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Research Article

EFFECT OF DIFFERENT SEED PRIMING METHODS FOR IMPROVING GERMINATION AND SEEDLING GROWTH OF SOME SELECTED SOLANACEAE CROPS: CHILLI, CAPSICUM AND TOMATO

G.P.A.N. Weerasuriya[1], S.R.W.M.C.J.K. Ranawana[1*], P.W. Jeewanthi[1], B.W. Wijesuriya[2]

[1]*Uva Wellassa University of Sri Lanka, Department of Export Agriculture, Badulla 90000, Sri Lanka*
[2]*Rubber Research Institute, Biometry Section, Agalawaththa 12200, Sri Lanka*

**Corresponding Author:*
E-mail: chandima@uwu.ac.lk

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ABSTRACT. Seed quality deterioration during storage, poor and uneven germination, low seed vigor, and weak seedling growth are major constraints in crop production. Seed priming, a controlled hydration treatment that activates pre-germinative metabolism without allowing radicle emergence, can effectively overcome these limitations. This study evaluated the effects of organic and chemical seed-priming treatments on the germination and seedling growth of tomato (*Solanum lycopersicum*), chilli (*Capsicum annuum*), and capsicum (*Capsicum annuum*). The priming treatments included moringa dry and fresh leaf extracts, coconut water, cow urine, rice husk ash-based solid matrix conditioning, distilled water, sucrose solution, eggshell–vinegar extract, and potassium nitrate (KNO_3) applied at different concentrations and soaking durations. Non–primed seeds served as the control. After priming, the seeds were washed, dried back to their original moisture content, and germinated under a completely randomized design with three replicates of ten seeds each. Treatments were grouped separately based on germination rate index (GRI) and seedling vigor index (SVI) using hierarchical cluster analysis, with the optimal number of clusters determined using SAS. Significant differences among clusters were assessed by one-way ANOVA under a generalized linear model followed by Duncan's multiple range test. For each crop, the best-performing clusters for GRI and SVI were identified from the cluster means, and treatments common to both were considered the most effective. Organic primers were given priority when their performance was comparable to that of chemical primers. The most effective treatments were coconut water (50%, 12 or 24 h) and sucrose solution (20%, 12 h) for chilli; cow urine (10%, 12 or 24 h; 20%, 12 h) and sucrose solution (10%, 12 h) for capsicum; and eggshell–vinegar extract (100%, 12 h), coconut water (50%, 24 h), moringa dry leaf extract (10%, 12 h), and KNO_3 (2%, 12 h) for tomato. Organic priming agents performed comparably to chemical primers, offering low-cost, eco-friendly, and accessible options for enhancing seed germination and seedling growth of the tested Solanaceae crops.

Keywords: *Germination rate index, Seedling vigor index, Organic priming agents, Solanaceae crops, Sustainable agriculture*

INTRODUCTION

The availability of high-quality seeds is essential for achieving optimum crop yield and superior produce quality. However, poor germination, uneven seedling establishment, hard seed coats, and low seed vigor continue to limit productivity, particularly in smallholder farming systems. These limitations often result from biological and physiological seed deterioration, exposure to abiotic and biotic stresses, and restricted access to certified or high-viability seeds [1]. Consequently, the development of effective,

low-cost strategies to enhance seed germination and early seedling growth is essential for improving crop establishment and yield stability.

Seed priming is a widely recognized pre-sowing technique that involves controlled hydration of seeds to activate early metabolic processes associated with germination, while preventing radicle protrusion. This partial hydration followed by dehydration advances the physiological state of the seed, enabling faster, more uniform germination and improved tolerance to early-stage environmental stresses upon sowing [2, 3]. Seed priming has been shown to enhance enzymatic activity, stimulate biochemical and metabolic pathways related to defense responses, and improve antioxidant metabolism, collectively contributing to greater seed vigor and stress resilience [4].

Several seed priming techniques have been developed based on the nature of the priming agent used and the intended physiological response, including hydropriming, osmopriming, hormonal priming, nutrient priming, matrix priming, and biopriming [5-7]. Chemical priming agents have been extensively studied and adopted [8-10]. Chemical priming offers several benefits, such as improving germination and enhancing stress tolerance, but it also has limitations, including potential toxicity, increased cost, and the possibility of over- or under-dosing. As a result, recent studies have shifted attention toward natural, low-cost alternatives that align with sustainable agricultural practices. The application of plant growth regulators and nutrient sources through pre-soaking, priming, and other pre-sowing treatments has been reported to improve seedling survival and growth across various crops, ultimately enhancing plant establishment and productivity [11].

Hydropriming is also a simple and cost-effective method that involves soaking seeds in water, while osmo-priming uses osmotic agents such as polyethylene glycol (PEG) or mannitol to regulate water uptake. Halopriming employs salt solutions such as potassium nitrate (KNO_3) or sodium chloride, whereas biopriming integrates beneficial microorganisms, including *Trichoderma* spp. and *Azospirillum* spp., to enhance germination and early seedling resistance to pathogens [12, 13]. Organic priming, which utilizes locally available bio-stimulants such as cow urine, coconut water, and plant extracts (e.g., *Moringa oleifera* leaf extract), has gained increasing attention as a cost-effective and eco-friendly alternative, particularly for resource-limited farmers [14, 15]. Solid matrix priming or matrix conditioning, in which seeds are mixed with moistened organic carriers such as ash, sand, or vermiculite, has also been identified as a low-cost alternative to expensive osmotic agents and has demonstrated positive effects on seedling performance in several horticultural crops [16].

