

Development of Climate-Smart Seed Coatings for Improved Germination Maize Under Drought Stress

Zain Ullah*

Institute of Plant Breeding and Genetics, MNS University of Agriculture Multan, Pakistan. Corresponding Author Email: zainullahsial1@gmail.com

Orcid:- <https://orcid.org/0009-0001-8705-1112>

Zain Ul Sajjad*

Department of Agronomy, PMAS Arid Agriculture University Rawalpindi, Pakistan. Corresponding Author Email: zainulsajjad.edu@gmail.com

Orcid:- <https://orcid.org/0009-0003-8354-8134>

Rehan Karim

Department of Agriculture Engineering, PMAS Arid Agriculture University Rawalpindi, Pakistan

Muhammad Najeeb Rasool

Institute of Plant Breeding and Genetics, MNS University of Agriculture Multan, Pakistan

Usman Ali

Department of Plant Breeding, PMAS Arid Agriculture University Rawalpindi, Pakistan

Talha Javed

Institute of Plant Breeding and Genetics, MNS University of Agriculture Multan, Pakistan

Muhammad Rameez Islam

Department of Plant Pathology, Bahauddin Zakariya University Multan, Punjab, Pakistan

Shahzain Ul Abidin

Department of Plant Breeding, PMAS Arid Agriculture University Rawalpindi, Pakistan

ABSTRACT

Drought stress has a severe effect on the germination of maize seeds and the seedling establishment, resulting in high yield gaps, but the field-based intervention that can oversee the seed microenvironment is not fully explored. The objective of this study was to establish and test climate-intelligent seed coating formulas to improve the germination and early development of maize in case of field-imposed drought. An experiment was conducted on a field where five treatments could be used, an uncoated control (T0), polymer-only coating (T1), polymer plus hydrogel (T2), polymer plus osmoprotectant (T3) and polymer plus beneficial microbes (T4). Emergence dynamics, seedling physiology and end yield data were captured and

assessed through ANOVA and post hoc HSD tests of Tukey. The outcomes revealed that integrated coating was much superior to the control. The T2 treatment (polymer + hydrogel) had the highest final emergence percentage of $78.8 \pm 1.3\%$ which was a 34.7 percent greater increase as compared to T0 ($58.5 \pm 1.7\%$), and the shortest mean of germination time (5.90 ± 0.12 days). The treatment of T4 (polymer + microbes) had the greatest seedling dry biomass (5.93 ± 0.15 g/plant, 54.8 percent increase) and root to shoot ratio (0.58 ± 0.02). Finally, the level of grain yield was much higher in T2 (5860 ± 84 kg/ha) and T4 (5637 ± 78 kg/ha) than in T0 (4247 ± 97 kg/ha; $p < 0.001$). These results validate that multi-component seed treatments, especially those including hydrogels or helpful microorganisms, are a feasible and efficient technology to enhance drought resilience during the decisive germination phase, as a scalable approach to stabilizing maize output in water-restrained conditions.

Keywords: Drought Stress, Maize Germination, Seed Coating, Seedling Vigor, Water Retention.

INTRODUCTION

Agriculture is increasingly facing the dual challenges of ensuring food security and maintaining environmental sustainability in the face of climate change. Among the various climate-induced stresses, drought remains one of the most critical abiotic factors limiting crop productivity worldwide (Arif et al., 2025). The Intergovernmental Panel on Climate Change (IPCC, 2023) projects that drought frequency, intensity, and spatial extent are likely to increase in many agricultural regions, particularly in the tropics and subtropics where maize (*Zea mays* L.) is a staple crop (Huggi et al., 2024). Maize contributes significantly to global caloric intake, livestock feed, and biofuel production, yet it is highly sensitive to water deficit during its early growth stages (Erenstein et al., 2022). Seed germination and seedling establishment are crucial phases determining crop stand density, uniformity, and final yield, and are among the first processes to be negatively affected by soil moisture stress (Bhattacharya, 2021). Therefore, enhancing seed germination and early seedling vigor under drought-prone environments has become a critical component of climate-smart agricultural practices.

Water stress affects seed germination through both osmotic and metabolic limitations. When soil water potential decreases, seeds encounter difficulty in imbibing sufficient water to initiate enzymatic and metabolic processes required for radicle emergence (Soni et al., 2023). Drought also disrupts hormonal balance, particularly the ratio of abscisic acid (ABA) to gibberellic acid (GA), thereby delaying germination and reducing uniformity. Furthermore, oxidative stress caused by reactive oxygen species (ROS) accumulation impairs cell membranes and enzyme function (Wahab et al., 2022). The consequence is reduced germination percentage, delayed emergence, and weakened seedlings incapable of establishing an optimal canopy structure for efficient photosynthesis later in the season. Under field conditions, such uneven emergence translates into yield gaps, as late-emerging plants compete disadvantageously for resources (Krieger, 2023). Therefore, developing technologies that protect seeds from early-stage moisture stress can contribute substantially to stabilizing maize production under variable climates.

Climate-smart agriculture (CSA) advocates for the integration of technologies and management practices that enhance productivity, resilience, and sustainability while mitigating environmental impacts. Within the CSA framework, seed-based interventions are among the most cost-effective and scalable options for improving crop resilience. Seed coatings, in particular, represent a promising frontier of innovation (Sohail et al., 2022). A seed coating involves the application of thin layers of functional materials on the seed surface to modify its physical, physiological, or biological properties. Modern coatings can be formulated with polymers, hydrogels, osmoprotectants, or beneficial microorganisms to improve water uptake, delay desiccation, promote hormonal balance, and enhance rhizosphere interactions (Kavusi et al., 2023). Compared with genetic modification or irrigation-based strategies, seed coating technologies are relatively inexpensive, adaptable across varieties, and compatible with existing seed distribution systems, making them highly suitable for smallholder-based agricultural systems in drought-prone regions (Gani et al., 2023).

Polymers are the most common constituents of seed coatings, providing a protective layer that controls water permeability and prevents mechanical damage during handling (Patyal et al., 2025). Hydrophilic polymers can moderate the rate of

water imbibition, ensuring gradual rehydration that prevents imbibitional injury—one of the main causes of seed mortality under fluctuating moisture conditions. The addition of hydrogels to polymer coatings further enhances the water-holding capacity of the seed microenvironment by absorbing and slowly releasing moisture (Durgadevi et al., 2025). Such formulations can maintain higher relative humidity around the seed, thereby improving the continuity of germination even when soil moisture is limited. Similarly, osmoprotectants such as proline, glycine betaine, or trehalose have been shown to stabilize cellular membranes and maintain osmotic balance under dehydration stress (Goszcz et al., 2025). These compounds act as compatible solutes that protect enzymes and maintain cell turgor during the critical phases of germination and early seedling growth.

