

Research Article

Enhancing drought resilience and sustainability in *Solanum lycopersicum* L cultivation: Synergistic effects of nano-fertilizer and hydrogels

M. Naga Jayasudha

Department of Life Sciences (Environmental Science Division), GITAM School of Sciences, GITAM (Deemed to be University), Visakhapatnam-530045 (Andhra Pradesh), India

M. Kiranmai Reddy*

Department of Life Sciences (Environmental Science Division), GITAM School of Sciences, GITAM (Deemed to be University), Visakhapatnam-530045 (Andhra Pradesh), India

A. Madhavi

Department of Microbiology, Karnatak University, Dharwad-580003 (Karnataka), India

*Corresponding author. E-mail: kmajji@gitam.edu

Article Info<https://doi.org/10.31018/jans.v17i2.6560>

Received: January 17, 2025

Revised: May 21, 2025

Accepted: May 29, 2025

How to CiteJayasudha, M. N. *et al.* (2025). Enhancing drought resilience and sustainability in *Solanum lycopersicum* L cultivation: Synergistic effects of nano-fertilizer and hydrogels. *Journal of Applied and Natural Science*, 17(2), 753 - 759. <https://doi.org/10.31018/jans.v17i2.6560>**Abstract**

Drought has a significant impact on agricultural practices in arid and semi-arid regions, reducing the quality of soil and impairing crop productivity. Innovative strategies are required to improve soil health and utilize optimum resources to overcome this situation. Despite improvements in fertilizer technology, there remains an essential research gap in understanding the synergistic effects of nano-fertilizers and hydrogels in mitigating water scarcity and enhancing nutrient efficiency. The present study explored the ability of Nano DAP fertilizer and hydrogels to improve soil parameters and the productivity of *Solanum lycopersicum* L (tomato) under drought conditions of Ananthapuramu district of Andhra Pradesh for two consecutive years (2022-2024). Five amendment combinations were analyzed: a control, traditional DAP fertilizer, DAP with hydrogel, Nano DAP, and a combination of Nano DAP and hydrogel. Of all these treatments, Nano DAP with hydrogel has shown significant improvement ($p < 0.05$), an enhanced water-holding capacity (78 ± 0.85 & $79 \pm 1.22\%$), and a reduction in bulk density (1.18 ± 0.051 & $1.15 \pm 0.03 \text{g/cc}$). Moreover, the treatment also improved the soil nitrogen by 199 ± 15.92 & 220 ± 29.1 kg/ha and organic carbon content (0.25 ± 0.017 & $0.026 \pm 0.013\%$, $p < 0.05$) respectively. The treatment also enhanced soil microbial activity, further improving micronutrient availability. The key findings display the potential of combining Nano DAP, hydrogel, and DAP with hydrogel as a sustainable approach to mitigate drought impacts, enhance soil properties, and improve agricultural productivity. The study emphasizes the need to further investigate nano-fertilizer and hydrogel technologies as scalable solutions for resilient and sustainable agriculture in drought-prone regions.

Keywords: Diammonium phosphate, Drought, Hydrogel, Nano-diammonium phosphate, *Solanum lycopersicum* L**INTRODUCTION**

The stress of drought is a significant question in global agriculture, specifically in arid and semi-arid regions, where water scarcity severely restricts crop production and soil quality. Recent improvements in agricultural sectors have emphasized the crucial role of hydrogels and nano fertilizers in minimizing the adverse effects of drought on crops. Hydrogels are well known for their better absorbent properties, which enhance soil water retention and nutrient availability, thus supporting plant growth under water-deficient conditions (Patra *et al.*, 2022). The past study reflects that using biodegradable hydrogels has been shown to conserve water, sustain

nutrients, and improve agricultural productivity during hydrological droughts (Skrzypczak *et al.*, 2020). However, hydrogels extracted from agricultural waste, such as watermelon rind, have explained substantial improvements in soil water retention, increasing drought resilience in barley by 77.46% (Teng *et al.*, 2024). These observations pose the versatility and effectiveness of hydrogels in improving drought tolerance across diverse cropping systems. Parallel to the advancements in hydrogel technology, nano fertilizers have emerged as a transformative solution for improving nutrient delivery and mitigating abiotic stresses. In previous research, nano-chelated fertilizers have improved water use efficacy and decreased yield losses

in wheat under minimal irrigation conditions (Tang *et al.*, 2023). Similarly, nano-silicon fertilizers have been reported to enhance physiological traits and nutrient uptake in crops exposed to drought stress (El-Beltagi *et al.*, 2023). The fusion of these technologies provides a synergistic approach to resolving the dual challenges of water scarcity and nutrient inefficiency in modern agriculture.