Both chemical and organic priming agents have been reported to improve seed germination and early seedling growth through different physiological mechanisms. Potassium nitrate priming has been associated with enhanced nitrate reductase activity, promoting nitrite and nitric oxide production, which can alleviate dormancy and accelerate germination, particularly in tomato seeds [17]. Crop-specific responses to coconut water priming have been reported in okra [18], jujube [19], *Diospyros discolor* [20], and rice, in which it significantly improved germination rate, reduced mean germination time, and enhanced seedling biomass accumulation [21]. Cow urine priming has also been shown to significantly enhance leaf area, shoot length, and overall seedling vigor compared with untreated seeds [22]. Similarly, the superior performance of *Moringa oleifera* primed seeds has been attributed to accelerated mobilization of seed reserves, enhanced enzymatic activity, and improved root and shoot development [23, 24]. Solid matrix priming using rice husk-based materials has demonstrated promising

results in improving seed germination and early seedling growth. Mercado and Fernandez [25] reported that rice hull and sawdust were effective solid matrix priming media across a range of moisture levels, enhancing germination performance in soybean within short incubation periods. More recently, Tritean et al. [26] demonstrated that biogenic silica nanoparticles derived from rice husk, when applied as seed coatings, enhanced antioxidant defense mechanisms and improved seedling tolerance to salinity stress. These findings provide a physiological basis for the effectiveness of rice husk-based solid matrix conditioning as a sustainable seed priming approach.

Numerous studies have confirmed the positive effects of seed priming on germination, seedling vigor, and stress tolerance across crop species. In tomato (*Solanum lycopersicum*), osmopriming, hormonal priming, biopriming, and hydropriming significantly improved germination percentage, speed, vigor, and uniformity under salinity and drought stress conditions [27]. Similarly, in chilli (*Capsicum annuum*), priming with KNO_3 or gibberellic acid (GA_3) enhanced germination and seedling performance under water-deficit stress [28]. Despite these benefits, the adoption of seed priming by farmers remains limited due to lack of awareness, the high cost of commercial priming agents, and limited access to laboratory facilities. Therefore, the identification of simple, locally available, and cost-effective priming materials is critical for the wider adoption of this technology in small-scale farming systems.

Members of the family Solanaceae, including chilli (*Capsicum annuum*), capsicum (*Capsicum annuum* var. *grossum*), and tomato (*Solanum lycopersicum*), often exhibit physiological dormancy associated with hard or partially impermeable seed coats that restrict water uptake and gas exchange [29]. Seed priming offers an effective strategy to overcome such dormancy by promoting water absorption and initiating pre-germinative metabolic processes, thereby improving germination efficiency and early seedling establishment.

Furthermore, these crops commonly exhibit slow and non-uniform germination, particularly under suboptimal temperature and moisture conditions. They are highly sensitive to abiotic stresses such as drought, salinity, and heat during early growth stages, resulting in poor seedling establishment and uneven crop stands [2, 30]. Their delicate seedlings and relatively weak early root development further increase transplant shock and mortality. These limitations can lead to significant economic loss, due to the high cost of hybrid seeds used in these crops. Therefore, these physiological and agronomic limitations highlight the need for seed priming to improve germination uniformity, early vigor, and stress resilience.

In this context, the present study aimed to evaluate the effects of different seed priming treatments including cow urine, coconut water, *Moringa oleifera* leaf extracts (fresh and dry), an eggshell-vinegar extract, sucrose solution, potassium nitrate solution, rice husk ash-based solid matrix conditioning, and distilled water applied at varying concentrations and soaking durations, on the germination and seedling growth of selected Solanaceae crops (chilli, capsicum, and tomato). The ultimate objective was to identify low-cost, accessible, and environmentally sustainable priming agents to enhance seed germination, seedling vigor, and uniform crop establishment.

MATERIALS AND METHODS

Plant Materials and Growing Conditions

This study was conducted under laboratory conditions at Uva Wellassa University of Sri Lanka. Seeds of chilli, capsicum and tomato, which belong to the family Solanaceae, were used to test the efficacy of different priming methods.

Seed Priming Treatments

Different seed priming treatments were applied separately to each seed type as a series of experiments, using different concentrations and soaking durations, as shown in Table 1. When selecting the priming treatments for this research, greater consideration was given to organic priming agents that are readily available to farmers, rather than to costly chemical agents.

