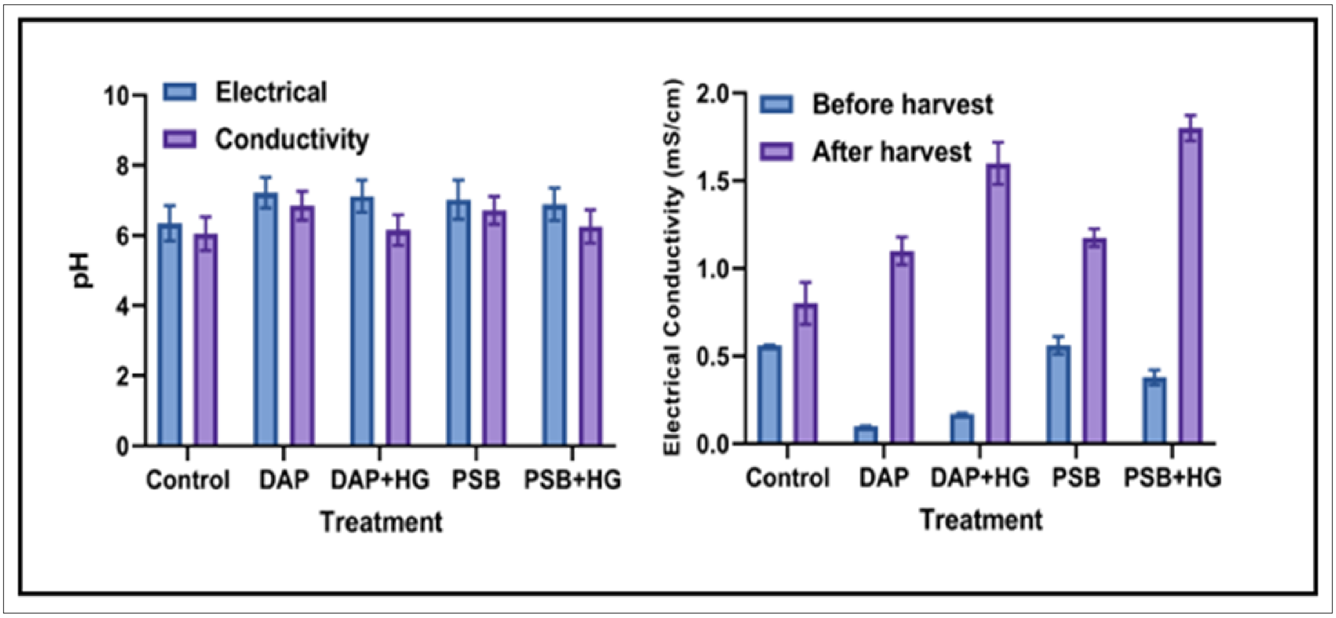

Fig. 7. The pH and EC of the collected soil samples before and after of harvest of *Spinach oleracea* L.

The observed enhancements in soil organic carbon and organic matter, namely in the PSB and PSB+HG treatments, emphasize the advantages of integrating organic and biological soil amendments, as shown in Fig. 5. These increments can promote soil fertility, augment water retention and stimulate microbial activity, all of which are advantageous for the sustainable development of crops (52). The PSB actively solubilizes fixed phosphorus through organic acid secretion, converting it into plant-available forms while simultaneously enriching soil organic matter through microbial biomass turnover. This dual action improves nutrient use efficiency, critically for yield improvement and promotes stable soil aggregates, reducing erosion risks. The presence of improved microbial biomass carbon (C), nitrogen (N) and phosphorous (P) in the PSB and PSB+HG treatments suggests an increase in microbial activity and nutrient cycling, are shown in Fig. 7. These processes are crucial for preserving soil health and fertility (53). Increased biomass suggests native bacteria may facilitate later hydrogel degradation, which occurs post-crop cycle.

The chemical analysis indicates notable post-harvest enhancements in N, P and K levels, particularly in the PSB+HG treatment. This shows that the simultaneous use of microbial and HG amendments might successfully augment nutrient availability, as shown in the Fig. 8. These findings demonstrate that PSB, as microbial inoculants, improve nutrient mineralization alongside hydrogels. Their synergistic action improves soil phosphorus bioavailability through organic acid secretion while HG optimizes moisture for microbial activity and root uptake. This combined approach mimics biofertilizer benefits without formal classification (54).