The combined treatment of hydrogels and nano fertilizers has improved drought resilience and enhanced crop productivity. In a study by Sharma *et al.* (2021), nano-composite hydrogels exhibiting nitrogen, phosphorus, and potassium fertilizer have been found to regulate nutrient release effectively while maintaining soil moisture. The synergistic use of iron oxide nanoparticles and hydrogels increased biomass and antioxidant enzyme activities under drought stress in rice cultivation, as to George *et al.* (2019). These findings emphasize the significance of exploring integrated approaches that leverage the strengths of both hydrogels and nano fertilizers.

Despite these innovations, significant research gaps remain in understanding these technologies' long-term impacts and scalability in diverse agroecological contexts. The benefits of hydrogels in maintaining soil structure and fertility during drought conditions have been validated in crops such as rice and wheat (Rajanna *et al.*, 2022), their performance in other value-added crops like *Solanum lycopersicum* L (tomato) remains underexplored. Likewise, the role of nano fertilizers in modulating osmolyte metabolism and improving antioxidant activities in tomatoes has been studied (Ahanger *et al.*, 2021), but there is a limited understanding of their combined effect with hydrogels on soil health and crop yield. Additionally, the environmental advantages of these technologies, such as reduced chemical usage and improved ecological sustainability, warrant further exploration to establish their potential as an alternative to traditional agricultural practices (Singh *et al.*, 2023).

The present study addresses the research gaps by assessing the combined effects of hydrogels and nano fertilizers on soil parameters and the productivity of *Solanum lycopersicum* L under drought conditions. This study aimed to understand sustainable strategies for improving agricultural resilience in drought-affected regions by systematically assessing the impacts of different treatment combinations, including traditional fertilizers and nano fertilizers, and their integration with hydrogels.

MATERIALS AND METHODS

In this study, commercially available liquid NANO DAP (Di-ammonium phosphate) (IFFCO, India), MAGIC HYDROGEL (Poly acrylate -Acuro Organic Limited Noida,

India) and solid DAP 18-46-0 (IFFCO, India) were procured from local agricultural vendors in Hyderabad. Seeds of *Solanum lycopersicum* L were also fetched from the local market in Ananthapuramu. The study was conducted in the arid region of Ananthapuramu district of Andhra Pradesh, India (latitude of 14.71031 and longitude of 77.8117), characterized by low annual precipitation averaging 600 mm, which radically reduces agricultural productivity.. Soil samples were collected from disparagingly water-lacking regions both before and after harvest. Standard physicochemical characteristics, including soil texture measured by Bouyocous method (Mwendwa 2022), bulk density was calculated by Blake and Hartage method (Jabro and Mikha 2021), moisture content using the gravimetry method (Susha *et al.*, 2014), water holding capacity, pH, electrical conductivity (EC) by Rhoades (Wang *et al.*, 2014) organic carbon (C) by Walkley-Black Chromic acid wet oxidation method (Nelson & Sommers, 1982), nitrogen (N) was determined by Kelpus apparatus, phosphorus (P) was measured by Olesences method (Olsen 1954), potassium (K) was determined by ammonium acetate extraction method (Hafez *et al.* 2021), microbial assessment such as soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN), was assessed by chloroform fumigation method (Witt *et al.*, 2000) were measured to confirm uniformity and suitability for *S.lycopersicum* L cultivation.

A completely randomized block design (CRBD) with five treatment groups and three replicates was used to estimate the effectiveness of fertilizers and hydrogels under drought conditions. Treatments included a control, full-dose traditional DAP (0.014 kg/sqm) (Chuma *et al.*, 2022), DAP with hydrogel (0.014kg/sqm + 0.00049 kg/sqm) (2% w/w), nano DAP at 50% dosage (0.12 ml/sqm), and nano DAP combined with hydrogel (0.12 ml/sqm + 0.5mg/sqm) (2% w/w). Hydrogel exhibited a 400 g/g water absorption capacity, and nano DAP facilitated gradual nutrient release. Seedlings were transplanted with 50x50 cm spacing. Irrigation followed local practices until controlled drought stress was imposed at the mid-flowering stage by withholding irrigation for 14 days. The nano DAP foliar application was performed. For every 25 days of the interval, the plant height of the selected crop was measured. Once the yield was taken, the complete height was measured.