Table 1. *Priming agents, respective concentrations and soaking time used in the study as treatment combinations.*

Priming agent	Concentration	Soaking time (hours)
Cow urine (CU)	5%, 10%, 20% (v/v)	12 and 24
Coconut water (CO)	50%, 100% (v/v)	
Eggshell-vinegar extract (E)	50%, 100% (v/v)	
Moringa (dry) extract (MD)	10%, 20% (w/v)	
Moringa (fresh) extract (MF)	1:30 dilution	
Sucrose solution (S)	5%, 10%, 20% (w/v)	
Rice husk ash and water (Solid Matrix conditioning) (R)	Seeds: Ash: Water 1st treatment; 1: 1.5: 1 2nd treatment; 1: 0.5: 0.5	
Distilled water (DW)	-	
KNO_3 solution (P)	1%, 2% (w/v)	6 and 12

Preparation and Application of Seed Priming Treatments

Cow urine (CU):

Fresh cow urine was filtered through cheesecloth and Whatman No.1 filter paper. Dilutions were prepared with distilled water to obtain 10% and 20% (v/v) solutions.

Coconut water (CO):

Fresh coconut water was filtered through cheesecloth and then by Whatman No.1 filter paper to remove suspended particles. A 50% solution was prepared by diluting coconut water with distilled water in a 1:1 ratio (v/v). The undiluted filtrate was used as the 100% concentration where applicable.

Egg shell-vinegar extract (E):

Eggshells were oven-dried at 175 °C for 30 min to remove residual moisture. The dried shells were crushed into small fragments and ground into a fine powder using a grinder. The powdered eggshells were mixed with white vinegar (acetic acid solution) as follows: on the first day, 200 mL of vinegar was added to 1½ cups of eggshell powder and allowed to react for 24 h. On the second day, a further 600 mL of vinegar was added to enhance

extraction and ensure complete reaction. The mixture was stirred thoroughly and left to ferment, with daily mixing, until the reaction subsided. The resulting mixture was sieved to remove undissolved residues, and the filtrate was collected as the stock solution. A 50% (v/v) solution was prepared by diluting 50 mL of stock solution to a final volume of 100 mL with distilled water. The undiluted filtrate was used as the 100% (v/v) treatment.

Moringa Dry Leaf extract (MD):

Fresh moringa leaves were separated from branches and large stems, thoroughly washed, and shade-dried at ambient temperature to constant weight while retaining their green color. Direct sunlight was avoided to minimize degradation of bioactive compounds. The dried leaves were ground into a fine powder using a grinder and sieved through a 1 mm mesh. A stock solution was prepared by dissolving 20 g of leaf powder in 100 mL of distilled water (20% w/v). The mixture was first filtered through four layers of cheesecloth to remove coarse debris, followed by centrifugation at 3000 rpm for 10 min. The supernatant was then vacuum-filtered through Whatman No.1 filter paper to obtain a clear extract. The prepared stock solution (20% w/v) was used directly as the 20% treatment. A 10% (w/v) solution was prepared by diluting the stock solution 1:1 with distilled water (50 mL stock solution + 50 mL distilled water).

Moringa Fresh leaf extract (MF):

Fresh leaves were washed and homogenized in a blender with a very small amount of distilled water. The homogenate was filtered through four layers of cheesecloth and then through Whatman No.1 filter paper to obtain the extract. Appropriate dilutions were prepared using distilled water to obtain the required concentrations.

Sucrose solution (S):

Sucrose solutions were prepared by dissolving 5 g, 10 g and 20 g of sugar in 100 mL of distilled water to obtain 5%, 10% and 20% (w/v) concentrations, respectively.

Rice husk ash (R) – matrix conditioning (R):

Rice husk ash was sieved (1 mm mesh) to obtain a uniform particle size. The required quantity of ash was moistened with distilled water according to the seed-to-ash ratios used, to achieve adequate moisture for matrix priming, ensuring uniform hydration without free water accumulation.

Distilled water (DW):

Distilled water was used as the hydropriming treatment.

Potassium nitrate (KNO_3) (P):

A 2% (w/v) potassium nitrate solution was prepared by dissolving analytical-grade KNO_3 in distilled water. After priming, the seeds were surface sterilized with 0.5-1% sodium hypochlorite solution, washed three times with distilled water and air-dried to their original moisture content. The primed seeds were then sown in sterilized nursery trays containing autoclaved/solarized media (coco peat: compost – 1:1 media) and allowed to germinate with optimum amounts of water and other conditions supplied.

Experimental Design

The experiment was laid out in a completely randomized design with three replicates (10 seeds each) per treatment combination. Non-primed seeds served as the control.

Data Collection

Data were collected over varying periods, depending on the seed type (7-14 days after sowing), where raw data such as number of germinated seedlings were counted daily and the shoot length in day-after-day interval and the root length, dry and fresh weights were obtained after uprooting the seedlings in 7-14 days, depending on the seed type. From these raw data, Germination Percentage (%) [31] (Table 2) and Germination Rate Index (GRI) [32] were calculated to evaluate germination performances. Seedling Vigor Index (SVI) [33] was calculated to obtain seedling performances.