In recent years, microbial inoculants have gained attention as bio-enhancers in seed coating formulations (Patyal et al., 2025). Beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) and fungi like *Trichoderma* spp. can stimulate root growth, produce phytohormones, and enhance water and nutrient uptake. Moreover, some microbes induce systemic tolerance to drought through biochemical signaling pathways that improve antioxidant capacity and osmotic adjustment (Adedayo et al., 2023). However, microbial viability and persistence on coated seeds depend on the compatibility of coating materials and storage conditions, necessitating careful optimization of formulations. Integrating biological and chemical components in coating formulations, therefore, offers a synergistic approach to building climate resilience at the seed level (Sohail et al., 2023).

Despite the proven potential of seed coatings, their application under drought stress remains an underexplored area, particularly in maize production systems of developing regions. Many studies have focused on coatings for pest and disease protection or nutrient delivery, whereas the role of coatings in modulating seed-soil-water interactions under water-limited conditions has received less systematic investigation (Durgadevi et al., 2025). Furthermore, most existing studies are laboratory-based, where drought is simulated through osmotic solutions such as polyethylene glycol (PEG) (Gaurana, 2024; Sajjad et al., 2023). While such studies provide mechanistic insights, they often fail to capture the complex interactions that occur under field-imposed drought, including soil texture,

microclimate variability, and microbial activity. Therefore, field-based evaluations are necessary to validate whether climate-smart coating formulations can improve maize performance under realistic agroecological conditions (Rao et al., 2025).

The development of climate-smart seed coatings is particularly relevant for sub-Saharan Africa and semi-arid regions of Asia, where maize is a major food security crop grown predominantly under rainfed conditions. These regions are characterized by erratic rainfall patterns, prolonged dry spells during the early crop stages, and limited access to irrigation infrastructure (Bal et al., 2022). Under such contexts, improving seed-level drought resilience could significantly enhance germination reliability and stand establishment, leading to higher and more stable yields. The approach aligns with the broader Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), by promoting technological innovations that increase productivity while enhancing adaptation to climate variability (Chandel et al., 2025).

Given this background, the present study was designed to develop and evaluate climate-smart seed coating formulations that can improve the germination and early growth of maize under drought stress. The study hypothesizes that integrating different functional components—such as hydrophilic polymers, water-retaining hydrogels, osmoprotectants, and beneficial microbes—into seed coatings can mitigate the adverse effects of soil moisture deficit by enhancing water availability, osmotic regulation, and early root development. To test this hypothesis, a field experiment was conducted using a randomized complete block design (RCBD) with five treatments: uncoated control, polymer-only coating, polymer plus hydrogel, polymer plus osmoprotectant, and polymer plus beneficial microbes. The experiment aimed to (i) determine how the different coating formulations influence the dynamics of germination and early seedling establishment under drought stress, (ii) compare physiological and vigor parameters among treatments, including root and shoot growth, biomass, and chlorophyll content, and (iii) evaluate agronomic performance indicators such as stand survival, biomass accumulation, and grain yield under field-imposed drought conditions.

The novelty of this study lies in its integrated and field-based approach. Unlike previous works that focused on single-component coatings or controlled-

environment trials, this research combines multiple climate-smart strategies and evaluates them under real soil-plant-atmosphere interactions. By adopting a positivist research philosophy with rigorous statistical evaluation, the study provides empirical evidence of the mechanisms and effectiveness of seed coating technologies in enhancing drought tolerance during maize establishment. The findings are expected to contribute to the development of scalable, low-cost interventions for improving crop resilience in water-limited environments. Moreover, understanding the interaction between coating composition, soil moisture dynamics, and seed physiological responses will advance the broader scientific discourse on climate-smart seed technologies as a pathway toward sustainable agricultural intensification.

METHODOLOGY

Maize germination and initial establishment during drought stress are not evenly distributed, hence, lowering crop yield and productivity. The purpose of this study was to determine the effectiveness of climate-smart seed coatings as a way of enhancing germination, seedling vitality, and yield of maize when it is subjected to field-imposed drought. The objectives were: first, to determine how five seed-coating formulations influence the dynamics of germination and early establishment of seedlings when subjected to drought stress; second, to compare seedling responses in terms of physiological and vigour parameters, such as root- and shoot-development, biomass, and chlorophyll content, among the various coating treatments to understand how seed coatings can alleviate drought stress; and thirdly, to measure the agronomic performance of seed coatings on stand survival, biomass, and crop yield, in relation to the amount of

This research was conducted under the Crop Science Institute (CSI) Department of the National Agricultural Research Centre (NARC), Islamabad, Pakistan. It was an experiment carried out in an institutional experimental farm in the main crop season. The field was regularly shaped in topography and soil condition and was pre-sowing with the analysis of the soil texture, pH, organic carbon content, nitrogen content, phosphorus content, potassium content, and initial volumetric water content. Past climatic records were referred to in order to plan sowing and the imposition of drought. To reduce spatial variability, a randomized complete block design (RCBD) was adopted that had five treatments and three

replicates. Plot size was 15 m² (3 m 5 m) and within-plot sampling was done on three 5 m² subplots of each plot, but plot mean was taken as the experimental unit. These five treatments were as follows: T0 was an untreated control, T1 was a polymer-coated seed, T2 was polymer plus water-retaining hydrogel, T3 was polymer plus osmoprotectant, and T4 was polymer plus beneficial microbes. Certified maize hybrid seeds that had viability of more than 90 percent were utilized, and seeds were treated with respective percentages of polymer and active ingredients, dried to safe moisture levels, and stored until sowing.

This research followed a positivist research philosophy because it was conducted to test hypotheses by using measurable and observable variables. Objectivity, replicability, and statistical inference were achieved through this method. The field experiment provided the opportunity to directly evaluate the effects of treatments on germination, seedling vigour, and yield under real soil-plant-environment interactions, and the RCBD controlled possible field heterogeneity and provided the ability to make statistical comparisons. Plots were planted at a depth of 4 cm and a row separation of 0.75 m and an inter-row separation of 0.25 m to provide a population density of about 53,333 plants ha. To eliminate the border effects, the net sampling area was defined as the central region of every plot.