Data analysis

Data were statistically assessed using ANOVA and Tukey's HSD test to determine significant differences ($p < 0.05$) between treatments.

RESULTS AND DISCUSSION

The soil texture for all amendments, including control, DAP, DAP+Hydrogel, Nano DAP and Nano

Table 1. Soil physicochemical and biological characteristics of studied regions

S.No.	Parameters	2022-2023	2023-2024
1	Soil Texture	Red sandy soil	Red sandy soil
2	Soil Bulk Density (g/cc)	1.51±0.007	1.49±0.010
3	Water Holding Capacity (%)	25.1±0.41	26.3±1.0
4	Moisture content (%)	1.44±0.03	1.40±0.08
5	pH	6.35±0.50	6.66±0.43
6	Electrical Conductivity (dS/m)	0.56±0.005	0.57±0.005
7	Organic Carbon (%)	0.09±0.004	0.10±0.007
8	Nitrogen (kg/ha)	167±10.3	171±18.3
9	Phosphorus (kg/ha)	36±2.44	39±4.33
10	Potassium (kg/ha)	351±28.17	362±33.87
11	Soil Microbial Biomass Carbon (µg/g)	51±3.22	54±3.45
12	Soil Microbial Biomass Nitrogen(µg/g)	6±0.32	6.5±1.20

DAP+Hydrogel, persisted uniform as red sandy soil both before and after harvest of the two consecutive year study of 2022 to 2024, as shown in Tables 1 and 2, which indicated that the applied treatments did not alter the intrinsic physical properties of the soil during a short period of time. Soil texture is a basic parameter that typically remains unchanged in the short term, agreeing with earlier research by Kiani *et al.* (2017), who remarked that soil alterations mostly influence chemical and biological parameters rather than physical texture. The stability of the red sandy soil texture improves its suitability for evaluating the effects of moisture-retaining extracts in this study.

The bulk density of the soil reduced significantly across all amendments, with the Nano DAP + Hydrogel treatment displaying the most noticeable reduction from 1.51±0.007 & 1.49±0.010 g/cc before to 1.18±0.051 & 1.15±0.03 g/cc post-harvest (Table 2). This decline emphasizes the improvements in soil structure accelerated by hydrogel incorporation, which generates micropores and increases porosity. The past study by Narjary and Aggarwal (2014) similarly reported reduced compaction in hydrogel-treated soils, which increases root penetration and water transport. The addition of Nano DAP further braced these structural enhancements by promoting particle aggregation, consistent with observations from Dimkpa *et al.* (2023). These reductions in bulk density are particularly beneficial in semi-arid conditions, as they improve aeration and root development, a crucial factor for plant growth. Soil water-holding capacity improved remarkably in hydrogel-treated plots, with the Nano DAP+hydrogel amendment attaining the most significant improvement from 29.3 ± 0.15% in 2022-23 years & 26.3±1.0% 2023-24 years pre-harvest to 78 ± 0.85 & 79±1.22% post-harvest (Table 2). The results emphasize the superabsorbent properties of hydrogels, which can retain and gradually release water into the soil. Skrzypczak *et al.* (2020) have given a similar study where the biodegradable hydrogel significantly improves water retention and mitigates crop stress. Furthermore, including Nano DAP + hydrogel improved water retention by reducing nutrient leaching, as corroborated by Teng *et al.* (2024), who

also showed that combining hydrogels with nano fertilizers improved soil hydration and nutrient efficiency in silt loam type of soil in Los Ban ños, South-Luzon . These findings suggested the effectiveness of such combinations in drought regions where water conservation is essential. Similarly, the moisture content of the soil also enhanced incredibly in the hydrogel-treated plots, with the nano DAP + hydrogel amendment attaining the highest post-harvest value of 2.17 ±0.13 & 2.91±0.23 % (Table 2), indicating the provision of hydrogels for the consistent water supply to the plants even during the extended dry periods. Similar findings showed that hydrogel prolongs soil moisture retention and improves crop resilience in sandy loam soils of Meybod (Yazd province, Iran) (Besharati *et al.*, 2022). The synergistic action of Nano DAP complements this benefit by releasing nutrients in alignment with water availability, as observed in earlier studies by Dimpka *et al.* (2023).