Table 2. *Equations used for the calculation of germination and seedling growth parameters derived from raw experimental data. The table presents each parameter together with its abbreviation and corresponding mathematical formula used for computation.*

Parameter	Equation	Abbreviations	Remarks
Germination percentage (%)	$\frac{\text{No. of seeds germinate}}{\text{Total No. of seeds sown}} * 100\%$		[31]
Germination Rate Index (GRI)	G1/1 + G2/2 +· · ·+ Gx/x	G1 = Germination percentage × 100 at the first day after sowing, G2 = Germination percentage × 100 at the second day after sowing Gx = Germination percentage × 100 at the last day of counting	[32]
Seedling Vigor Index (SVI)	Seedling length (cm) × Germination%		[33]

Data Analysis

Cluster analysis was performed to group the treatment combinations into different clusters based on the similarity of their performances in GRI, and SVI separately. The optimal number of clusters was assessed by one-way analysis of variance (ANOVA) under a generalized linear model using SAS OnDemand for Academics.

The best performing clusters were then identified by comparing the cluster means for GRI and SVI separately for each seed type, following the Duncan grouping method, subsequently the treatment combinations in the best performing cluster/clusters of both SVI and GRI were compared and the treatment combinations which satisfy to perform well in both GRI (Germination performances) and SVI (seedling performances) were selected as the best treatment combinations for selected seed types.

RESULTS AND DISCUSSION

Chilli

The dendrograms from the hierarchical cluster analysis of chilli (*Capsicum annuum* L.) based on mean GRI (Fig. 1) and mean SVI (Fig. 2) are presented below, illustrating

how the treatment combinations were grouped by performance. The hierarchical cluster analysis of mean GRI values was used to determine the optimal number of clusters, and the dendrogram was cut at an average linkage distance of 0.30, resulting in the separation of the treatments into five distinct clusters (Fig. 1; G1-G5). This clustering pattern reflects the relative similarity and dissimilarity among the priming treatment combinations with respect to their germination performance.

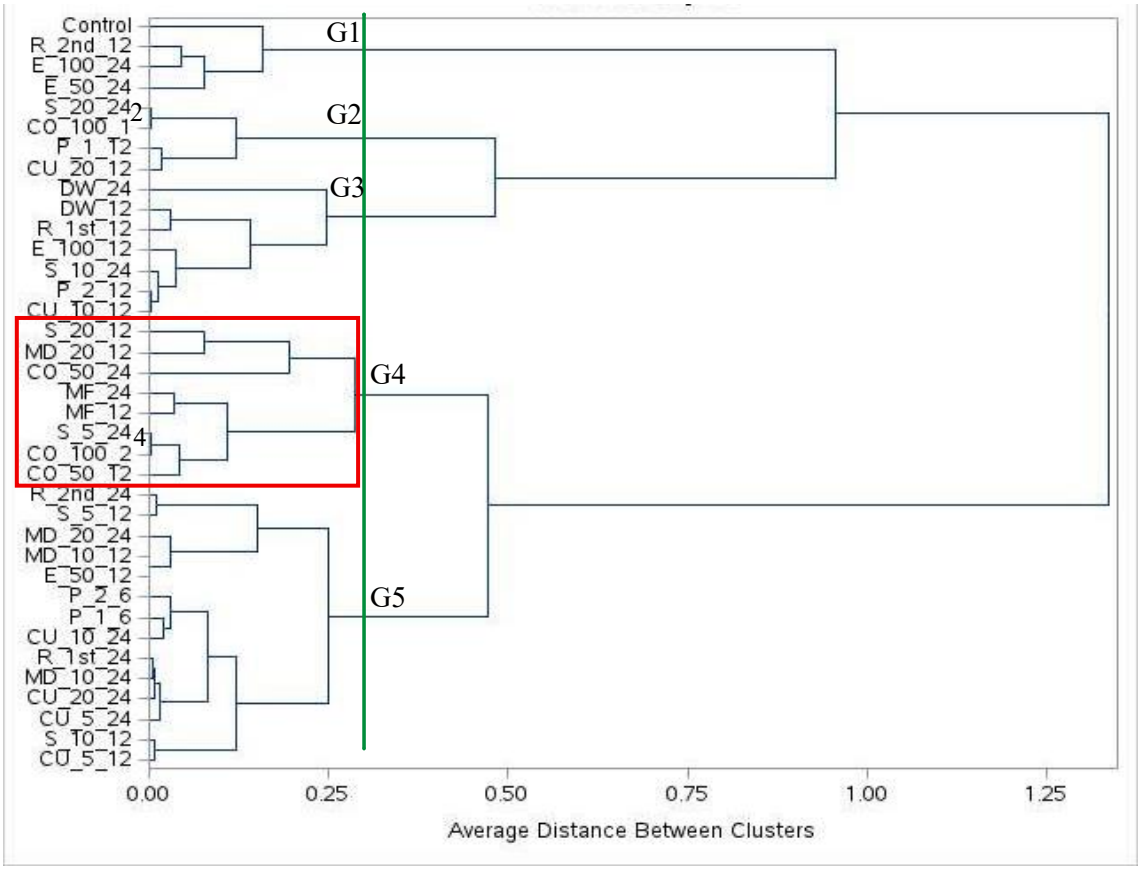


Fig. 1. *Hierarchical dendrogram illustrating the clustering of 37 priming treatment combinations for chilli (Capsicum annuum L.) based on mean GRI values. Clusters were generated using hierarchical cluster analysis to depict the similarity among treatments in terms of germination performance, with shorter linkage distances indicating greater similarity*

Based on the hierarchical cluster analysis of mean SVI values for chilli, the dendrogram was cut at an average linkage distance of 0.50, the optimal number of clusters. This cut-off separated the treatments into six distinct clusters that represent differing seedling vigor responses among the evaluated priming treatments (Fig. 2; S1–S6). The observed clustering highlights the variation in treatment effectiveness with respect to early seedling growth and overall seedling vigor.