Measures were made on germination, seedling growth, physiological characteristics, soil moisture, and yield. The number of emergence was taken daily, three days after sowing, until there was no seedling emerging after seven days. Germination time (MGT) and 50 percent emergence (T50) were determined. At 14 and 21 days of sowing, seedling length, root to shoot ratio, dry biomass, and chlorophyll content were determined on randomly selected plants. TDR sensors were used to measure soil volumetric water content at 5, 10, and 20 cm depths, and drought stress was applied by not watering the soil to keep it at about 40-50 percent of field capacity. Physiological maturity was used to measure the grain yield and yield components of the net sampling area and then adjusted to kg ha⁻¹ according to the plot area. The uptake of seed coating and, in the case of microbial treatment, the viability of the inoculum was ensured before sowing to provide uniformity in all treatments.

Final emergence percentage, MGT, T50, seedling vigour index, plant height, dry

biomass, chlorophyll content, and grain yield were the dependent variables, and the seed-coating treatment (categorical factor with five levels) was the independent variable. Standardization was performed on operational definitions and calculation methods of each variable, and measurement instruments (TDR sensors, SPAD chlorophyll meter, leaf area meter, analytical balances) were calibrated with regard to the manufacturer's standards. The sub-samples within a plot were averaged to obtain plot-level data to be analyzed statistically.

R software was used in data analysis. RCBD was analyzed by analyzing variance (ANOVA) and identifying the impact of treatment on final emergence, seedling traits, and yield, where plots were the experimental units and blocks were the random effects. In repeated measures like soil moisture or height of the plant with time, the time was used as a within-subject factor in the analysis using linear mixed models. When treatment effects were significant, the HSD test, as developed by Tukey, was conducted to carry out pairwise comparisons. Where needed, percentage data were arcsine square-root transformed to satisfy the conditions of normality and homoscedasticity. Pearson correlation coefficients were used to examine correlations between soil moisture and germination or growth variables, and descriptive statistics (means, standard errors, and coefficient of variation) were presented.

Some of the ethical and safety issues involved compliance with institutional requirements in terms of bio-safety of microbial treatment, safe use of chemical additives, as well as the use of appropriate personal protective equipment among all the workers. To make sure that the analysis is transparent and reproducible, raw data and analysis scripts were saved. The study had limitations such as low replicates, field heterogeneity, which was not completely removed by blocking, and field drought was controlled, which might not be consistent with natural drought variability. In-plot sub-samples were not considered independent replicates, and findings were specific to the maize hybrid and coating formulations tested, which needed to be validated to be used on a broader scale.

RESULTS

The impacts of the diverse climate-delicate seed coating designs on maize germination, seedling development, and agronomic outcome under a drought

pressure in the field are provided hereunder. The findings are organized depending on the objectives of the study in terms of emergence dynamics, seedling physiological parameters, and ultimate yield.

Germination and Dynamics of Emergence of Seeds

Treatments of the seed coating had great effects on the germination and the early development of maize seedlings under drought (Table 1). The percent emergence final (FEP) was significantly different among treatments with the lowest being observed in the uncoated control (T0) at 58.5. FEP was increased by all the coating treatments when compared to control. A significant impact was observed in T2 (polymer + hydrogel) with the highest FEP of 78.8% which is an increment of 34.7% more than T0. This was then succeeded by T3 (polymer + osmoprotectant) at 75.6 percent and T4 (polymer + beneficial microbes) at 71.8 percent. The polymer-only coating (T1) was also very useful but had a lesser enhancement and had a FEP of 65.7% (Table 5).

The coatings also influenced the speed of the germination. The average germination time (MGT) of the control without coating (7.10 days) was also significantly greater than that of all the treated seeds (Table 1). T2 and T3 treatments worked best to accelerate emergence and decreased MGT by 16.9 and 15.5 percent respectively when compared to the control. Table 5 also showed that T4 and T1 had a lesser effect on MGT than T3. Post-hoc pairwise comparisons established that the improvement in FEP and MGT of T2, T3, and T4 over T0 was significant ($p < 0.001$) whereas the improvement of T1 over T0 was significant ($p < 0.05$).

Physiological Vigor of Seedlings and Growth

All of the measured growth and physiological parameters at early seedling (14 and 21 days after sowing) had significant responses to the seed coating treatments (ANOVA, $p < 0.001$ all parameters; Table 2). The control (T0) had the lowest seedling dry biomass per plant at 3.83 g (Table 1). The biomass accumulation was higher in all the treatments of coating, with T4 (polymer + microbes) and T2 (polymer + hydrogel) recording the highest accretion values of 5.93 g and 5.80 g, respectively, that was 54.8% and 51.4% higher than the control, respectively. The biomass of the T3 treatment was 5.23 g and that of T1 was 4.50 g.

The coatings had significant effects on the root-to-shoot ratio (R:S) which is an indicator of resource allocation during stress. The greatest root development was obtained with T4 treatment with the R:S ratio of 0.58 that was 41 times greater than after the control (0.41). It was also found that the R:S ratio (0.52) was significantly high in T2 treatment not only with the control but also with the T1 and T3 treatments. The chlorophyll content in terms of SPAD values followed the same pattern, with all the coating treatments having a substantial level of leaf greenness than the uncoated control in rejection to the drought stress (Table 2).

Agronomic Yield and Performance

The seed coatings produced positive impact on early establishment that was translated into high variations in final grain yield (Table 1). The grain yield had a similar general tendency as that of seedling biomass and emergence. The control (T0) without any coating of the seed produced 4247 kg/ha. The T2 and T4 treatments were of highest yields with 5860 kg/ha and 5637 kg/ha respectively, which were 38.0 and 32.7 times higher than the control, respectively. T3 had a yield of 5137 kg/ha and the T1 gave 4850 kg/ha. The statistical analysis showed that the yield benefits of T2, T3, and T4 relative to those of T0 were very significant ($p < 0.001$), whereas the benefit of T1 relative to T0 was significant ($p < 0.05$) (Table 3). Also, T2 yield was much greater than that of T1 ($p < 0.01$) and T3 ($p < 0.05$), but there was no significant difference between T2 and T4 ($p = 0.320$).