The pH of the soil remained constant in all treatments, with the Nano DAP + Hydrogel treatment maintaining a near neutral of 6.08±0.43 & 7.10±0.68 post-harvest (Table 2). This stability is crucial for optimizing nutrient availability and microbial activity. Dimpka *et al.* (2023) reported that nano fertilizers help regulate soil pH in phosphate-depleted soils from New Haven, Connecticut, United States, by inhibiting the rapid accumulation of acidic residues, thereby assisting long-term soil fertility. Even the EC has shown an increment in all amendments, with the DAP treatment showing the highest value of 1.6±0.12 & 1.56±0.71 dS/m. This specifies nutrient accumulation in the soil, which is reliable with the findings of Dou *et al.* (2023) in Atlanta, US, who stated that hydrogels and nano fertilizers decrease leaching loss, improving nutrient retention and conductivity. The organic carbon content increased significantly with the Nano DAP + Hydrogel treatment, showing the highest post-harvest value of 0.25 ±0.078 & 0.26±0.013 % (Table 2). This increment ($p<0.05$) implies enhanced organic matter decomposition due to the moisture-retaining properties of hydrogels, which create promising conditions for the activity of microbes. Hydrogel-treated soils exhibit higher organic carbon

Table 2. Soil physicochemical and biological characteristics after the harvest of the crop

Treatments/ Parameters	ST	SBD (g/cc)		SWHC (%)		SMC (%)		pH		EC dS/m	
		2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024
Control	Red Sandy soil	1.38±0.025	1.36±0.10	55±0.37	56±0.78	1.47±0.001	1.49±0.10	6.05±0.48	6.12±0.31	0.8±0.12	0.86±0.13
DAP	Red Sandy soil	1.28±0.015	1.22±0.09	60±0.40	63±1.22	1.83±0.023	1.91±0.12	6.85±0.46	6.99±0.54	1.1±0.08	1.2±0.1
DAP + Hydrogel	Red Sandy soil	1.22±0.005	1.18±0.05	75±0.015	77±4.5	2.01±0.017	2.11±0.019	6.15±0.44	6.17±0.47	1.6±0.12	1.8±0.05
Nano DAP	Red sandy soil	1.25±0.002	1.20±0.09	65±0.24	66±9.33	1.92±0.021	1.94±0.14	6.76±0.41	6.91±0.89	1.3±0.70	1.38±0.06
Nano DAP + Hydrogel	Red sandy soil	1.18±0.051	1.15±0.03	78±0.85	79±1.22	2.17±0.010	2.91±0.23	6.98±0.43	7.10±0.68	1.4±0.03	1.56±0.71
Treatments/ Parameters	OC (%)	N (kg/ha)		P (kg/ha)		K (kg/ha)		SMBC (µg/g)		SMBN (µg/g)	
		2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024
Control	0.12±0.006	0.128±0.007	173±16.8	177±22.3	40±2.10	42±10.2	361±34.03	366±36.3	58±3.12	59.1±2.6	10±0.52
DAP	0.17±0.042	0.18±0.04	187±14.4	191±34.1	48. ±3.23	51±9.6	420±28.18	469±41.2	62±3.23	67±4.3	28±1.45
DAP + Hydrogel	0.20±0.034	0.21±0.05	190±11.62	199±22.1	51±3.54	57±12.1	425±23.17	498±41.2	65±3.11	69±4.1	30±1.28
Nano DAP	0.23±0.056	0.255±0.004	196±16.07	201±31.1	53±3.12	62±7.2	427±23.28	475±33.2	66±3.14	71±3.9	27±1.48
Nano DAP + Hydrogel	0.25±0.078	0.26±0.013	199±10.53	220±29.1	55.3.33	69±3.8	430±20.16	501±88.6	68±3.17	75±5.1	29±1.17

Where ST- soil Texture; SBD-Soil Bulk Density; SWHC-Soil Water Holding Capacity SMC- Soil Moisture Content; EC-Electrical Conductivity OC-Organic Carbon; N-Nitrogen; P-Phosphorus; K-Potassium; SMBC-Soil Microbial Biomass Carbon; SMBN-Soil Microbial Biomass Nitrogen

