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Enhancing Germination and Early Seedling Growth of Groundnut through Chemical, Growth Regulator and Hydrothermal Pod Treatments

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ABSTRACT: Groundnut (*Arachis hypogaea* L.) is an important oilseed and food legume crop widely grown in tropical and subtropical regions, where rapid and uniform crop establishment is essential for maximizing productivity under rainfed conditions. However, direct pod sowing often results in delayed germination and poor seedling establishment due to pod shell barriers and uneven water imbibition. This study evaluated the effects of chemical, hormonal and hydrothermal pre-sowing treatments on germination, seedling growth and vigour of groundnut under direct pod sowing conditions. The experiment was conducted in grow bags at the School of Agriculture, VISTAS, Pallavaram, Chennai, India, using a completely randomized design with eight treatments and three replications. The growing medium consisted of red loamy soil, river sand and well-decomposed farmyard manure (2:1:1 v/v/v). Treatments included sulphuric acid (10%), nitric acid (10%), potassium nitrate (1%), gibberellic acid (1%), hydrogen peroxide (1%), hot water (60°C), cold-water soaking and an untreated control. Although all treatments achieved 100% germination, significant differences were observed in germination time, seedling growth, biomass and vigour indices. Hydrogen peroxide (1%) soaking for 12 hours was the most effective treatment, reducing germination time and significantly improving seedling growth, biomass accumulation and seedling vigour. Hot- and cold-water soaking also enhanced early growth compared with the control, whereas acid treatments showed moderate effects and sulphuric acid was the least effective. The findings indicate that hydrogen peroxide-induced reactive oxygen species signaling promotes rapid germination and vigorous seedling establishment, making it a simple and effective pre-sowing treatment for improving direct pod sowing of groundnut under semi-arid conditions.

Keywords: Groundnut, Pod-sowing treatment, Hydrogen peroxide, Hydrothermal treatment, Germination, Seedling vigour.

1. INTRODUCTION

Groundnut (*Arachis hypogaea* L.) is an important oilseed and food legume crop cultivated widely in tropical and subtropical regions. It is a major source of edible oil, protein, vitamins and minerals and contributes significantly to food security and livelihoods in semi-arid and rainfed ecosystems. India is one of the leading groundnut-producing countries, where successful crop establishment is essential for achieving higher productivity (2.13 t ha^{-1}). However, direct pod sowing often results in delayed germination and poor seedling establishment due to the hard pod shell, dormancy and slow water imbibition. Therefore, pre-sowing treatments such as chemical scarification, growth regulator soaking and hydrothermal treatments are widely used to improve germination and seedling growth (Copeland &

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McDonald, 2001; Finch-Savage & Bassel, 2016).

Seed germination is a complex physiological process involving imbibition, enzyme activation, mobilization of stored food reserves and cell elongation. Reactive oxygen species (ROS) act as important signalling molecules that regulate seed dormancy, metabolic activation and seedling establishment while also contributing to defence against pathogens (Bailly, 2004; Mittler et al., 2011; Wojtyla et al., 2022). Sulphuric acid and nitric acid enhance germination through scarification, whereas potassium nitrate acts as a nitrate signal to stimulate enzyme activity. Gibberellic acid (GA_3) promotes dormancy breaking by inducing hydrolytic enzymes such as α-amylase (Bewley et al., 2013). Hydrogen peroxide (H_2O_2) regulates antioxidant activity and hormonal balance, thereby improving germination, seedling growth and stress tolerance (Bailly, 2004; Mittler et al., 2011; Nadarajah, 2021). Hydrothermal treatments, including hot- and cold-water soaking, improve water uptake and activate metabolic processes, providing a simple and economical method for enhancing seedling vigour (Baidalina et al., 2025).

Although several studies have investigated seed priming in cereals and pulses, information on the comparative effects of acid scarification, growth regulator and hydrothermal treatments under direct pod sowing conditions in groundnut remains limited. Therefore, the present study was undertaken to evaluate the effectiveness of these pre-sowing treatments on germination, seedling growth, biomass accumulation and seedling vigour of groundnut under direct pod sowing conditions.