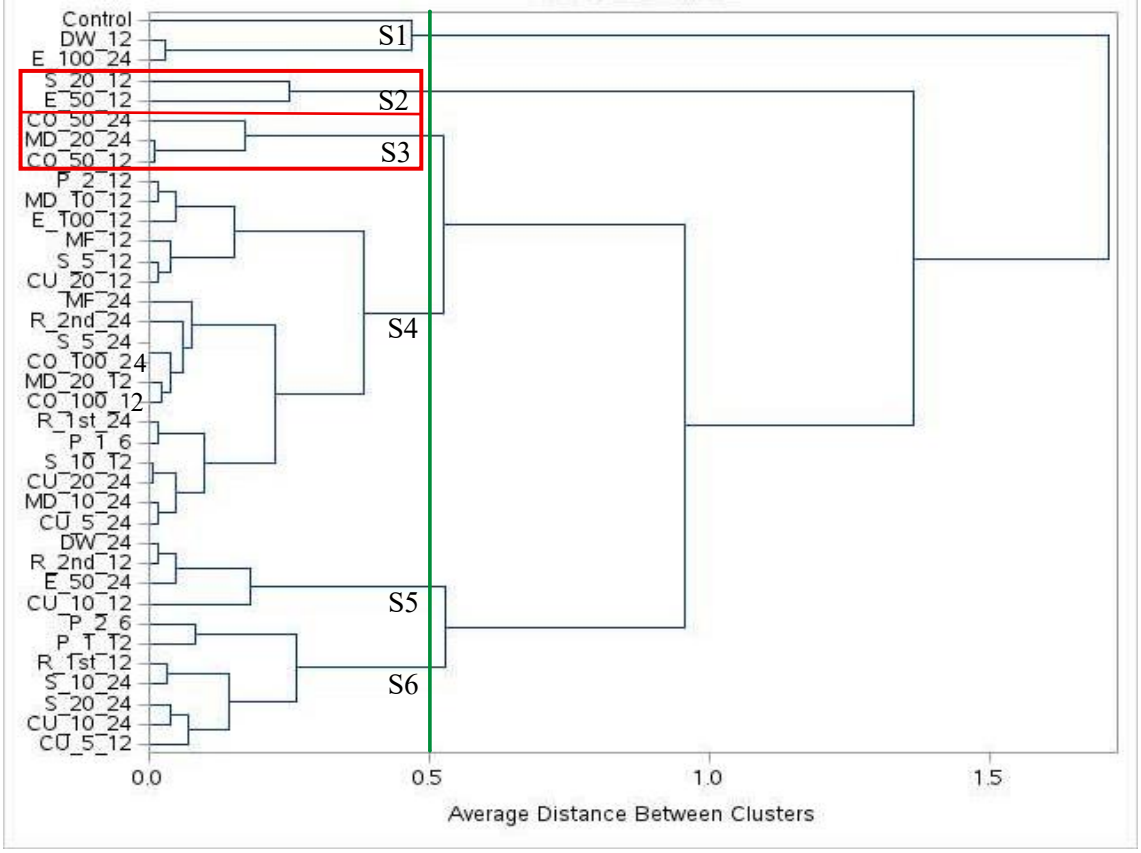


Fig. 2. *Hierarchical dendrogram showing the grouping of 37 priming treatment combinations for chilli (Capsicum annuum L.) based on mean SVI values. The dendrogram was generated using hierarchical cluster analysis to illustrate similarities among treatments with respect to seedling vigor, where lower linkage distances represent greater similarity in performance.*

Based on Duncan's multiple range test, the clusters with the highest mean values for GRI and SVI were identified as the best-performing groups. Cluster G4 had the highest mean GRI (51.02), while cluster S2 (602.07) had the highest mean SVI, followed by S3 (530.87). These clusters are highlighted in Table 3, and outlined in Fig. 1 (GRI) and Fig. 2 (SVI). The best-performing clusters were selected for further analysis and discussion in the subsequent sections.

Table 3. *Cluster-wise mean values of GRI and SVI for chilli (Capsicum annuum L.) derived from hierarchical cluster analysis, with statistical grouping based on Duncan's multiple range test (DMRT). Within each parameter, cluster means followed by different letters indicate significant differences at $P \leq 0.05$ for both GRI and SVI. (GRI: $R^2 = 0.97$, SVI: $R^2 = 0.94$).*

Cluster No.	Cluster Mean
GRI	
G4	51.02[a]
G5	46.88[b]
G2	41.75[c]
G3	37.23[d]
G1 (with control)	29.97[e]
SVI	
S2	602.07[a]
S3	530.87[b]
S4	469.37[c]
S6	388.45[d]
S5	323.28[e]
S1 (with control)	242.73[f]

The mean GRI and mean SVI values of chilli under the treatment combinations grouped within the best-performing cluster are presented in Table 4.