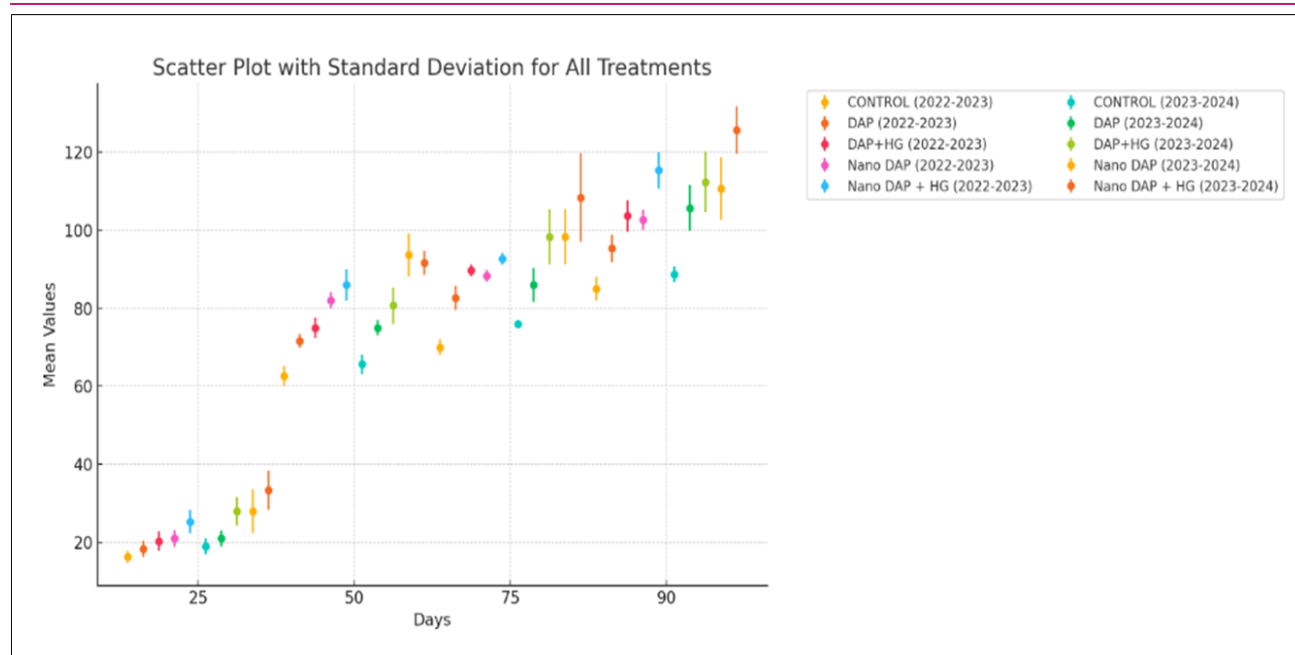


Fig. 1. Illustrating the scatter plot of plant height of (*Solanum lycopersicum* L) on different days till harvest in 2022-23 & 2023-24 years

levels, which improve soil fertility and structure, according to Dhiman *et al.* (2021); even Nano DAP additionally contributed to the enhancement by encouraging microbial proliferation and organic matter cycling, with previous research conducted in Quebec, Canada.

The concentration of nitrogen (N), phosphorus (P), and potassium (K) improved across all the amendments, with the Nano DAP +Hydrogel treatment showing a maximum level of 199 ± 10.53 & 220 ± 29.1 kg/ha post-harvest (Table 2). The foliar application of Nano DAP + Hydrogel has enhanced nutrient availability in the soil, which has been observed by similar studies performed by Ahmadian *et al.* (2021) in West Azerbaijan, Iran, noticing that the nano fertilizers increased nutrient use efficiency and reduced the environmental impact of traditional fertilizers. Similarly, phosphorus and potassium levels of the Nano DAP + Hydrogel have improved post-harvest ($p < 0.05$), mitigated leaching and supporting plant growth; these discoveries align with Patra *et al.* (2022), who testified that hydrogels regulate nutrient release to match plant requirements, thereby improving nutrient accessibility when experiments were performed in Nadia, West Bengal.

The study on biological aspects, which includes soil microbial biomass carbon (MBC) and soil microbial biomass nitrogen (MBN), showed significant improvements in soils treated with hydrogels and Nano DAP (Table 2). The Nano DAP + Hydrogel has shown an increase in microbial biomass nitrogen at 29 ± 1.17 & 35 ± 0.12 $\mu\text{g/g}$. This improvement reflects a favorable environment for microbial growth, driven by improved soil moisture and nutrient availability. Similar observations were made by Rahim *et al.* (2021) that using hy-

drogels and nano fertilizers enhanced microbial activity, facilitating nutrient cycling, which is important for soil health.