2. MATERIALS AND METHODS

2.1. Experiment Site, Crop Management and Measurement of Observations

The experiment was conducted during Kharif 2025 at the School of Agriculture, Vels Institute of Science, Technology & Advanced Studies (VISTAS), Pallavaram, Chennai, Tamil Nadu, India. A tropical semi-arid climate with warm temperatures and moderate rainfall characterizes the experimental site. The soil used for the grow-bag experiment was red loamy soil: river sand: Well-decomposed farmyard yard manure (FYM) = 2: 1 : 1 (v/v/v).

Groundnut pods of variety TMV 14 were used for the study. The variety TMV 14 was selected because of its wider adaptability, uniform pod size and suitability for direct pod sowing under Tamil Nadu conditions. Healthy, uniform and mature pods were selected and used for direct pod sowing of intact pods.

Three pods were sown per bag at a depth of 3–4 cm. The experiment was maintained under regular watering and uniform environmental conditions to ensure proper germination and seedling growth. Observations on germination and seedling growth parameters were recorded up to 15 days after sowing.

2.2. Methodology and Pre-sowing Treatments

The experiment was laid out in a completely randomized design (CRD) comprising eight treatments with three replications. The groundnut pods were subjected to various chemical and physical pre-sowing treatments prior to sowing. The treatments included sulphuric acid (H_2SO_4) at 10% concentration for 5 min, nitric acid (HNO_3) at 10% concentration for 5 min, potassium nitrate (KNO_3) at 1% concentration for 12 hours of soaking, gibberellic acid (GA_3) at 1% concentration for 12 hours of soaking and hydrogen peroxide (H_2O_2) at 1% concentration for 12 hours of soaking.

Hydrothermal treatments included hot water treatment at 60°C for 5 min and cold-water soaking for 5 min. Untreated pods served as the control treatment. Following treatment application, acid-treated pods were thoroughly washed with distilled water and shade-dried before sowing.

2.3. Observations Recorded

Observations on germination and seedling growth parameters were recorded systematically. Germination percentage and the number of days to germination were recorded to assess the speed and uniformity of emergence. Seedling growth parameters such as root length, shoot length and total seedling length were measured in centimetres. The number of leaves per seedling was also recorded. Biomass parameters, including the fresh and dry weights of the shoot and root, were measured separately, and the total fresh and dry weights were computed.

Seedling vigour was evaluated using Vigour Index I and Vigour Index II as suggested by Abdul-Baki and Anderson (1973). Vigour Index I was calculated by multiplying germination percentage by total seedling length, and Vigour Index II was calculated by multiplying germination percentage by seedling dry weight.

The magnitude of inhibition or stimulation was evaluated using response index (RI) as described by Williamson and Richardson (1988) using the following formula:

If $T > C$, $RI = 1 - (C/T)$

If $T = C$, $RI = 0$

If $T < C$, $RI = (T/C) - 1$

where T is the treatment mean, and C is the control mean.

2.4. Statistical Analysis

The experiment was conducted in a completely randomized design (CRD) with three replications. The experimental data were subjected to analysis of variance (ANOVA) using the AGRES Statistical Software Package (Version 7.01) following the procedure described by Gomez and Gomez (1984). Treatment means were compared at the 5% level of significance ($P = 0.05$), and the standard error of difference (SEd) and critical difference (CD) were calculated to determine the significance of treatment effects.