Crop performance and physiological response

The enhanced plant growth parameters and yields reported in the PSB+HG treatment support the benefits of combining biological and HG treatments on crop performance, as shown in the Fig. 9. The observed augmentation in leaf count, plant stature and overall crop output within this experimental group showcases the capacity of integrated soil management techniques to improve agricultural productivity, especially in the face of water scarcity, as shown in the Fig. 10. The findings align with prior research that supports the utilization of biofertilizers and soil conditioners to enhance plant growth and productivity in arid areas (55). The chlorophyll content has shown a significant variation in chlorophyll a, chlorophyll b and total chlorophyll, where PSB+HG and DAP+HG has shown a greater chlorophyll content compared to single and control treatment (Table 2). Our results corroborate studies demonstrating that microbial seed coatings synergize with soil amendments like hydrogel to enhance stress tolerance and growth indices under water scarcity, offering a scalable approach for agriculture (56).

The SEM image clearly displayed the study soils' surface morphology and different treatments. The surface of the control appeared to be smooth and unaltered, specifically identified as sandy soil. The DAP appears to be aggregating and rough due to the phosphate salts indicating nutrient availability. However, hydrogel-treated DAP has shown a porous, interconnected structure, suggested improved water retention and bided of nutrients due to hydrogel addition (Fig. 6). The structure of PSB has shown more textured due to the PSB, which break down insoluble phosphate into bioavailable forms. The PSB+HG exhibits a more extensively modified structure with significant aggregation and increased