Here, the scatter plot emphasizes the performance of various treatments over four time points, with Nano DAP+HG showing higher results across all days (Fig. 1). This treatment achieved superior mean values, particularly at 75 and 90 days, representing its strong effectiveness. Nano DAP also performed well, maintaining higher values compared to other amendments. While other treatments like DAP and DAP HG also performed moderately, the control with no treatments showed weak performance. The present studies were correlated with Motamedi *et al.* (2023), who studied in Karaj, Iran, where the DAP and hydrogel combination showed a moderate height of the tomato plant. The crop yield has shown a significant increase in Nano DAP + Hydrogel in the two consecutive years, which is clearly seen in Fig. 2.

The study is innovative in its focus on integrating these two technologies to enhance water retention, nutrient efficiency, and microbial activity in soils subjected to prolonged water deficiency. The combined application of Nano DAP and hydrogels supported a synergistic effect on improving soil parameters under drought conditions. Notable enhancements in water retention, nutrient availability, and microbial activity underscore the potential of these amendments for promoting sustainable agriculture. These findings align with prior research and provide compelling evidence for adopting such technologies to mitigate drought impacts in sandy loam soils of semi-arid Ananthapuramu district and improve agricultural productivity of *S. lycopersicum* L in arid regions.

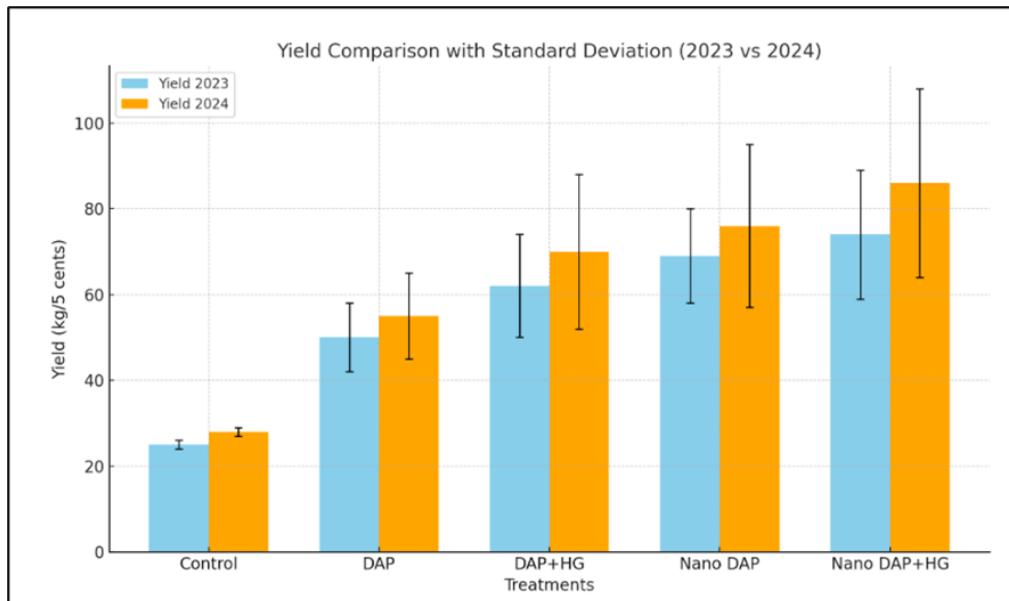


Fig. 2. Yield comparison in two consecutive years of different amendments

Conclusion

The integration of Nano DAP and Hydrogel showed significant improvements in soil characteristics and *S. lycopersicum* L crop yield under drought conditions of Ananthapuramu district of Andhra Pradesh, with the Nano DAP + Hydrogel amendment delivering the most significant benefits. Improved water retention, decreased bulk density, enhanced nutrient availability, and elevated activity of microbes collectively emphasized the potential for these treatments to support sustainable agriculture in arid regions. These results feature a practical and effective approach to mitigating the adverse effects of drought while propagating long-term agricultural resilience and productivity.

ACKNOWLEDGEMENTS:

The authors thank Gandhi Institute of Technology and Management (GITAM-Deemed to be University) for the laboratory facility provided to carry out the work.

Conflict of interest

The authors declare that they have no conflict of interest.