3. RESULTS AND DISCUSSION

The present study revealed that chemical and physical pre-sowing treatments significantly influenced germination behaviour, seedling growth, biomass accumulation and vigour of groundnut under direct pod-sowing conditions. Although all treatments recorded 100% germination, substantial differences were observed in the speed of germination, seedling development and vigour indices, indicating that the treatments primarily enhanced physiological performance and seedling establishment rather than final germination percentage. Similar findings were reported in seed priming studies where pre-sowing treatments accelerated metabolic activity and improved seedling vigour without altering germination percentage (Ashraf & Foolad, 2005; Farooq et al., 2019). The observed improvement in seedling establishment has ecological significance under semi-arid and rainfed agro-ecosystems where rapid germination and vigorous early growth are essential for crop survival and resource-use efficiency (Ndlovu et al., 2023).

3.1. Germination and Days to Germination

Significant variation was observed in the number of days required for germination among the treatments (Table 1). Hydrogen peroxide (H_2O_2) 1% soaking (T_5) and nitric acid treatment (T_2) resulted in the earliest germination (7 days), whereas untreated control pods required 12 days for germination. Faster germination in chemically treated pods may be attributed to enhanced water imbibition, activation of hydrolytic enzymes and stimulation of embryo growth. Hydrogen peroxide functions as a reactive oxygen species (ROS) signalling molecule regulating seed dormancy release, cellular metabolism and mitochondrial respiration

Table 1. Effect of pre-sowing treatments on germination and seedling growth of groundnut under direct pod sowing

Treatments	Germination (%)	Number of days to germination	Root length (cm)	Shoot length (cm)	Total length (cm)	No. of leaves	Vigour index-I
T1 - Sulphuric Acid (H_2SO_4) (10%) treatment of Groundnut Pod (5 minutes)	100	8.00	1.03	1.60	2.63	1.06	263
T2 - Nitric Acid (HNO_3) (10%) treatment of Groundnut Pod (5 minutes)	100	7.00	4.60	6.30	15.00	5.16	1500
T3 - Potassium Nitrate (KNO_3) (1%) treatment of Groundnut Pod (12 hours soaking)	100	8.00	1.37	3.00	4.37	1.08	437
T4 - Gibberellic Acid (GA_3) (1%) treatment of Groundnut Pod (12 hours soaking)	100	10.00	2.40	4.60	7.00	2.01	700
T5 - Hydrogen Peroxide (H_2O_2) (1%) treatment of Groundnut Pod (12 hours soaking)	100	7.00	5.90	17.30	23.00	6.51	2300
T6 - Hot Water (60°C) treatment of Groundnut Pod (5 minutes)	100	9.00	2.60	12.58	20.03	5.46	2000
T7 - Cold Water treatment of Groundnut Pod (5 minutes)	100	9.00	2.70	16.60	21.06	6.08	2100
T8 - Control (intact pod)	100	12.00	0.98	1.52	2.50	0.95	250
SEd (±)	NS / NA	0.21	0.07	0.19	0.25	0.08	25.63
CD (P=0.05)	NS / NA	0.46	0.16	0.37	0.57	0.18	58.90

NS – Non-significant due to absence of variation among treatments.
NA – Not applicable.

during germination (Bailly, 2004). Improved germination speed under H_2O_2 treatment may therefore be associated with enhanced energy metabolism and cellular activation leading to rapid radicle emergence. Hydrogen peroxide at optimum concentration functions as a signalling molecule that activates respiratory metabolism, ATP synthesis and antioxidant defence systems during the early phase of germination. It also promotes the activity of hydrolytic enzymes such as α-amylase and proteases, which facilitate rapid mobilization of stored food reserves for embryo growth. Furthermore, H_2O_2-mediated loosening of cell walls and regulation of hormonal balance between abscisic acid and gibberellins enhance cell elongation and radicle protrusion, thereby accelerating seedling emergence and establishment. Similar promotory effects of H_2O_2 on germination metabolism, ROS signalling and early seedling growth were reported by Barba-Espín et al. (2011); Hasanuzzaman et al. (2020); Nadarajah (2021); Wojtyla et al. (2022).