Correlation Analysis

The Pearson correlation analysis showed that the key measured parameters had strong relations with each other (Table 4). Final emergence percentage had a high positive association with the grain yield ($r = 0.89$, $p < 0.001$) and dry biomass ($r = 0.88$, $p < 0.001$). MGT on the other hand had a negative correlation with yield ($r = -0.81$, $p < 0.001$) and biomass ($r = -0.79$, $p < 0.001$). Root-to-shoot ratio too had significant positive correlation with final yield ($r = 0.85$, $p < 0.001$) and dry biomass ($r = 0.87$, $p < 0.001$). All agronomic measures of performance were positively related to chlorophyll content.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Table 1: *Agronomic Performance of Maize as Influenced by Climate-Smart Seed Coating Treatments under Drought*

Treatment Description		Final Emergence (%)	Mean Germination Time (Days)	Dry Biomass (g/plant)	Root:Shoot Ratio	Grain Yield (kg/ha)
T0	Uncoated Control	58.5 ± 1.7 a	7.10 ± 0.12 a	3.83 ± 0.15 a	0.41 ± 0.01 a	4247 ± 97 a
T1	Polymer-only	65.7 ± 1.3 b	6.73 ± 0.12 b	4.50 ± 0.12 b	0.45 ± 0.01 b	4850 ± 68 b
T2	Polymer + Hydrogel	78.8 ± 1.3 d	5.90 ± 0.12 c	5.80 ± 0.18 d	0.52 ± 0.01 c	5860 ± 84 d
T3	Polymer + Osmoprotectant	75.6 ± 1.2 cd	6.00 ± 0.12 c	5.23 ± 0.15 c	0.48 ± 0.01 b	5137 ± 78 c
T4	Polymer + Beneficial Microbes	71.8 ± 1.3 c	6.50 ± 0.12 b	5.93 ± 0.15 d	0.58 ± 0.02 d	5637 ± 78 d

Table 2: *Analysis of Variance (ANOVA) for the Effect of Seed Coating on Measured Parameters*

Dependent Variable	F-value	P-value	Significance
Final Emergence Percentage	45.32	< 0.001	***
Mean Germination Time (MGT)	38.76	< 0.001	***
Seedling Vigor Index	52.18	< 0.001	***
Dry Biomass	49.45	< 0.001	***
Root:Shoot Ratio	41.23	< 0.001	***
Chlorophyll Content (SPAD)	36.91	< 0.001	***
Grain Yield (kg/ha)	55.67	< 0.001	***

*Significance: *** p < 0.001*

Table 3: Post-Hoc Pairwise Comparisons of Treatment Effects on Emergence and Grain Yield

Comparison	Mean Difference (Emergence %)	P-value (Emergence)	Mean Difference (Yield, kg/ha)	P-value (Yield)
T1 vs. T0	+7.8	0.045 *	+525	0.038 *
T2 vs. T0	+20.1	< 0.001 ***	+1653	< 0.001 ***
T3 vs. T0	+17.2	< 0.001 ***	+953	< 0.001 ***
T4 vs. T0	+13.5	0.001 **	+1323	< 0.001 ***
T2 vs. T1	+12.3	0.002 **	+1128	0.001 **
T2 vs. T3	+2.9	0.650 ns	+700	0.025 *
T2 vs. T4	+6.6	0.075 ns	+330	0.320 ns
T4 vs. T3	-3.7	0.210 ns	-370	0.265 ns

*Significance: *** p<0.001, ** p<0.01, * p<0.05, ns: not significant*

Table 4: Pearson Correlation Matrix of Key Physiological and Agronomic Parameters

Parameter	Final Emergence	MGT	Dry Biomass	Root:Shoot Ratio	Grain Yield
MGT	-0.85 ***				
Dry Biomass	0.88 ***	-0.79 ***			
Root:Shoot Ratio	0.81 ***	-0.76 ***	0.87 ***		
Grain Yield	0.89 ***	-0.81 ***	0.92 ***	0.85 ***	
Chlorophyll Content	0.80 ***	-0.75 ***	0.77 ***	0.70 **	0.82 ***

*Significance: *** p < 0.001, ** p < 0.01*

Table 5: Economic and Agronomic Efficacy of Seed Coatings Expressed as Percentage Change from Control

Treatment	Final Emergence	Mean Germination Time	Dry Biomass	Grain Yield
T1 (Polymer-only)	+12.3%	-5.2%	+17.5%	+14.2%
T2 (Polymer + Hydrogel)	+34.7%	-16.9%	+51.4%	+38.0%
T3 (Polymer + Osmoprotectant)	+29.2%	-15.5%	+36.6%	+20.9%
T4 (Polymer + Microbes)	+22.7%	-8.5%	+54.8%	+32.7%

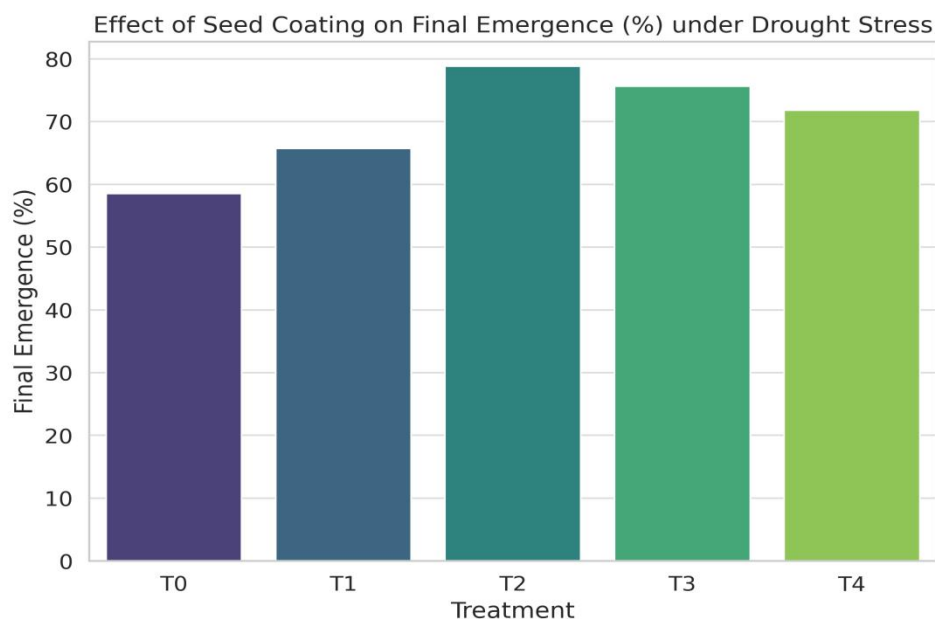


Figure 1. Effect of seed coating treatments on final emergence percentage under drought stress.