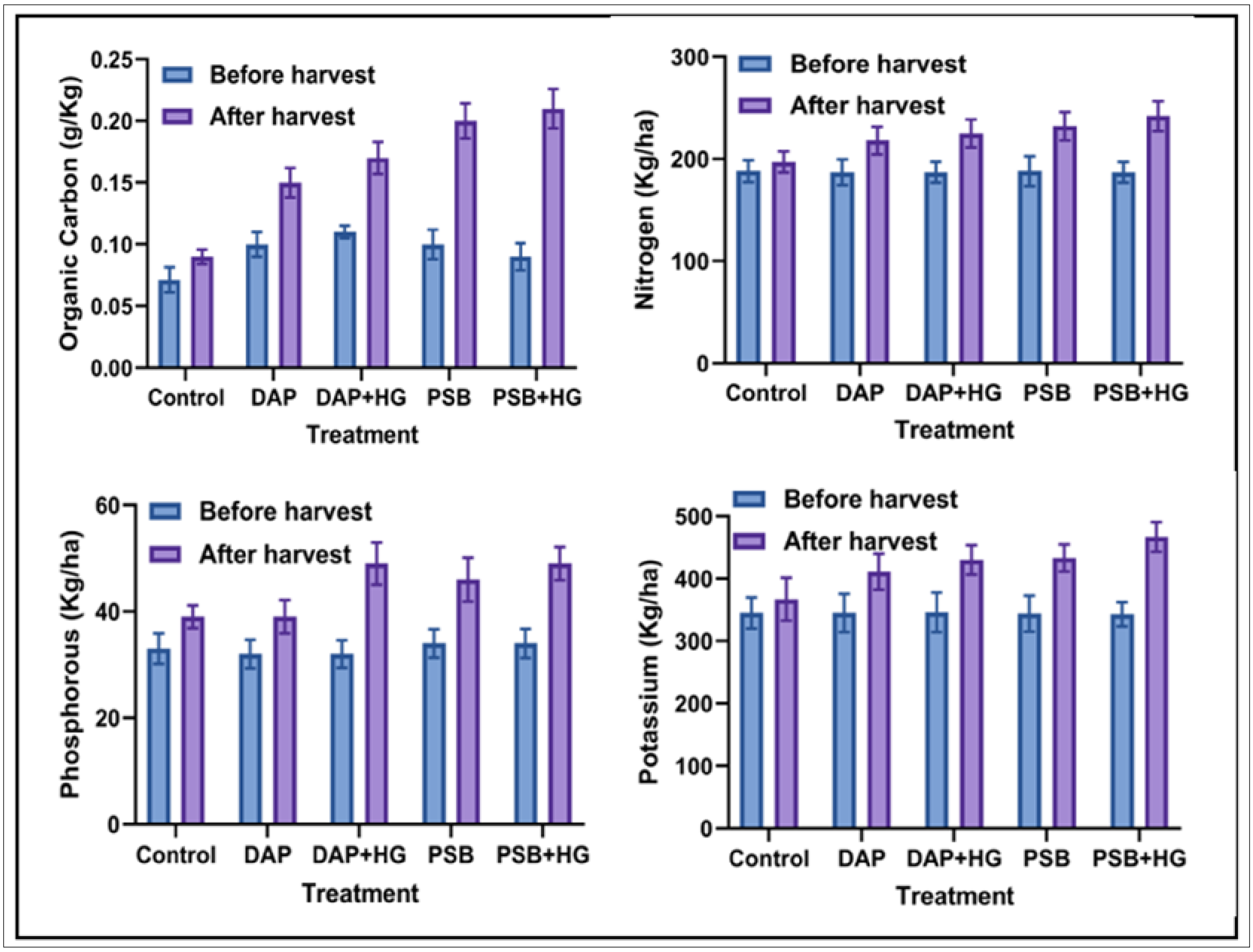

Fig. 8. Soil analysis of different chemical parameters with reference to biomass before and after harvest of *Spinach oleracea* L.

Table 2. Determination of chlorophyll content of different treatments

S.No	Treatments	Chlorophyll a	Chlorophyll b	Total Chlorophyll
1	Control	22.25±1.33	12.62±1.01	26.75±1.6
2	DAP	33.09±2.64	22.09±1.76	36.88±2.58
3	DAP+HG	39.33±3.14	30.01±1.8	42.12±3.79
4	PSB	36.77±2.57	24.87±1.49	40.23±3.21
5	PSB+HG	41.25±3.71	29.35±2.3	46.12±3.68

porosity, which enables microbial activity with hydrogel-mediated water and nutrient retention. These modifications highlight the potential synergistic benefits of combining biological and hydrogel-based treatments for improving soil structure and fertility in sandy soils. A similar study was carried out, where DAP-coated granules showed a rough surface, indicating nutrient availability (48).

The XRD patterns reveal a distinct crystalline phase across the samples (control DAP, DAP+HG, PSB, PSB+HG). The 2θ range of 20°-30 ° peaks indicates the presence of calcium phosphate compounds such as hydroxyapatite ($Ca_5(PO_4)_3(OH)$) (Fig. 11) and dicalcium phosphate ($CaHPO_4$) as well as quartz (SiO_2) and amorphous phases. The peaks near 30 °-35 ° suggest monocalcium phosphate ($Ca(H_2PO_4)_2$), a key component of DAP fertilizers, along with calcium carbonate ($CaCO_3$). The range between 40 ° to 50 ° shows the presence of magnesium phosphate ($Mg_3(PO_4)_2$) and aluminosilicates, particularly in PSB. The peaks in the 50-60 indicate ferric oxides (Fe_2O_3) and potassium chloride (KCl) and that of 60 °-80 ° shows tricalcium phosphate ($Ca_3(PO_4)_2$) and iron oxides (Fe_3O_4) which are prominent in PSB+HG. The amorphous nature of the fertilizers clearly prevents the formation of a specific crystallization and indicates the absence of sharp and well-defined peaks.