Hydrothermal treatments also reduced germination duration compared to the control. Softening of the pod shell through hot and cold water soaking possibly improved moisture penetration and gas exchange, thereby accelerating metabolic activity during germination. Early germination under direct pod sowing conditions is particularly important in rainfed ecosystems because rapid establishment enables seedlings to escape early-season moisture stress and enhances crop competitiveness under marginal environments (Figure 1).

3.2. Seedling Growth Parameters

Pre-sowing treatments significantly improved root length, shoot length and total seedling length compared to untreated pods (Table 1). Among the treatments, hydrogen peroxide soaking (T_5) recorded the highest root length (5.90 cm), shoot length (17.30 cm) and total seedling length (23.00 cm), followed by cold water treatment (T_7) and hot water treatment (T_6). The control treatment recorded the lowest seedling growth. Enhanced seedling growth under H_2O_2 treatment may be due to increased cell division, cell elongation and efficient mobilization of seed reserves during germination. Hydrogen peroxide is known to interact with

Figure 1. Influence of chemical and physical pre-sowing treatments on seedling growth and root development of groundnut (*Arachis hypogaea* L.) under direct intact pod sowing. Representative seedlings were photographed after germination to illustrate the effects of different treatments on shoot and root growth. Treatments were: T_1 - Sulphuric acid (H_2SO_4, 10%) for 5 min, T_2 - Nitric acid (HNO_3, 10%) for 5 min, T_3 - Potassium nitrate (KNO_3, 1%) for 12 h soaking, T_4 - Gibberellic acid (GA_3, 1%) for 12 h soaking, T_5 - Hydrogen peroxide (H_2O_2, 1%) for 12 h soaking, T_6 - Hot water (60°C) for 5 min, T_7 - Cold water for 5 min, and T_8 - Untreated intact pod (control). The photograph provides a visual comparison of treatment effects on early seedling establishment, demonstrating enhanced shoot and root development in H_2O_2-treated pods compared with the other treatments

phytohormonal pathways involving gibberellins and auxins, thereby promoting seedling growth and tissue differentiation (Barba-Espín et al., 2011).

Improved seedling growth under hydrothermal treatments indicates that physical softening of the pod shell enhanced hydration and activated metabolic enzymes involved in reserve mobilization. Improved root proliferation under hydrothermal and priming treatments may be attributed to enhanced water imbibition, activation of metabolic enzymes and stimulation of cellular division and elongation during early seedling development. Enhanced root growth enables seedlings to explore a greater soil volume for water and nutrient acquisition, thereby improving drought adaptation and establishment under semi-arid conditions (Hasanuzzaman et al., 2020). Hydrothermal treatments may also soften the pod shell and facilitate rapid activation of physiological processes associated with germination and root differentiation. In addition, seed priming treatments are known to enhance membrane repair, antioxidant activity and osmotic adjustment, which collectively contribute to improved seedling vigour and stress tolerance. Similar improvements in seedling growth, root development and early vigour due to hydrothermal and priming treatments were reported by Ndlovu et al. (2023) and Sabongari & Aliero (2024).

3.3. Number of Leaves and Biomass Production

The number of leaves and biomass production were significantly influenced by pre-sowing treatments (Table 2). Hydrogen peroxide treatment recorded the highest number of leaves, fresh biomass and dry biomass accumulation, followed by cold water and hot water treatments. Increased biomass accumulation indicates improved photosynthetic activity, efficient nutrient mobilization and enhanced physiological performance of seedlings. Enhanced dry matter production under H_2O_2 treatment may be associated with improved antioxidant enzyme activity and reduced oxidative damage during early seedling development (Gill & Tuteja, 2010).