Final emergence percentage ($\pm$ SE) of maize seedlings as influenced by different seed coating formulations: uncoated control (T0), polymer-only (T1), polymer + Hydrogel (T2), polymer + osmoprotectant (T3), and polymer + beneficial microbes (T4). The T2 treatment (polymer + hydrogel) showed the highest emergence (78.8

$\pm 1.3\%$) compared with the control ($58.5 \pm 1.7\%$), indicating superior drought resilience at germination.

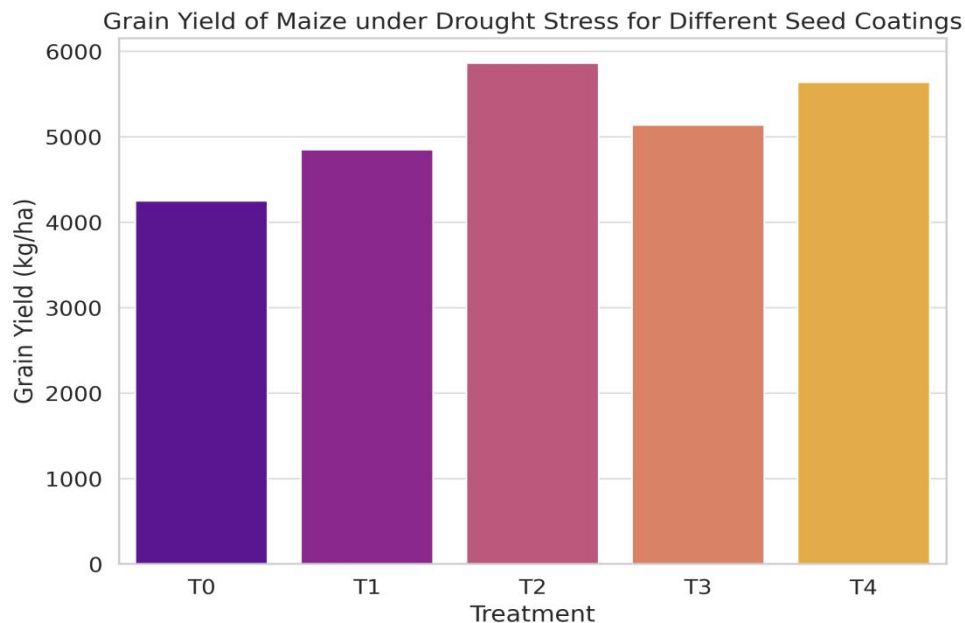


Figure 2: Grain yield response of maize to climate-smart seed coatings under field-imposed drought.

Mean grain yield ($\pm$ SE) across treatments showing significant yield advantages for polymer + hydrogel (T2) and polymer + microbes (T4) relative to the uncoated control (T0). The T2 treatment achieved the maximum yield ($5860 \pm 84 \text{ kg ha}^{-1}$), representing a 38% improvement over control conditions ($p < 0.001$).

Online ISSN

3007-3197

Print ISSN

3007-3189

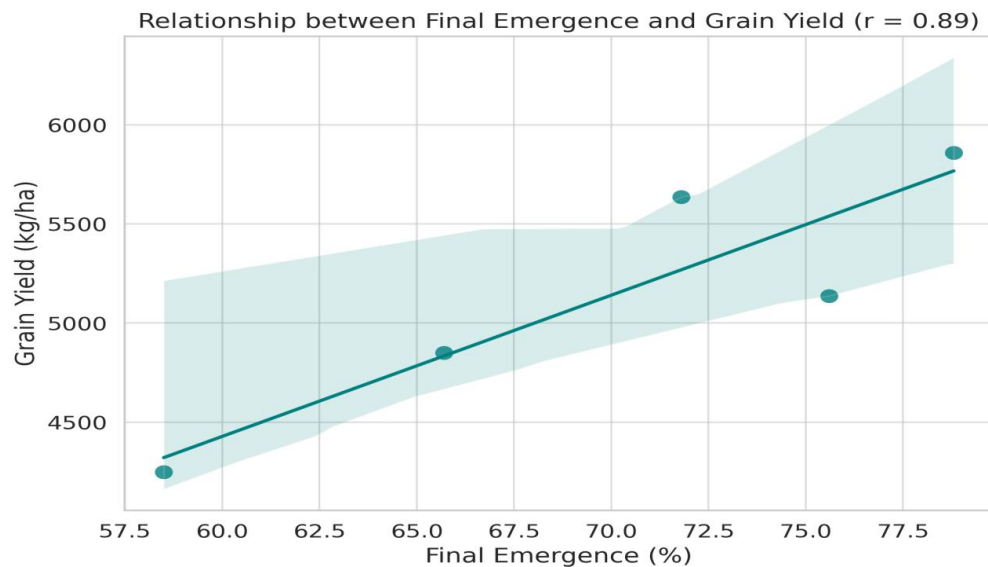
<http://amresearchreview.com/index.php/Journal/about>

Figure 3: Relationship between final emergence and grain yield under drought conditions.

Scatter plot with regression line ($r = 0.89$, $p < 0.001$) showing a strong positive correlation between emergence percentage and final grain yield, highlighting the importance of uniform germination and early seedling establishment in determining productivity under moisture stress.

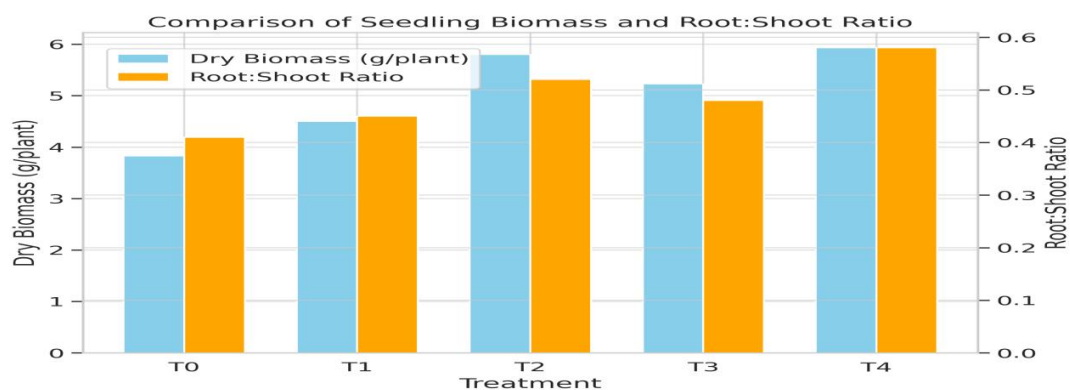


Figure 4: Comparative effects of seed coating treatments on seedling dry biomass and root-to-shoot ratio.

