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CLIMATE RESILIENCE IN GROUNDNUT (*ARACHIS HYPOGAEA* L.): EFFECTS OF PGPR SEED PRIMING ON GROWTH, YIELD, AND ECONOMIC PERFORMANCE UNDER HEAT STRESS

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ABSTRACT

Heat stress significantly constrains groundnut productivity in semi-arid regions, particularly during germination and flowering stages. A field experiment was conducted at the M.S. Swaminathan Vayal Kudam, Department of Agricultural Engineering, Paavai Engineering College, Namakkal, to evaluate the influence of seed priming strategies on growth, yield, and economic performance of groundnut (*Arachis hypogaea* L.) under elevated temperature conditions. The experimental soil was sandy loam in texture, slightly alkaline in reaction (pH 7.6), low in available nitrogen, medium in available phosphorus, and high in potassium. The study was laid out in a Randomized Complete Block Design with six treatments and three replications: T_1–Control (non-primed seeds), T_2–Hydropriming, T_3–*Bacillus subtilis* priming, T_4–*Pseudomonas fluorescens* priming, T_5–Consortium of *Bacillus subtilis* + *Pseudomonas fluorescens*, and T_6–Nutrient priming with 1% potassium nitrate (KNO_3). Heat stress conditions prevailed during vegetative and flowering stages, with maximum temperatures ranging from 39–42°C. Results revealed that seed priming significantly enhanced germination percentage, seedling vigor index, plant height, chlorophyll content, and dry matter production compared to the control under heat stress. Among treatments, the microbial consortium (T_5) recorded the highest improvement in pod yield (approximately 24% over control), followed by nutrient priming (T_6). Economic analysis indicated superior gross returns, net returns, and benefit–cost ratio in PGPR treatments, with T_5 achieving the highest B:C ratio, while nutrient priming also showed improved profitability compared to non-primed seeds. The findings demonstrate that microbial and nutrient-based seed priming strategies enhance thermotolerance, stabilize productivity, and improve economic returns, providing a climate-resilient and sustainable approach for groundnut cultivation in heat-prone regions.

***Keywords* :** PGPR, Seed biopriming, Nutrient priming, Heat stress, Climate resilience, Groundnut, Economic analysis.

Introduction

Climate change is intensifying temperature extremes in semi-arid agro-ecosystems, directly threatening oilseed crop productivity. Groundnut (*Arachis hypogaea* L.), a major legume–oilseed crop, is highly sensitive to elevated temperature during flowering and pod development stages, which leads to impaired pollen viability, reduced fertilization, and poor pod filling (Bita & Gerats, 2013; Hasanuzzaman *et al*., 2013). The Intergovernmental Panel on Climate Change has projected increased frequency of heat waves across tropical regions, further aggravating reproductive losses in groundnut (IPCC, 2023).

Heat stress disrupts photosynthesis, membrane integrity, and enzymatic stability, resulting in oxidative damage and metabolic imbalance (Farooq *et al*., 2009; Hasanuzzaman *et al*., 2013). Under such conditions, sustainable biological interventions are required to stabilize crop productivity. Seed priming is an effective pre-sowing strategy that enhances uniform germination, accelerates metabolic activation, and improves stress adaptation (Grover *et al*., 2011;

Paparella *et al*., 2015; Jisha *et al*., 2013). Among priming approaches, microbial seed priming using plant growth-promoting rhizobacteria (PGPR) has gained importance due to its eco-friendly and climate-resilient potential (Jatana *et al*., 2024; Backer *et al*., 2018; Rouphael & Colla, 2020).