REFERENCES

- Ahanger, M.A., Qi M, Huang, Z., Xu X, Begum, N, Qin C, Zhang ,C, Ahmad, N, Mustafa, N.S. & Ashraf, M. (2021) Improving growth and photosynthetic performance of drought stressed tomato by application of nano-organic fertilizer involves up-regulation of nitrogen, antioxidant and osmolyte metabolism. *Ecotoxico. and Environ. Saf.* 216,112-195 <https://doi.org/10.1016/j.ecoenv.2021.112195>
- Ahmadian, K., Jalilian, J. & Pirzad, A. (2021) Nano-fertilizers improved drought tolerance in wheat under deficit irrigation. *Agric. Water Manag.* 244,106-544 <https://doi.org/10.1016/j.agwat.2020.106544>
- Besharati, J., Shirmard , M., Meftahizadeh, H., Ardakani, M.D., & Ghorbanpour, M. (2022) Changes in growth and quality performance of Roselle (*Hibiscus sabdariffa* L.) in response to soil amendments with hydrogel and compost under drought stress. *S Afr J Bot.* 145, 334-347 <https://doi.org/10.1016/j.sajb.2021.03.018>
- Chuma, G.B., Mulalisi, B., Mondo, J.M. Ndeko, A. B., Bora, F.S., Bagula, E. M., Mushagalusa, G.N. & Civava, R. (2022) Di-ammonium phosphate (DAP) and plant density improve grain yield, nodulation capacity, and profitability of peas (*Pisum sativum* L.) on ferralsols in eastern D.R. Congo. *CABI Agric Biosci* 3, 65. <https://doi.org/10.1186/s43170-022-00130-6>
- Prasher, S.O., ElSayed, E., Patel, R.M., Nzediegwu, C., & Mawof, A. (2021) Effect of hydrogel based soil amendments on heavy metal uptake by spinach grown with wastewater irrigation. *J. Clean. Prod.* 311,127-644 <https://doi.org/10.1016/j.jclepro.2021.127644>
- Dimkpa, C.O., Deng ,C., Wang ,Y., Adisa, I.O., Zhou, J., & White ,J.C. (2023) Chitosan and zinc oxide nanoparticle -enhanced tripolyphosphate modulate phosphorus leaching in soil. *ACS AST.* 3,487-498 <https://doi.org/10.1021/acscagitech.3c00054>
- Dou, Z., Bini Farias, M.V., Chen, W., He, D., Hu ,Y., & Xie, X. (2023) Highly degradable chitosan-montmorillonite (MMT) nano-composite hydrogel for controlled fertilizer release. *FESE.* 17, 53 <https://doi.org/10.1007/s11783-023-1653-9>
- El-Beltagi, H. S., Shehata, W. F., Ahmad, A., Hassim, M. F., & Hadid, M. L. (2023). Role of silica nanoparticles in enhancing drought tolerance of cereal crops. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 51, 13480-13480..
- George, D., Maheswari, P.U., & Begum, K.M.S. (2019) Synergic formulation of onion peel quercetin loaded chitosan-cellulose hydrogel with green zinc oxide nanoparticles towards controlled release, biocompatibility, antimicrobial and anticancer activity. *Int. J. Biol. Macromol.*