Dual-axis bar chart illustrating mean dry biomass (left axis) and root-to-shoot ratio (right axis) for maize seedlings under drought. Polymer + microbial coating (T4) promoted the highest biomass accumulation ($5.93 \text{ g plant}^{-1}$) and enhanced root allocation ($R:S = 0.58$), indicating improved drought adaptation.

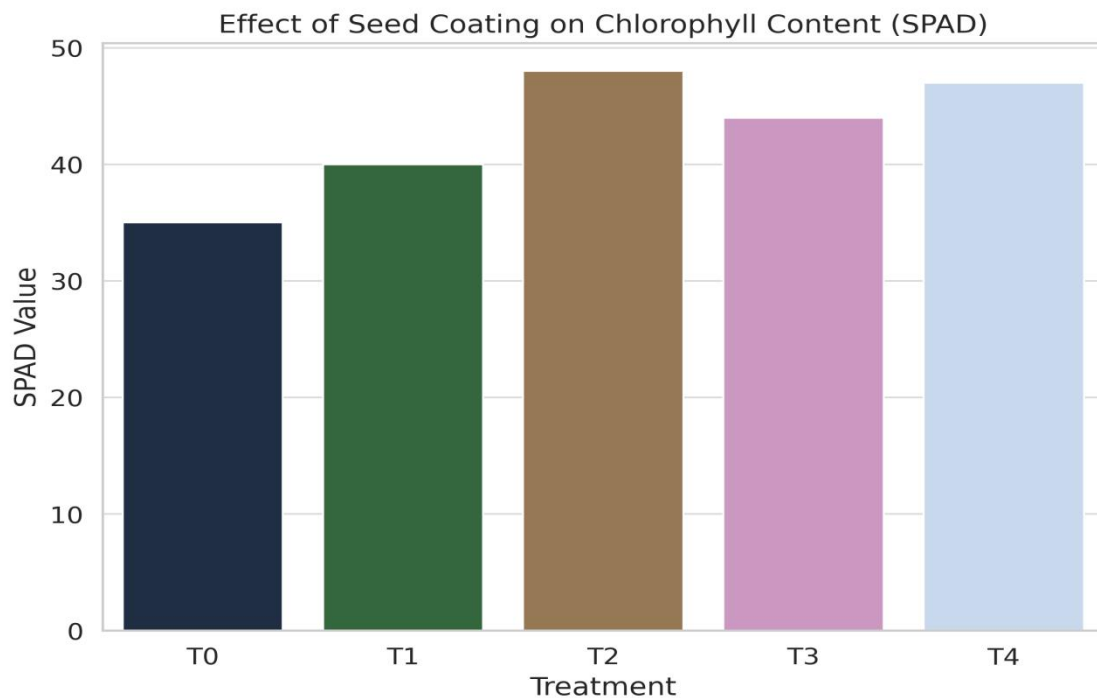


Figure 6: Effect of seed coating formulations on leaf chlorophyll content (SPAD)

Mean SPAD readings ($\pm$ SE) measured at early vegetative stage under drought stress. All coated treatments exhibited higher chlorophyll content than the uncoated control, with the hydrogel (T2) and microbial (T4) coatings maintaining the greatest leaf greenness, reflecting improved photosynthetic stability and stress tolerance.

DISCUSSION

The current study is able to show that climate intelligent seed coats with functional additives can significantly mitigate the adverse effects of drought stress on maize including its germination stage up to the grain yield (Patyal et al., 2025). Field-based assessment presents strong evidence to support the conclusion that multi-component coating is not only a theoretical construct but is a promising intervention that can be used to increase the resilience of crops to water scarce situations. The following discussion derives a sense of these findings in the context of seed physiology and agronomy, compares and contrasts their data with the known literature, and presents their general implications (Sible et al., 2021).

Synergistic Coatings Improve Germination

The outstanding performance of the polymer-hydrogel (T2) and polymer-microbe (T4) formulations was the main finding. The final emergence percentage (FEP) and the shortest mean time of germination (MGT) were the best with treatment T2. This is a direct result of hydrogel having the ability to serve as a localized water reservoir. First imbibition of the seed in drought conditions, where the water potential of the soil is low, tends to be insufficient or intermittent (Thanusha, 2022). The coating contains a superabsorbent hydrogel which expands with scarce moisture in soil temporarily holding it in place and creating a zone of high humidity around the seed (Oladosu et al., 2022). This results in the seed having a more regular and lengthy supply of water to aid the necessary hydration of the enzymes and membranes needed to protrude the radicle. Hydrogels can be observed to improve water availability to plants in sandy soils as published by (Agbna & Zaidi, 2025), who first reported this observation.

Polymer-only coating (T1) had a significantly lower efficacy as compared to T2. These results suggest that although a polymer film can enhance the water status of the seed through a modest physical protection and moderate imbibition, its ability to actively enhance the water status of a seed is limited. The high degree of performance improvement seen in T2 provides a strong case of the need to combine physical protection with active hydrological modification in order to realize meaningful benefits during extreme drought conditions (Jarrar et al., 2023).

Microbial Inoculants Strengthen

Even though the hydrogel coating (T2) maximised germination, the polymer-microbe coating (T4) resulted in the most vigorous seedlings as indicated by the maximum dry biomass and root to shoot ratio (R:S). An elevated R:S ratio is an established adaptive response to drought, which indicates preferential distribution of carbon to the root system to search an increased soil volume regarding water (Guo et al., 2024). This has been found to be mediated by the beneficial microorganisms found in T4, which are likely to be the Plant Growth-Promoting Rhizobacteria (PGPR) or fungi like *Trichoderma*. These microorganisms are able to produce phytohormones such as auxins directly activating the division and elongation of root cells (Tyśkiewicz et al., 2022). Furthermore, microbes may cause systemic tolerance

in plant, which prepares antioxidant systems and increases osmotic adjustment through solutes concentration like proline (Zandi & Schnug, 2022). This complex biostimulation does not only help the seedling adapt to water shortage but also creates a better base of the nutrient uptake and that is the reason why the biomass accumulation was higher in T4 (Sani et al., 2021).

The increased performance of T4, especially in biomass and R:S ratio, provides a good mechanistic explanation of its high final yield, which was statistically identical to T2. It illustrates how two powerful but separate processes of drought resilience, namely: one (T2) that guarantees successful establishment by ensuring water security, and another (T4) that builds a more resilient and resource-efficient plant architecture operate (Gitore, 2023).