PGPR such as *Bacillus subtilis* and *Pseudomonas fluorescens* promote plant growth through phytohormone production, nutrient solubilization, induced systemic tolerance, and antioxidant enzyme activation (Mahmood *et al*., 2016; Swarnalakshmi *et al*., 2020). Under thermal stress, PGPR enhance membrane stability, regulate osmolyte accumulation, and mitigate reactive oxygen species (ROS) toxicity (Munir S. 2025; Prasad *et al*., 2020; Kumar *et al*., 2020). Recent studies indicate that microbial consortia exhibit synergistic effects by improving rhizosphere colonization and functional complementarity, leading to better stress resilience compared to single-strain inoculation (Singh *et al*., 2025; Bigatton *et al*., 2024; Kausar *et al*., 2018).

Although PGPR-mediated stress tolerance has been widely reported in cereals and legumes (Vurukonda *et al*., 2016; Al-Turki *et al*., 2023), field-based validation under high-temperature stress in groundnut remains limited. Therefore, the present investigation aimed to evaluate the influence of PGPR seed priming on emergence, growth performance, yield attributes, and economic returns of groundnut under heat stress conditions.

Materials and Methods

Experimental Site Description

The field experiment was conducted during the summer season at the M.S. Swaminathan Vayal Kudam, Department of Agricultural Engineering, Paavai Engineering College, Namakkal region, Tamil Nadu, India. The experimental site is located in a semi-arid agro-climatic zone characterized by high summer temperatures and moderate rainfall. During the crop growth period, the maximum temperature ranged between 39°C and 42°C, particularly during vegetative and flowering stages, creating natural heat stress conditions.

Soil Physicochemical Properties

Prior to sowing, composite soil samples (0–30 cm depth) were collected from the experimental field and analyzed using standard laboratory procedures. The soil was classified as sandy loam in texture. Physicochemical characteristics of the experimental soil are presented below:

Parameter	**Value**	**Method Used**	**Reference**
Texture	Sandy loam	Hydrometer method	Bouyoucos (1962)
Soil pH	7.6	Digital pH meter (1:2.5 soil–water suspension)	Jackson (1973)
Electrical Conductivity (dS m^{-1})	0.38	Conductivity meter	Jackson (1973)
Organic Carbon (%)	0.52	Walkley–Black wet oxidation method	Walkley & Black (1934)
Available Nitrogen (kg ha^{-1})	245	Alkaline $KMnO_4$ method	Subbiah & Asija (1956)
Available Phosphorus (kg ha^{-1})	18.4	Olsen's extraction method	Olsen *et al*. (1954)
sAvailable Potassium (kg ha^{-1})	312	Flame photometry	Jackson (1973)

The soil was slightly alkaline, low in available nitrogen, medium in phosphorus, and high in potassium.

Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with six treatments and three replications. Each plot measured 4 m × 3 m with recommended spacing of 30 cm × 10 cm. The treatments were:

T_1: Control (non-primed seeds)
T_2: Hydropriming (seeds soaked in distilled water)
T_3: Seed priming with *Bacillus subtilis*
T_4: Seed priming with *Pseudomonas fluorescens*
T_5: Microbial consortium (*Bacillus subtilis* + *Pseudomonas fluorescens*)
T_6: Nutrient priming with 1% potassium nitrate (KNO_3)

The recommended package of practices for groundnut cultivation was uniformly followed for all treatments.

Seed Priming Procedures

Hydropriming (T_2)

Seeds were soaked in distilled water for 8 hours at room temperature (25 ± 2°C), followed by shade drying to original moisture content before sowing.

PGPR Priming (T_3, T_4, T_5)

Certified cultures of *Bacillus subtilis* and *Pseudomonas fluorescens* were multiplied in nutrient broth to achieve a population density of approximately 10^8 CFU mL^{-1}. Seeds were surface sterilized using 1% sodium hypochlorite solution and rinsed thoroughly with sterile distilled water.

Seeds were soaked in bacterial suspension for 10 hours under aseptic conditions. After soaking, seeds were shade dried to near-original moisture content before sowing.

For consortium treatment (T_5), equal proportions of both bacterial suspensions were mixed prior to seed soaking.

Nutrient Priming (T_6)

Seeds were soaked in 1% potassium nitrate (KNO_3) solution for 8 hours and dried back to original moisture content before sowing.