Biomass accumulation during the early establishment phase is an important ecological indicator because vigorous seedlings possess greater adaptive capacity under fluctuating environmental conditions. Treatments that improved biomass production may therefore contribute to

Table 2. Effect of pre-sowing treatments on biomass and vigour index-ii of groundnut under direct pod sowing

Treatments	Fresh weight of shoot (g)	Dry weight shoot (g)	Fresh weight of root (g)	Dry weight root (g)	Total fresh weight (g)	Total dry weight (g)	Vigour index-II
T1 - Sulphuric Acid (H_2SO_4) (10%) treatment of Groundnut Pod (5 minutes)	0.10	0.07	0.30	0.23	0.40	0.30	30
T2 - Nitric Acid (HNO_3) (10%) treatment of Groundnut Pod (5 minutes)	0.36	0.21	0.53	0.30	0.80	0.52	52
T3 - Potassium Nitrate (KNO_3) (1%) treatment of Groundnut Pod (12 hours soaking)	0.50	0.13	0.36	0.29	0.94	0.42	42
T4 - Gibberellic Acid (GA_3) (1%) treatment of Groundnut Pod (12 hours soaking)	0.61	0.20	0.66	0.52	1.34	0.72	72
T5 - Hydrogen Peroxide (H_2O_2) (1%) treatment of Groundnut Pod (12 hours soaking)	1.58	0.61	1.18	0.90	2.65	1.90	190
T6 - Hot Water (60°C) treatment of Groundnut Pod (5 minutes)	1.46	0.58	1.16	0.55	1.38	1.14	114
T7 - Cold Water treatment of Groundnut Pod (5 minutes)	1.50	1.02	1.20	0.82	2.52	1.84	184
T8 - Control (intact pod)	0.10	0.07	0.29	0.22	0.38	0.29	29
SEd	0.02	0.01	0.02	0.01	0.03	0.02	1.88
CD (P=0.05)	0.04	0.02	0.03	0.02	0.06	0.04	4.22

improved field establishment and sustainable crop productivity under semi-arid agro-ecosystems.

3.4. Vigour Index I and II

Seedling vigour indices were significantly enhanced by pre-sowing treatments (Table 1 and Table 2). Hydrogen peroxide treatment recorded the highest Vigour Index I (2300) and Vigour Index II (190), followed by cold water and hot water treatments. The untreated control recorded the lowest vigour indices. Higher vigour indices indicate improved seedling establishment potential, faster growth and greater biomass accumulation. Vigour indices are considered reliable indicators of seed quality and field establishment performance under stress-prone environments (Abdul-Baki & Anderson, 1973). The enhanced vigour indices observed under hydrogen peroxide treatment may be attributed to improved metabolic activation, rapid mobilization of seed reserves and enhanced antioxidant defence during germination and early seedling growth. Increased seedling length and biomass accumulation contributed directly to higher vigour index values, indicating superior physiological performance and establishment potential. Hydrogen peroxide-mediated ROS signalling may have stimulated cellular respiration, enzyme activity and hormonal regulation, thereby promoting Vigourous seedling development. Similarly, hydrothermal treatments such as hot water and cold-water soaking improved vigour by facilitating rapid water imbibition and activation of metabolic processes associated with germination. Enhanced seedling vigour is particularly important under rainfed and semi-arid agro-ecosystems, where rapid establishment and early biomass accumulation improve stress tolerance and resource-use efficiency. Similar improvements in seedling vigour due to seed priming and hydrothermal treatments were reported by Ndlovu et al. (2023) and Wojtyla et al. (2022).

Enhanced vigour under H_2O_2 treatment may be associated with ROS-mediated signalling mechanisms that regulate antioxidant defence systems and cellular growth processes. Improved vigour under hydrothermal treatments further demonstrates the potential of low-cost and eco-friendly pre-sowing techniques for enhancing crop establishment in resource-limited farming systems.

3.5. Effect of Acid and Growth Regulator Treatments

Nitric acid treatment significantly improved seedling growth and vigour compared to the control. Acid scarification may have facilitated improved water absorption and oxygen diffusion through partial weakening of the pod shell, resulting in enhanced germination and seedling growth. Potassium nitrate treatment also improved seedling performance due to nitrate-mediated signalling involved in dormancy release and enzyme activation. Gibberellic acid treatment promoted seedling growth through enhanced synthesis of hydrolytic enzymes responsible for mobilization of stored food reserves (Finch-Savage & Leubner-Metzger, 2006).