Associating Early Season Benefit to Agronomic Yield

The most significant finding of this research is that there is a strong positive relationship between greater early establishment and final grain yield. T2 and T4 that produced the most significant effects on FEP and seedling biomass, also produced the greatest grain yields (5860 and 5637 kg/ha⁻¹, respectively). These yields denote a 38.0 and a 32.7 percent increase in the yields over the uncoated control, respectively. This relationship shows that it is a basic agronomic principle that a uniform and healthy crop stand that is in place at the start of the season is a prerequisite in assuring the maximal yield potential (Kumar et al., 2024).

The variability in the size of plants is brought about by delayed and uneven emergence, as was seen in the control. The larger and old plants then outcompete the smaller and late-emerging neighbours in access to light, water and nutrients and cause a decline in effective plant population and yield (Duenk et al., 2023). The high-quality seed coverings alleviated this intra-crop competition by ensuring a swift, consistent and intensive germination. The plants were, therefore, put into critical stages of flowering and grain fills with a more homogeneous canopy and a robust root system, thus making them more resilient to prolonged drought stress. The osmoprotectant treatment (T3) too fared fairly well and this must have been due to stabilisation of cellular membrane and enzymes during dehydration- a mechanism that has been well-established in the literature (González et al., 2025). But its intermediate outcomes make it appear that although osmoprotection has its benefits,

water availability (T2) and root plasticity (T4) could have a stronger impact under the given drought regime used in this study (Sartori, 2024).

Climate-Smart Agriculture Implications

The implications of such findings are enormous to the sustainable agriculture, especially to rainfed regimes in drought prone areas. Seed coating is a scalable technology that can be incorporated in the current seed supply chains with minimum inconvenience. It is a more convenient and immediate solution to smallholder farmers than the long development periods of drought-tolerant cultivars or the expensive capital expense of the irrigation infrastructure (Zhang et al., 2022; Senturk et al., 2023). The current study can provide a roadmap to success: it is necessary to go beyond the simple protective coating to the integrated formulation that would tackle a particular abiotic stressor.

Limitations and Future Research

This paper is limited in a number of ways. Experimental control of the field drought was done which although necessary to achieve methodological rigor, might not accurately reflect the variability of natural drought patterns. It was also established that the investigation can be done using one maize hybrid and that the particular composition of the polymer, hydrogel, and microbial consortium can impact the results. These findings need to be further confirmed by research in future under a wider range of genotypes, soil type and under agro-climatic conditions. Furthermore, there should be economic studies aimed at determining the cost-benefit ratio of such high-tech coatings to the farmers. Another research frontier that is of great concern is the long-term shelf-life of the coated seeds, and more specifically the viability of the microbial inoculants.

CONCLUSION

This paper was able to establish that climate smart seed coatings can greatly help in promoting germination and seedling development of maize when subjected to drought conditions by the field. The major observation was that the incorporation of functional agents such as hydrogels, osmoprotectants or useful microbes within a polymer base was more efficient in comparison to a polymer coating on its own. The polymer-plus-hydrogel treatment appeared to be especially impressive, with the highest emergence percentage and an increase in the grain yield of 38 per cent. in

comparison with the control. By measuring increment of the emergence dynamics, the seedling vigor and the ultimate yield, the research effectively achieved its goals, and there were significant correlations among these parameters. Its overall message is that these seed coatings are a viable, scalable technology which can be used to enhance crop climate resilience. This research has scientific value because it presents evidence of the synergetic action of multi component coatings in the field that has been verified. Future studies must concentrate on the enhancement of coating blended in particular soils and climates, the economic sustainability of these coating blends in the short and long terms to farmers, and their effectiveness in other major cereal crops.

REFERENCES

- Adedayo, A. A., & Babalola, O. O. (2023). Fungi that promote plant growth in the rhizosphere boost crop growth. *Journal of Fungi*, 9(2), 239.
- Agbna, G. H., & Zaidi, S. J. (2025). Hydrogel Performance in Boosting Plant Resilience to Water Stress—A Review. *Gels*, 11(4), 276.
- Arif, M., Fiaz, S., Kandegama, W. M. W. W., Sheth, S., & Li, L. (2025). Evaluating the impacts of environmental stresses on agriculture in the context of climate resilience. *Plant Molecular Biology*, 115(4), 73.
- Bal, S. K., Sandeep, V. M., Kumar, P. V., Rao, A. S., Pramod, V. P., Manikandan, N., ... & Bhaskar, S. (2022). Assessing impact of dry spells on the principal rainfed crops in major dryland regions of India. *Agricultural and Forest Meteorology*, 313, 108768.
- Bhattacharya, A. (2021). Effect of soil water deficit on growth and development of plants: a review. *Soil water deficit and physiological issues in plants*, 393-488.
- Chandel, A., Yadav, M., & Nguyen, P. M. (2025). Climate Change and Sustainable Development: How Can Climate Change Be Addressed Within the Framework of Sustainable Development Goals?. In *Effects of climate change on social and economic factors* (pp. 387-422). IGI Global.
- Duenk, E. (2022). Optimization of weed control in E3 soybean [Glycine max (L.) Merr.] (Doctoral dissertation, University of Guelph).
- Durgadevi, P., Girigoswami, K., & Girigoswami, A. (2025). Biodegradable nanomaterials in boosting seed vigor and germination: seed coating towards