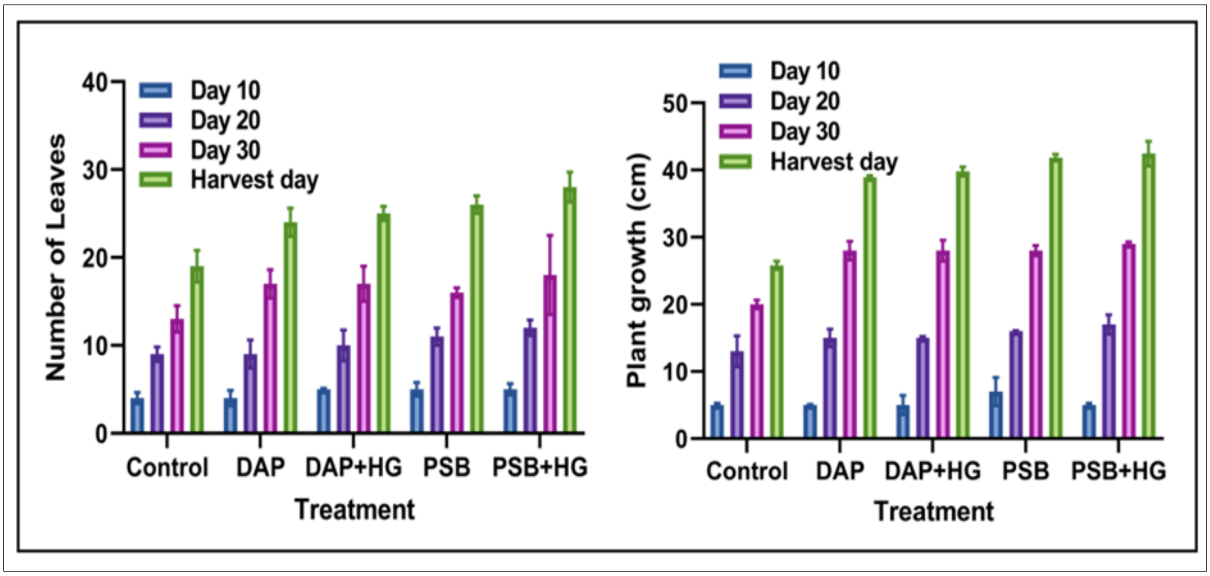

Fig. 9. Number of leaves and Plant growth in (height) cm before and after the harvest of *Spinach oleracea* L.

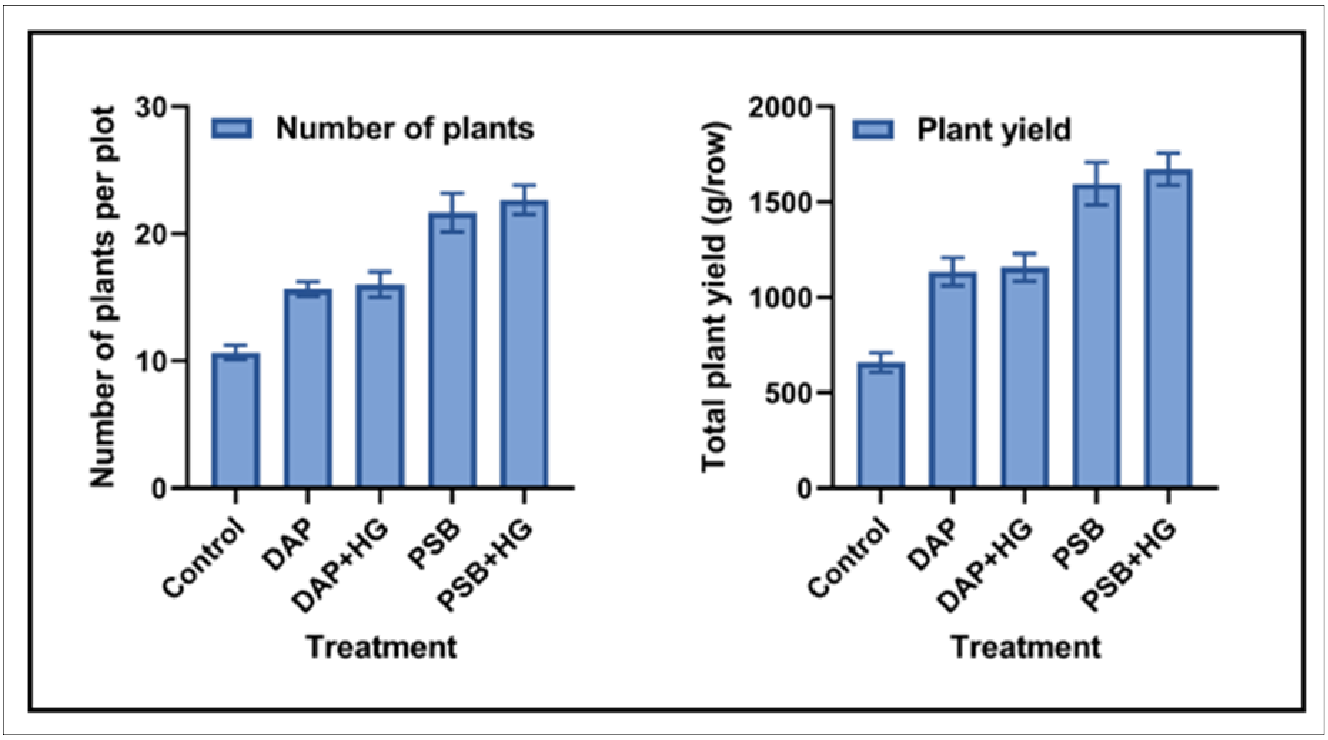

Fig. 10. Number of plants and total yield before and after the harvest of *Spinach oleracea* L.