Crop Management

Groundnut variety suitable for the Namakkal region was sown manually. Recommended fertilizer dose (25:50:75 kg N: P_2O_5: K_2O ha^{-1}) was applied uniformly. Irrigation was scheduled based on crop requirement, and standard agronomic practices were followed to maintain uniform crop stand.

Observations Recorded

The study recorded comprehensive observations covering emergence, growth, yield, and economic performance of groundnut under different seed priming treatments.

Under emergence parameters, germination percentage (%), mean germination time (days), and seedling vigor index were assessed to evaluate early establishment and seedling robustness. Germination percentage was calculated based on the total number of normal seedlings emerged, while mean germination time reflected the speed of germination. Seedling vigor index was computed by integrating germination percentage with seedling length to determine overall seedling strength.

For growth parameters, plant height (cm) was measured at 30 and 60 days after sowing (DAS) to assess vegetative development. Leaf area index was determined to quantify canopy development and photosynthetic potential, and chlorophyll content was measured using a SPAD meter to evaluate leaf greenness and physiological status. Total dry matter production (g plant^{-1}) was recorded by oven-drying sampled plants to constant weight, indicating biomass accumulation efficiency.

The yield attributes included number of pods per plant, 100-kernel weight (g), pod yield (kg ha^{-1}), and haulm yield (kg ha^{-1}), which collectively represented reproductive performance and final productivity.

An economic analysis was conducted using standard cost–return methodology. Gross return (Rs. ha^{-1}) was calculated by multiplying pod yield with prevailing market price. Net return (Rs. ha^{-1}) was derived by subtracting cost of cultivation from gross return, and the Benefit–Cost (B:C) ratio was computed as the ratio of gross return to cost of cultivation to assess economic feasibility of the treatments.

Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) appropriate for RCBD. Treatment means were compared using Least Significant Difference (LSD) at 5% probability level. Statistical analysis was performed using standard agricultural statistical software. Percentage data were arcsine transformed before analysis where necessary.

Results and Discussion

Emergence and Seedling Growth

Seed priming significantly influenced germination and early seedling vigor under heat stress (Table 1). Primed treatments exhibited higher germination percentage than the non-primed control. The consortium treatment (T_5) recorded the highest germination (91.4%), followed by PGPR individual strains (T_3 and T_4). Hydropriming (T_2) and nutrient priming (T_6) also improved emergence compared to the control.

Table 1 : Effect of Seed Priming on Emergence Parameters Under Heat Stress

Treatment	Germination (%)	Mean Germination Time (days)	Seedling Vigor Index
T_1 – Control	76.2 ± 1.8c	6.2 ± 0.1a	820 ± 12d
T_2 – Hydropriming	80.5 ± 2.1b	5.8 ± 0.1b	910 ± 15c
T_3 – *Bacillus subtilis*	86.8 ± 1.5a	5.4 ± 0.1c	1,020 ± 18b
T_4 – *Pseudomonas fluorescens*	85.2 ± 1.7a	5.5 ± 0.1c	995 ± 16b
T_5 – Consortium	91.4 ± 1.2a	5.1 ± 0.1d	1,120 ± 14a
T_6 – Nutrient (1% KNO_3)	83.7 ± 1.9b	5.7 ± 0.1b	950 ± 17c
LSD (5%)	2.5	0.2	45

Note: Values are mean ± SE. Means followed by different letters differ significantly at $p < 0.05$.

Enhanced emergence performance may be attributed to accelerated metabolic repair, enzyme activation, and improved membrane reorganization during imbibition (Ashraf *et al.*, 2005; Paparella *et al.*, 2015; Jisha *et al.*, 2013). Microbial priming further stimulates early root proliferation and phytohormone production, particularly indole-3-acetic acid (IAA), leading to rapid seedling establishment under stress (Mahmood *et al.*, 2016; Backer *et al.*, 2018).