However, sulphuric acid treatment showed comparatively lower growth and vigour than other treatments. Reduced performance under sulphuric acid treatment may be due to excessive scarification causing slight injury to embryonic tissues. Similar observations regarding reduced seedling growth under strong acid treatments were reported by Copeland and McDonald (2001).

3.6. Response Index of Pre-sowing Treatment of Pod Sowing of Groundnut

The response index (RI) analysis clearly demonstrated the stimulatory effects of pre-sowing treatments on growth and vigour parameters of groundnut (Table 3). Negative RI values for days to germination indicated beneficial reduction in germination duration compared to the control. Hydrogen peroxide and nitric acid treatments recorded the highest reduction in germination duration, confirming their effectiveness in promoting rapid seedling emergence.

Positive RI values observed for root length, shoot length, biomass production and vigour indices indicated strong stimulatory effects of the treatments on seedling development. Hydrogen peroxide treatment recorded the highest positive RI values for most growth parameters, followed by cold water and hot water treatments (Wojtyla et al., 2022). These findings demonstrate that both chemical signalling mechanisms and hydrothermal conditioning effectively enhanced physiological activity and seedling vigour. Hydrogen peroxide-mediated ROS signalling may have stimulated antioxidant defence, respiratory metabolism and hormonal regulation, thereby enhancing seedling establishment and biomass accumulation. Similarly, hydrothermal conditioning likely improved water imbibition, membrane repair and metabolic activation during germination, resulting in improved physiological performance and vigour. Enhanced response index values observed in the present study therefore indicate strong stimulatory effects of the treatments on early seedling

Table 3. Response index (RI) of pre-sowing treatments on growth and vigour parameters of groundnut

Treatments	Number of days to germination	Root length (cm)	Shoot length (cm)	Total length (cm)	No of leaves	Fresh weight of shoot (g)	Dry weight shoot(g)	Fresh weight of root (g)	Dry weight root (g)	Total fresh weight (g)	Total dry weight (g)	Vigour index-I	Vigour index-II
T1 - Sulphuric Acid (H_2SO_4) (10 %) treatment of Groundnut Pod (5 minutes)	-0.33	0.05	0.05	0.05	0.12	0.00	0.00	0.03	0.05	0.05	0.03	0.05	0.03
T2 - Nitric Acid (HNO_3) (10 %) treatment of Groundnut Pod (5 minutes)	-0.42	0.79	0.76	0.83	0.82	0.72	0.67	0.45	0.27	0.53	0.44	0.83	0.44
T3 - Potassium Nitrate (KNO_3) (1 %) treatment of Groundnut Pod (12 hours soaking)	-0.33	0.28	0.49	0.43	0.12	0.80	0.46	0.19	0.24	0.60	0.31	0.43	0.31
T4 - Gibberellic Acid (GA_3) (1 %) treatment of Groundnut Pod (12 hours soaking)	-0.17	0.59	0.67	0.64	0.53	0.84	0.65	0.56	0.58	0.72	0.60	0.64	0.60
T5 - Hydrogen Peroxide (H_2O_2) (1 %) treatment of Groundnut Pod (12 hours soaking)	-0.42	0.83	0.91	0.89	0.85	0.94	0.89	0.75	0.76	0.86	0.85	0.89	0.85
T6 - Hot Water (60°C) treatment of Groundnut Pod (5 minutes)	-0.25	0.62	0.88	0.88	0.83	0.93	0.88	0.75	0.60	0.72	0.75	0.88	0.75
T7 - Cold Water treatment of Groundnut Pod (5 minutes)	-0.25	0.64	0.91	0.88	0.84	0.93	0.93	0.76	0.73	0.85	0.84	0.88	0.84
T8 - Control (intact pod)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

development and stress adaptation under direct pod sowing conditions. Similar response index interpretations and improvements in seedling vigour due to priming and hydrothermal treatments were reported in seed physiology and stress adaptation studies by Ndlovu et al. (2023), in addition to the classical interpretation proposed by Williamson & Richardson (1988).