Table 4. *Mean GRI and mean SVI of chilli (Capsicum annuum L.) under the treatment combinations grouped within the best-performing clusters, identified from hierarchical cluster analysis of GRI and SVI. Highlighted treatments represent the top-performing priming treatments that were common to the best-performing clusters for both GRI and SVI, indicating their consistent effectiveness in enhancing both seed germination and seedling vigor.*

		GRI	
Cluster No.	**Treatment Combination**	**Treatment**	**Mean GRI**
G4	CO_50_12	Coconut water, 50%, 12 h	49.93 ± 2.44[a]
	CO_50_24	Coconut water, 50%, 24 h	53.85 ± 2.48[a]
	CO_100_24	Coconut water, 100%, 24 h	49.53 ± 2.18[a]
	MD_20_12	Moringa Dry extract, 20%, 12 h	52.38 ± 2.21[a]
	MF_12	Moringa Fresh extract, 12 h	50.50 ± 1.99[a]
	MF_24	Moringa Fresh extract, 24 h	50.83 ± 1.92[a]
	S_5_24	Sucrose solution, 5%, 24 h	49.50 ± 1.78[a]
	S_20_12	Sucrose solution, 20%, 12 h	51.63 ± 1.75[a]
		SVI	
Cluster No.	**Treatment Combination**	**Treatment**	**Mean SVI**
S2	E_50_12	Eggshell-vinegar extract, 50%, 12 h	586.00 ± 73.51[a]
S2	S_20_12	Sucrose solution, 20%, 12 h	618.13 ± 70.48[a]
S3	CO_50_12	Coconut water, 50%, 12 h	524.06 ± 64.23[a]
S3	CO_50_24	Coconut water, 50%, 24 h	545.58 ± 63.36[a]
S3	MD_20_24	Moringa Dry extract, 20%, 24 h	522.95 ± 61.07[a]

Cluster G4 consisted of treatment combinations involving seed priming with 50% coconut water for 12 and 24 h, 100% coconut water for 24 h, 20% moringa dry leaf extract for 12 h, moringa fresh leaf extract for both 12 and 24 h, 5% sucrose solution for 24 h, and 20% sucrose solution for 12 h. Statistical analysis indicated that the mean GRI values

among these treatments did not differ significantly ($P \leq 0.05$), suggesting comparable germination performance across all treatment combinations within this best-performing cluster, G4.

Cluster S2 included eggshell-vinegar extract at 50% concentration soaked for 12 h and sucrose solution at 20% concentration soaked for 12 h. Cluster S3 consisted of coconut water at 50% concentration soaked for 12 and 24 h, and moringa dry leaf extract at 20% concentration soaked for 24 h (Table 4). Statistical analysis indicated that the mean SVI values among these treatments were not significantly different ($P \leq 0.05$), suggesting similar effectiveness in enhancing seedling vigor.

A comparative evaluation of the best-performing clusters for both GRI and SVI revealed three treatment combinations that performed consistently well on both parameters. These common treatments were coconut water at 50% concentration soaked for 12 and 24 h, and sucrose solution at 20% concentration soaked for 12 h. Accordingly, these priming treatments can be considered the most effective for improving both germination and seedling vigor of chilli seeds.

Overall, the results indicate that coconut water can be used effectively to enhance germination and early seedling performance of chilli seeds, offering a viable, low-cost, readily accessible, and environmentally friendly alternative to chemical primers such as sucrose solution, which produced comparable outcomes in the present study. The effectiveness of coconut water as a priming agent can be attributed to its rich composition of plant growth-promoting substances, including amino acids, nitrogenous compounds, organic acids, enzymes, sugars, lipids, mineral nutrients, and naturally occurring phytohormones such as auxins (IAA), abscisic acid (ABA), gibberellins, and cytokinins including zeatin, kinetin, and trans-zeatin [34-38]. The synergistic action of these bioactive constituents promotes rapid cellular division, enhances enzymatic activity, and facilitates the mobilization of seed reserves during germination, thereby accelerating early metabolic processes and improving seedling establishment. From a practical perspective, coconut water at 50% concentration with a soaking duration of 12 or 24 h can be considered the most suitable organic priming treatment for chilli seeds, particularly for small-scale and rural farming systems.

The positive influence of coconut water priming has also been attributed to its ability to promote vigorous juvenile growth, higher dry matter accumulation, and improved root-shoot development. Okoli [39] reported that priming heavy seeds with coconut water enhanced early emergence and sustained seedling vigor, likely owing to the combined effects of increased food reserves and hormonal stimulation during early growth stages. Similar improvements in seedling vigor index, plant height, root depth, and overall seedling vigor have been observed in jujube when seeds were primed with coconut water, particularly at moderate concentrations and optimal soaking durations [19].