Improved early growth under consortium treatment indicates enhanced rhizosphere colonization and nutrient mobilization. PGPR-mediated nitrogen fixation and phosphorus solubilization likely contributed to better root-shoot development (Swarnalakshmi *et al.*, 2020; Vejan *et al.*, 2016). Similar improvements in early vigor under microbial priming were reported by Bigatton *et al*. (2024) in peanut and by Kumar *et al*. (2020) under heat stress conditions.

Growth Attributes

Significant differences were observed in plant height, leaf area index, chlorophyll content, and total dry matter production. The consortium treatment showed superior performance at 60 DAS (Table-2). Enhanced chlorophyll retention under PGPR treatments suggests improved photosynthetic efficiency and protection against thermal-induced chlorophyll degradation (Hasanuzzaman *et al.*, 2013; Kumar *et al.*, 2020).

Heat stress typically reduces photosystem stability and carbon assimilation (Farooq *et al.*, 2009). However, PGPR treatments appear to enhance antioxidant defense mechanisms and osmoprotectant accumulation, thereby stabilizing cellular metabolism (Egamberdieva *et al.*, 2017; Al-Turki *et al.*, 2023). Increased dry matter production under consortium treatment may result from improved nutrient uptake and hormonal balance, which regulate biomass partitioning (Rouphael & Colla, 2020; Singh *et al.*, 2019).

Table 2 : Effect of Seed Priming on Growth Attributes at 60 DAS

Treatment	**Plant Height (cm)**	**Leaf Area Index**	**Chlorophyll (SPAD)**	**Dry Matter (g plant^{-1})**
T_1 – Control	48.5 ± 1.3d	2.15 ± 0.08d	32.8 ± 0.9d	21.7 ± 0.8d
T_2 – Hydropriming	53.1 ± 1.5c	2.42 ± 0.07c	36.2 ± 1.0c	24.9 ± 0.7c
T_3 – *Bacillus subtilis*	57.8 ± 1.2b	2.68 ± 0.06b	39.4 ± 0.8b	27.1 ± 0.6b
T_4 – *Pseudomonas fluorescens*	56.4 ± 1.4b	2.61 ± 0.07b	38.7 ± 0.9b	26.4 ± 0.9b
T_5 – Consortium	62.3 ± 1.1a	2.89 ± 0.05a	42.1 ± 0.7a	29.2 ± 0.5a
T_6 – Nutrient (1% KNO_3)	54.7 ± 1.6c	2.50 ± 0.08c	37.5 ± 1.1c	25.8 ± 0.8c
LSD (5%)	2.8	0.10	1.7	1.2

Yield Attributes and Productivity

Seed priming significantly improved yield parameters under heat stress (Table 3).

Table 3 : Effect of Seed Priming on Yield and Yield Attributes

Treatment	**Pods plant^{-1}**	**100-kernel Weight (g)**	**Pod Yield (kg ha^{-1})**	**Haulm Yield (kg ha^{-1})**
T_1 – Control	18.2 ± 0.6d	38.5 ± 0.9d	1,830 ± 45d	3,210 ± 70d
T_2 – Hydropriming	20.5 ± 0.8c	40.1 ± 1.1c	2,040 ± 53c	3,520 ± 76c
T_3 – *Bacillus subtilis*	22.8 ± 0.7b	42.6 ± 1.2b	2,260 ± 48b	3,840 ± 69b
T_4 – *Pseudomonas fluorescens*	22.1 ± 0.9b	42.0 ± 1.0b	2,210 ± 52b	3,790 ± 72b
T_5 – Consortium	24.6 ± 0.5a	44.2 ± 0.9a	2,520 ± 41a	4,120 ± 65a
T_6 – Nutrient (1% KNO_3)	21.7 ± 0.8c	41.4 ± 0.8c	2,160 ± 50c	3,680 ± 68c
LSD (5%)	1.2	1.6	90	130

Yield attributes including number of pods per plant and 100-kernel weight were significantly enhanced under PGPR treatments, with maximum values recorded in the consortium (T_5). Pod yield (2520 kg ha^{-1}) and haulm yield (4120 kg ha^{-1}) were markedly higher than control. Elevated temperature during reproductive stage often reduces pollen viability and peg formation (Bita & Gerats, 2013). The improved yield performance suggests that PGPR priming mitigated heat-induced reproductive losses.