Among the treatments, hydrogen peroxide (T_5) recorded the highest positive response index values for root length, shoot length, total seedling length, number of leaves, biomass and vigour indices, indicating its strong promotory effect on seedling growth and vigour. Cold water (T_7) and hot water (T_6) treatments also recorded high RI values, showing that hydrothermal treatments significantly improved seedling growth by enhancing water imbibition and metabolic activity (Figure 2). Nitric acid and gibberellic acid treatments showed moderate stimulatory effects, while potassium nitrate showed comparatively lower response. Sulphuric acid treatment recorded very low RI values, indicating minimal improvement over control (Bailly, 2004). Overall, the response index analysis confirmed that hydrogen peroxide treatment was the most effective, followed by cold water and hot water treatments for improving groundnut seedling vigour under direct pod sowing conditions. These findings agree with earlier studies on seed priming and ROS-mediated enhancement of seedling growth and vigour (Farooq et al., 2019; Mittler et al., 2011).

3.7. Ecological Relevance and Practical Implications

The study demonstrated that pre-sowing treatments significantly improved seedling establishment and early vigour of groundnut under direct pod sowing conditions. Rapid germination, improved root growth and higher biomass accumulation are particularly important under semi-arid agro-ecosystems where crops frequently encounter soil moisture deficit during establishment. Among the treatments evaluated, hydrogen peroxide soaking (1% for 12 hours) proved most effective, followed by cold water and hot water treatments.

The improvement in seedling growth and vigour observed under hydrogen peroxide and hydrothermal treatments aligns with the findings of Baidalina et al. (2025), who reported enhanced crop establishment and productivity following pre-sowing seed treatment and growth stimulant application.

Hydrothermal treatments are low-cost, eco-friendly and easily adoptable by farmers without requiring sophisticated