Crop-specific responses to coconut water priming have been reported in okra [18], jujube [19], *Diospyros discolor* [20], and rice, where priming with coconut water significantly improved germination rate, reduced mean germination time, and enhanced seedling biomass accumulation [21]. These findings consistently highlight coconut water as a nutrient-rich, environmentally friendly, organic, and locally accessible priming agent capable of improving early crop establishment.

Capsicum

The dendrograms from the hierarchical cluster analysis of capsicum (*Capsicum annuum* L.), based on mean GRI (Fig. 3) and mean SVI (Fig. 4) are presented below. These dendrograms illustrate how the priming treatment combinations were classified according to their relative performance, highlighting similarities and differences in germination behavior and seedling vigor among the evaluated treatments.

The hierarchical clustering of capsicum (*Capsicum annuum* L.) treatment combinations based on mean GRI revealed six distinct clusters (Fig. 3; G1-G6) when segmented at an average linkage distance of 0.40. This clustering delineates the relative similarities and differences in germination performance among the priming treatments, emphasizing the variability in their effectiveness in promoting early germination and uniformity across treatments (Fig. 3).

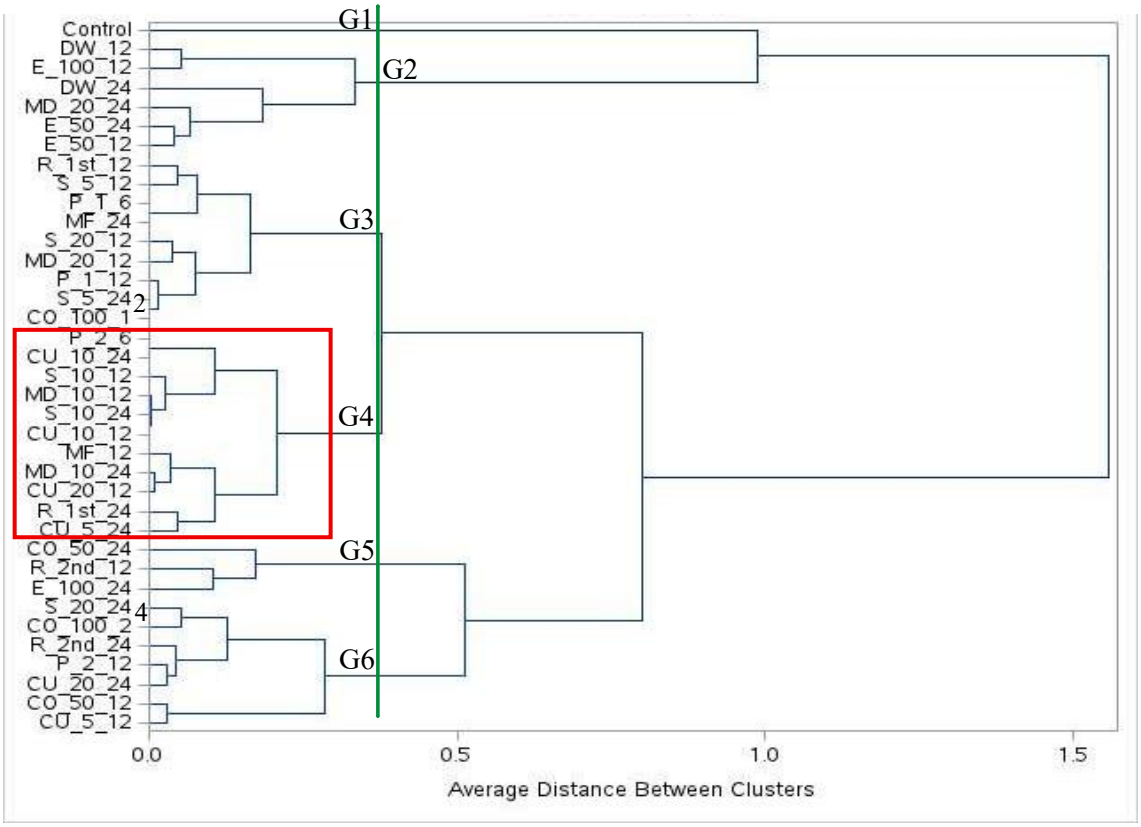


Fig. 3. *Hierarchical dendrogram illustrating the clustering of 37 priming treatment combinations for capsicum (Capsicum annuum L.) based on mean GRI values. Clusters were generated using hierarchical cluster analysis to depict the similarity among treatments in terms of germination performance, with shorter linkage distances indicating greater similarity.*

The hierarchical clustering of *Capsicum annuum* L. treatment combinations based on mean SVI resulted in six discrete clusters (Fig. 4; S1-S6) at an average linkage distance of 0.40. This clustering reflects the relative similarities in seedling vigor among the evaluated priming treatments, highlighting differential performance in promoting early growth and overall seedling robustness (Fig. 4).