Synergistic microbial interactions in consortium treatments may enhance root architecture and assimilate translocation, thereby improving pod filling efficiency (Singh *et al.*, 2025; Bigatton *et al.*, 2024). Similar yield enhancement in legumes under PGPR priming was reported by (Swarnalakshmi *et al.*, 2020; Dey *et al.*, 2004 and Mahmood *et al.*, 2016). Enhanced radiation use efficiency and improved nitrogen metabolism under microbial treatments may also explain the yield increment (Bigatton *et al.*, 2024).

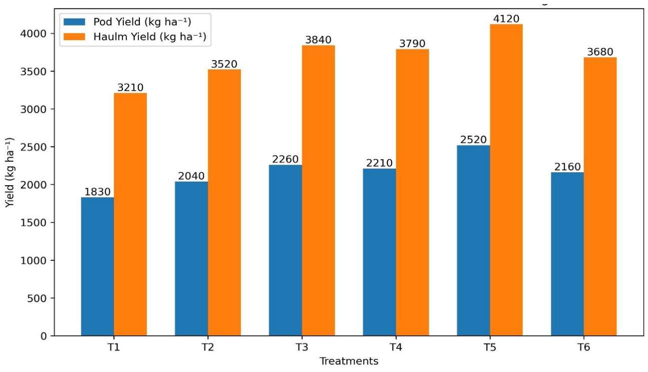

Fig. 1 : Combined comparison of pod yield and haulm yield (kg ha^{-1}) of groundnut as influenced by different seed priming treatments under heat stress conditions.

Economic Analysis

Economic analysis revealed that seed priming enhanced profitability compared to the control (Table 4).

Table 4 : Economic Analysis of Seed Priming Treatments

Treatment	Cost of Cultivation (Rs. ha^{-1})	Gross Return (Rs. ha^{-1})	Net Return (Rs. ha^{-1})	B:C Ratio
T_1 – Control	52,200	91,500	39,300	1.75
T_2 – Hydropriming	53,100	102,000	48,900	1.92
T_3 – *Bacillus subtilis*	54,400	113,000	58,600	2.08
T_4 – *Pseudomonas fluorescens*	54,400	110,500	56,100	2.03
T_5 – Consortium	55,800	126,000	70,200	2.26
T_6 – Nutrient (1% KNO_3)	53,900	107,500	53,600	1.99

Economic evaluation revealed maximum gross return and Benefit–Cost ratio under consortium treatment. The economic advantage indicates that microbial seed priming is not only biologically effective but also financially viable for farmers in heat-prone regions. Sustainable bio-inoculant technologies have been increasingly recognized as cost-effective climate adaptation tools (Rouphael & Colla, 2020; Al-Turki *et al*., 2023; Jyothi *et al*., 2025).

Overall Discussion the present study demonstrates that PGPR seed priming, particularly with a microbial consortium, significantly improved emergence, growth, yield, and profitability of groundnut under heat stress. Enhanced performance under stress can be attributed to improved phytohormone regulation, nutrient acquisition, antioxidant defense, and osmotic balance mediated by PGPR (Backer *et al*., 2018; Egamberdieva *et al*., 2019; Singh *et al*., 2025).

These results reinforce the concept that biopriming and nutrient priming are effective strategies for mitigating heat stress in groundnut, making them suitable for climate-resilient agronomic practices in semi-arid regions.

Conclusion

The present study demonstrates that PGPR-based seed priming significantly enhances emergence, growth, yield attributes, and economic returns of groundnut under heat stress conditions. Among the treatments evaluated, the microbial consortium exhibited superior performance by improving germination efficiency, accelerating early seedling vigor, and promoting greater biomass accumulation. Enhanced physiological activity, including improved nutrient uptake and stress mitigation mechanisms, translated into higher pod yield (2520 kg ha^{-1}) and haulm yield (4120 kg ha^{-1}) compared to control.