- 132,784-794 <https://doi.org/10.1016/j.ijbiomac.2019.04.008>
9. Hafez, E. M., Osman, H. S., El-Razek, U. A. A., Elbagory, M., Omara, A. E. D., Eid, M. A., & Gawayed, S. M. (2021). Foliar-applied potassium silicate coupled with plant growth-promoting rhizobacteria improves growth, physiology, nutrient uptake and productivity of faba bean (*Vicia faba* L.) irrigated with saline water in salt-affected soil. *Plants*, 10, 894. <https://doi.org/10.3390/plants10050894>
10. Jabro, J.D., & Mikha, M.M. (2021). Determination of Infiltration Rate and Bulk Density in Soils. *Soil Health Series*, 69-77.
11. Kiani, M., Hernandez-Ramirez, G., Quideau, S., Smith, E., Janzen, H., Larney, F.J., & Puurveen, D. (2017) Quantifying sensitive soil quality indicators across contrasting long-term land management systems: Crop rotations and nutrient regimes. *Agric. Ecosyst. Environ.* 248,123-135 <https://doi.org/10.1016/j.agee.2017.07.018>
12. Motamedi, E., Safari, M., & Salimi, M. (2023). Improvement of tomato yield and quality using slow release NPK fertilizers prepared by carnauba wax emulsion, starch-based latex and hydrogel nanocomposite combination. *Sci. Rep.*, 13, 11118. <https://doi.org/10.1038/s41598-023-38445-7>
13. Mwendwa S (2022). Revisiting soil texture analysis: Practices towards a more accurate Bouyoucos method. *Heliyon*. 8, e09395 <https://doi.org/10.1016/j.heliyon.2022.e09395>
14. Narjary, B., & Aggarwal, P. (2014) Evaluation of soil physical quality under amendments and hydrogel applications in a soybean–wheat cropping system. *Commun Soil Sci Plant Anal.* 45,1167-1180. <https://doi.org/10.1080/00103624.2013.875191> Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 2 chemical and microbiological properties*, 9, 539-579.
15. Olsen, S. R. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture.
16. Patra, S.K., Poddar, R., Brestic, M., Acharjee, P.U., Bhattacharya, P., Sengupta, S., Pal, P., Bam, N., Biswas, B., & Barek, V. (2022) Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition. *Int. J. Polym. Sci.* 2022,491-4836 <https://doi.org/10.1155/2022/4914836>
17. Rajanna, G., Manna, S., Singh, A., Babu, S., Singh, V., Dass, A., Chakraborty, D., Patanjali, N., Chopra, I., & Banerjee, T. (2022) Biopolymeric superabsorbent hydrogels enhance crop and water productivity of soybean–wheat system in Indo-Gangetic plains of India. *Sci. Rep.* 12,11-55 <https://doi.org/10.1038/s41598-022-16049-x>
18. Susha Lekshmi, Singh D.N, Shojaei, & Baghini, M. (2014). A critical review of soil moisture measurement. *Measurement*, 54, 92-105.
19. Sharma, N., Singh, A., & Dutta, R.K. (2021) Biodegradable fertilizer nanocomposite hydrogel based on poly (vinyl alcohol)/kaolin/diammonium hydrogen phosphate (DAhP) for controlled release of phosphate. *Polym. Bull.* 78,2933-2950 <https://doi.org/10.1007/s00289-020-03252-x>
20. Singh, A., Rajput, V.D., Pandey, D., Sharma, R., Ghazaryan, K., & Minkina, T. (2023) Nano zinc-enabled strategies in crops for combatting zinc malnutrition in human health. *Front. Biosci.* 28,1-58 <https://doi.org/10.31083/j.fbl2808158>
21. Skrzypczak, D., Mikula, K., Kosińska, N., Wiedera, B., Warchoń, J., Moustakas, K., Chojnacka, K., & Witek-Krowiak, A. (2020) Biodegradable hydrogel materials for water storage in agriculture-review of recent research. *J. Sci. Commun.* 194,324-332 <https://doi.org/10.5004/dwt.2020.25436>
22. Skrzypczak, D., Mikula, K., Kosińska, N., Wiedera, B., Warchoń, J., Moustakas, K., Chojnacka, K. & Witek-Krowiak, A. (2020). Biodegradable hydrogel materials for water storage in agriculture-review of recent research. *J. Sci. Commun.*, 194, 324-332. <https://doi.org/10.5004/dwt.2020.25436>
23. Tang, Y., Zhao, W., Zhu, G., Tan, Z., Huang, L., Zhang, P., Gao, L., & Rui, Y. (2023) Nano-pesticides and fertilizers: solutions for global food security. *Nanomater.* 14,90 <https://doi.org/10.3390/nano14010090>
24. Teng, B., Wu, J., Zhong, Y., Cai, L., Qi, P., & Luo, Z. (2024) Enhancing Drought Tolerance in Barley through the Application of Watermelon Rind Hydrogels: A Novel Approach to Sustainable Agriculture. *Agronomy* 14,23-29 <https://doi.org/10.3390/agronomy14102329>
25. Ur, Rahim, H., Qaswar, M., Uddin, M., Giannini, C., Herrera, M.L., & Rea, G. (2021) Nano-enable materials promoting sustainability and resilience in modern agriculture. *Nanomater.* 11,20-68 <https://doi.org/10.3390/nano11082068>
26. Wang, J.J., Provin, T., & Zhang, H. (2014) Measurement of soil salinity and sodicity. *Soil test methods from the southeastern United States*; 185.
27. Witt, C., Gaunt, J. L., Galicia, C. C., Ottow, J. C., & Neue, H. U. (2000). A rapid chloroform-fumigation extraction method for measuring soil microbial biomass carbon and nitrogen in flooded rice soils. *Biol. Fertil. Soils*, 30, 510-519. <https://doi.org/10.1007/s003740050030>