- sustainability. *Discover Applied Sciences*, 7(7), 695.
- Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. M. (2022). Global maize production, consumption and trade: trends and R&D implications. *Food security*, 14(5), 1295-1319.
- Gani, A., Mamat, R., Nizar, M., Yana, S., Rosdi, S. M., Zaki, M., & Eko Sardjono, R. (2023). The Business Model for Access to Affordable RE on Economic, Social, and Environmental Value: A Review. *Geomatics and Environmental Engineering*, 17(5).
- Gaurana-Nuñez, M. L. (2024). Screening and selection of drought-tolerant rainfed lowland rice seedlings based on early seedling vigor under Polyethylene Glycol-Induced Stress. *Annals of Tropical Research*, 46(2), 75-90.
- Gitore, S. A. (2023). Phenotypic characterization and evaluating the response of sweetpotato genotypes for drought tolerance as an adaptation to climate change in Ethiopia (Doctoral dissertation, Doctoral thesis, Kenyatta University).
- González, J., Villarreal-Huerta, D., Rosas-Paz, M., & Segal-Kischinevzky, C. (2025). Biotechnological applications of yeasts under extreme conditions. In *Extremophilic Yeasts* (pp. 459-501). Cham: Springer Nature Switzerland.
- Goszcz, A., Furtak, K., Stasiuk, R., Wójtowicz, J., Musiałowski, M., Schiavon, M., & Dębiec-Andrzejewska, K. (2025). Bacterial osmoprotectants-a way to survive in saline conditions and potential crop allies. *FEMS Microbiology Reviews*, fuaf020.
- Guo, Y., Du, Y., Niu, X., Ma, Y., Song, G., Cao, C., ... & Siddique, K. H. (2024). Comparison of drought stress responses in large-and small-rooted rice lines: Physiological, anatomical, and hormonal changes. *Journal of Plant Growth Regulation*, 43(8), 2922-2936.
- Huggi, L., Thimmegowda, M. N., Sridhara, S., Manjunatha, M. H., & Das, B. (2024). Climate change-induced spatiotemporal monsoon variability: assessment of its implications on global and regional production systems. In *Climate Change Impacts on Soil-Plant-Atmosphere Continuum* (pp. 713-758). Singapore: Springer Nature Singapore.
- Ifeanyi-Obi, C. C., Issa, F. O., Aderinoye-Abdulwahab, S., O. Ayinde, A. F., Umeh, O.

- J., & Tologbonse, E. B. (2022). Promoting uptake and integration of climate smart agriculture technologies, innovations and management practices into policy and practice in Nigeria. *International Journal of climate change strategies and management*, 14(4), 354-374.
- IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.
- Jarrar, H., El-Keblawy, A., Ghenai, C., Abhilash, P. C., Bundela, A. K., Abideen, Z., & Sheteiwy, M. S. (2023). Seed enhancement technologies for sustainable dryland restoration: Coating and scarification. *Science of the Total Environment*, 904, 166150.
- Kavusi, E., Shahi Khalaf Ansar, B., Dehghanian, Z., Asgari Lajayer, B., Nobaharan, K., Ma, Y., & Glick, B. R. (2023). Delivery of beneficial microbes via seed coating for medicinal and aromatic plant production: a critical review. *Journal of Plant Growth Regulation*, 42(2), 575-597.
- Krieger, M. T. (2023). Managing a native invader in wet grasslands: Effects on target species, community composition and grassland multifunctionality (Doctoral dissertation, Technische Universität München).
- Kumar, A., Sharma, M. J., Mahajan, A., & Kumar, J. (2024). Principles and Practices For Modern Agronomy. Academic Guru Publishing House.
- Oladosu, Y., Rafii, M. Y., Arolu, F., Chukwu, S. C., Salisu, M. A., Fagbohun, I. K., ... & Haliru, B. S. (2022). Superabsorbent polymer hydrogels for sustainable agriculture: A review. *Horticulturae*, 8(7), 605.
- Patyal, D., Sachdeva, K., Sharma, K., & Khan, R. R. (2025). An Innovative and Sustainable Seed Coating Technology for Improving Seed Quality and Crop Performance. *Journal of Scientific Research and Reports*, 597-607.
- Patyal, D., Sachdeva, K., Sharma, K., & Khan, R. R. (2025). An Innovative and Sustainable Seed Coating Technology for Improving Seed Quality and Crop Performance. *Journal of Scientific Research and Reports*, 597-607.
- Rao, N., Sathe, R., & Grist, N. (2025). Gender, intersectionality and climate smart agriculture in South Asia: A review. *PLOS Climate*, 4(2), e0000482.

- Sajjad, Z. U., Fatima, Z., Awais, M., Waheed, A., Ali, A., Hashmi, Q. A., ... & Sufyan, A. (2023). Effect of Polyethylene Glycol (PEG) on Germination and Seedling Parameters of Maize Varieties. *Asian Journal of Research in Crop Science*, 8(4), 410-420.
- Sani, M. N. H., & Yong, J. W. (2021). Harnessing synergistic biostimulatory processes: A plausible approach for enhanced crop growth and resilience in organic farming. *Biology*, 11(1), 41.
- Sartori, A. (2024). Effects of drought/recovery cycles on tissue osmoregulation, water relations and root exudation in plants.
- Senturk, S., Senturk, F., & Karaca, H. (2023). Industry 4.0 technologies in agri-food sector and their integration in the global value chain: A review. *Journal of Cleaner Production*, 408, 137096.
- Sible, C. N., Seebauer, J. R., & Below, F. E. (2021). Plant biostimulants: A categorical review, their implications for row crop production, and relation to soil health indicators. *Agronomy*, 11(7), 1297.
- Sohail, M., Pirzada, T., Opperman, C. H., & Khan, S. A. (2022). Recent advances in seed coating technologies: transitioning toward sustainable agriculture. *Green Chemistry*, 24(16), 6052-6085.
- Sohail, M., Pirzada, T., Opperman, C. H., & Khan, S. A. (2022). Recent advances in seed coating technologies: transitioning toward sustainable agriculture. *Green Chemistry*, 24(16), 6052-6085.
- Soni, P. G., Basak, N., Rai, A. K., Sundha, P., Chandra, P., & Yadav, R. K. (2023). Occurrence of salinity and drought stresses: status, impact, and management. In *Salinity and drought tolerance in plants: Physiological perspectives* (pp. 1-28). Singapore: Springer Nature Singapore.
- Thanusha, N. R. (2022). Standardization of Seed Enhancement Techniques and Media for Healthy Production of Radish and Sunflower Microgreens (Doctoral dissertation, University of Agricultural Sciences, GKVK, Bangalore).
- Tyśkiewicz, R., Nowak, A., Ozimek, E., & Jaroszek-Ścisł, J. (2022). Trichoderma: The current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. *International journal of molecular sciences*, 23(4), 2329.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- Wahab, A., Abdi, G., Saleem, M. H., Ali, B., Ullah, S., Shah, W., ... & Marc, R. A. (2022). Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: A comprehensive review. *Plants*, 11(13), 1620.
- Zandi, P., & Schnug, E. (2022). Reactive oxygen species, antioxidant responses and implications from a microbial modulation perspective. *Biology*, 11(2), 155.
- Zhang, K., Khan, Z., Yu, Q., Qu, Z., Liu, J., Luo, T., ... & Luo, L. (2022). Biochar coating is a sustainable and economical approach to promote seed coating technology, seed germination, plant performance, and soil health. *Plants*, 11(21), 2864.