The integration of beneficial rhizobacteria, particularly *Bacillus subtilis* and *Pseudomonas fluorescens*, either alone or in consortium, proved effective in mitigating heat-induced reproductive losses such as flower drop and poor pod filling. Economic analysis further confirmed the feasibility of PGPR priming, with the consortium treatment yielding the highest net return and Benefit–Cost ratio, indicating its practical suitability for farmers facing elevated temperature stress.

Overall, PGPR consortium seed priming emerges as a climate-resilient, sustainable, and economically viable strategy for enhancing groundnut productivity under rising temperature scenarios. Its adoption can contribute to stabilizing yield performance and improving profitability in heat-prone agro-ecological regions.

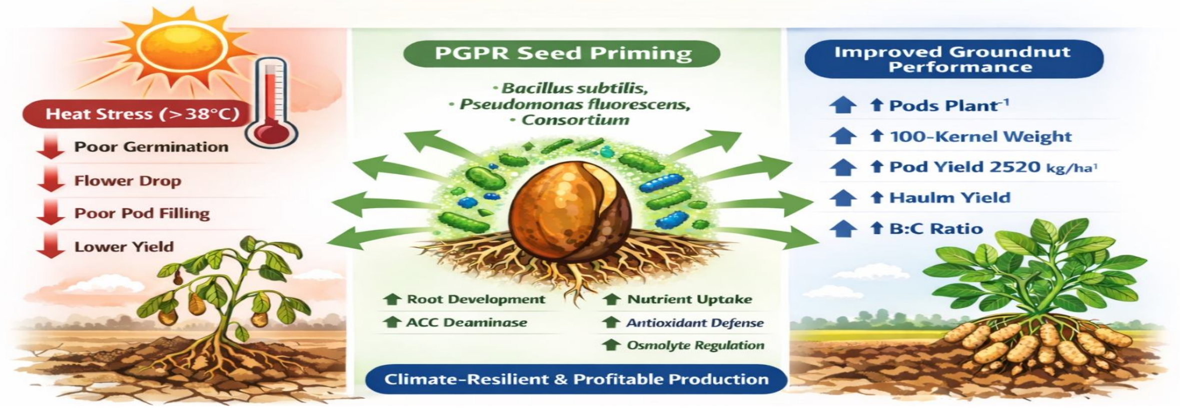

Fig. 2 : Graphical abstract illustrating the role of PGPR seed priming (*Bacillus subtilis*, *Pseudomonas fluorescens*, and consortium) in enhancing heat stress tolerance (>38 °C) and improving growth, yield, and economic returns of groundnut (*Arachis hypogaea* L.) through improved root development, nutrient uptake, antioxidant defense, and ACC deaminase activity.

Future Scope

Future research may focus on validating PGPR consortium seed priming across diverse agro-climatic zones and multiple growing seasons to assess its stability under varying heat stress intensities. Molecular and physiological investigations are needed to elucidate gene-level regulation of heat-responsive pathways, antioxidant enzyme activation, and hormonal modulation induced by *Bacillus subtilis* and *Pseudomonas fluorescens*. Integration of PGPR priming with other climate-smart practices such as micronutrient fortification, biochar application, and precision irrigation could further enhance stress resilience and yield stability.

Long-term studies evaluating soil microbial dynamics and rhizosphere sustainability will provide insights into ecological impacts and persistence of introduced strains. Additionally, the development of commercially viable bioformulations with improved shelf life and farmer-friendly delivery systems can accelerate large-scale adoption. Techno-economic modeling and life-cycle assessment approaches may also be employed to quantify environmental benefits and carbon mitigation potential under climate change scenarios.

Conflicts of Interest

The authors declare no conflicts of interest.

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