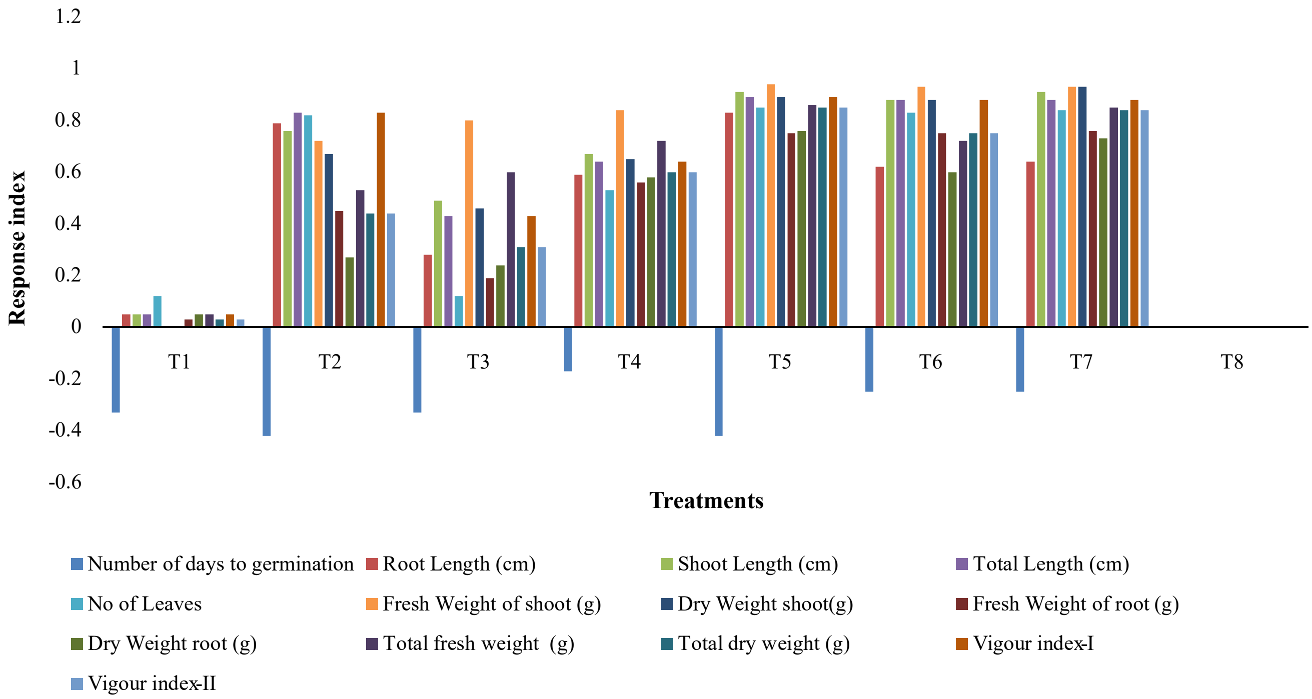

Figure 2. Response Index (RI) showing the influence of different pre-sowing treatments on germination rate, seedling growth, and seedling vigour of direct-sown intact pod groundnut. T_1 - Sulphuric acid (H_2SO_4, 10%) for 5 min, T_2 - Nitric acid (HNO_3, 10%) for 5 min, T_3 - Potassium nitrate (KNO_3, 1%) for 12 h soaking, T_4 - Gibberellic acid (GA_3, 1%) for 12 h soaking, T_5 - Hydrogen peroxide (H_2O_2, 1%) for 12 h soaking, T_6 - Hot water (60°C) for 5 min, T_7 - Cold water for 5 min, and T_8 - Untreated intact pod (control). The Response Index (RI) was calculated relative to the untreated control (T_8), where positive RI values indicate enhancement, negative values indicate inhibition, and zero indicates no change. Higher positive RI values represent greater improvement in germination rate, seedling growth, and seedling vigour resulting from the respective pre-sowing treatment

inputs, thereby making them suitable for sustainable ecological crop management. The findings of the present study therefore align with the scope of the Indian Journal of Ecology by emphasizing sustainable agricultural practices, ecological crop establishment and resource-efficient technologies suitable for rainfed farming systems.

4. CONCLUSION

The present study demonstrated that pre-sowing treatments significantly improved seedling establishment, growth and vigour of groundnut under grow bag conditions of direct intact pod sowing. Among the treatments, 1% hydrogen peroxide (H_2O_2) soaking for 12 hours was the most effective, recording the earliest germination and the highest seedling growth, biomass accumulation, and vigour indices. Cold water and hot water soaking also enhanced seedling establishment, while nitric acid showed moderate improvement and sulphuric acid was comparatively less effective. Based on the overall performance, 1% H_2O_2 soaking for 12 hours is recommended as an effective pre-sowing treatment for direct pod sowing of groundnut, with hydrothermal treatments serving as simple, economical and eco-friendly alternatives for improving crop establishment under rainfed conditions.

Credit authorship contribution statement

Anbarasu Mariyappillai: Conceptualization, Methodology, Supervision, Writing – review & editing; **Aaron Aarputharaj Arputham:** Investigation, Data curation, Formal analysis, Writing – original draft; **Deepa Raju:** Investigation, Data curation, Writing – original draft; **Mageshwarman Keerthi**: Formal analysis, Validation, Visualization; **Srikantha Jayapal:** Resources, Data curation, Review & editing; **Sriram Padmanaban:** Methodology, Software, Formal analysis; **Yamini Priya Boobalan:** Writing – review & editing, Validation.

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Conflict of interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that AI tools were used only for language editing during manuscript preparation. All scientific content and conclusions are solely the responsibility of the authors.

Data availability statement

The data generated and analysed during the current study are available from the corresponding author upon reasonable request.

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