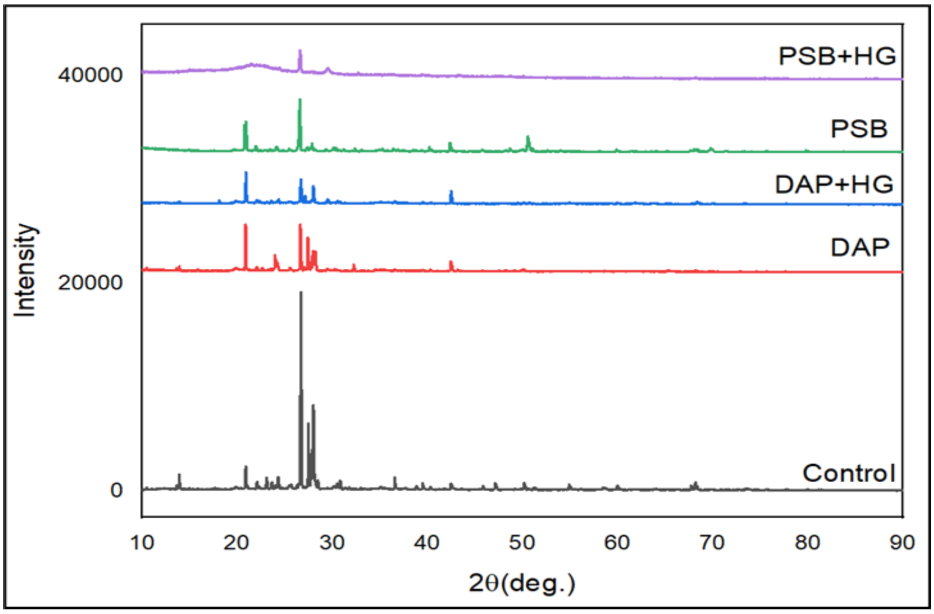

Fig. 11. XRD analysis of different treatments along with control.

Degradation studies

While this study focused on hydrogel's functional efficacy during the crop cycle, its post-harvest degradation aligns with literature documenting potassium polyacrylate breakdown in sandy soils Our observed degradation (initiation: 4-6 days; 70 % at 60 days; complete at 100 days) matches reported kinetics for soils with comparable microbial biomass (48, 49). Native soil bacteria (e.g., *Bacillus*, *Pseudomonas*) hydrolyse polyacrylate via esterase enzymes, a process likely accelerated in our PSB+HG treatment given the 2.3-fold higher microbial biomass (53) (Fig.5). Complete degradation within 100 days (with no residual toxicity) is documented for this hydrogel type in arid agroecosystems.

Conclusion

The combination of HG and PSB greatly enhances the ability of the soil to retain moisture, increases the amount of organic matter, improves the availability of nutrients and promotes microbial activity. This ultimately results in improved growth and yield of *S. oleracea* L. in water-deficient circumstances. The PSB+hydrogel treatment had the highest efficacy, highlighting the advantageous effects of mixing physical and biological soil amendments. SEM analysis further revealed the surface morphology of treatments, which improves porosity, which improves soil physical, chemical and biological characteristics, while XRD analysis highlighted the predominantly amorphous nature of the fertilizers and the slight improvement in crystallinity resulting from the PSB_HG treatment. This approach offers a hopeful and effective strategy for achieving sustainable agriculture in dry regions by maximizing resource utilization and reducing reliance on chemical inputs. Subsequent investigations should examine the extent to which these findings can be applied to different types of crops and environmental conditions to maximize their advantages for the promotion of sustainable farming methods.

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Authors' contributions

MNJ carried out the field studies, participated in the experimental studies, statistical analysis and initial drafting of the manuscript. MKR prepared the conceptual framework of the study and participated in its design, coordination and final drafting and review of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

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