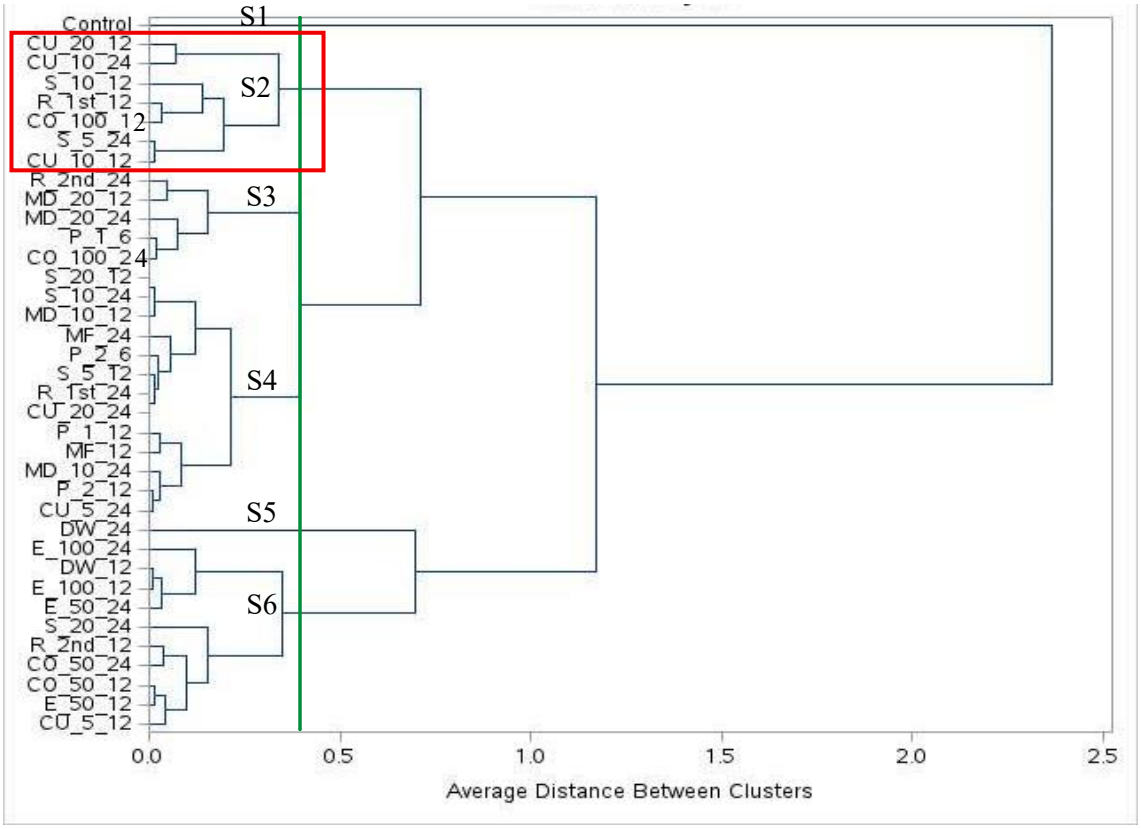


Fig. 4. *Hierarchical dendrogram illustrating the clustering of 37 priming treatment combinations for capsicum (Capsicum annuum L.) based on mean SVI values. The dendrogram was generated using hierarchical cluster analysis to depict similarities among treatments in terms of seedling vigor, where shorter linkage distances indicate higher similarity in performance.*

Based on the results of Duncan's multiple range test, the clusters with the highest mean values for GRI and SVI were designated as the best-performing groups. For capsicum, cluster G4 exhibited the highest mean GRI (57.36), while cluster S2 recorded the highest mean SVI (592.96). These best-performing clusters are highlighted in Table 5 and outlined in Fig. 3 (GRI) and Fig. 4 (SVI).

Table 5. *Cluster-wise mean values of GRI and SVI for Capsicum (Capsicum annuum L.) derived from hierarchical cluster analysis, with statistical grouping based on Duncan's multiple range test. Within each parameter, cluster means followed by different letters indicate significant differences at $P \leq 0.05$ (GRI: $R^2 = 0.97$, SVI: $R^2 = 0.94$).*

Cluster No.	Cluster Mean
GRI	
G4	57.36[a]
G3	54.36[b]
G6	50.98[c]
G5	46.81[d]
G2	42.59[e]
G1 (with control)	34.22[f]
SVI	
S2	592.96[a]
S4	485.68[b]
S3	415.14[c]
S6	305.13[d]
S5	175.94[e]
S1 (with control)	55.25[f]

The best-performing treatment combinations for capsicum, based on mean GRI, are presented in Table 6. These treatments included cow urine at 5% for 24 h, 10% for 12 and 24 h, and 20% for 12 h; moringa dry extract at 10% for 12 and 24 h; moringa fresh extract (1:30 dilution) for 12 h; sucrose solution at 10% for 12 and 24 h; potassium nitrate at 2% for 6 h; and rice husk solid matrix conditioning (first treatment ratio) for 24 h. Statistical analysis indicated no significant differences among these treatments ($P \leq 0.05$), suggesting comparable effectiveness in promoting germination.

For seedling vigor, the best-performing cluster, S2, comprised cow urine at 10% for 12 and 24 h, and 20% for 12 h; coconut water at 100% for 12 h; sucrose solution at 5% for 24 h and 10% for 12 h, and rice husk solid matrix conditioning (first treatment ratio) for 12 h (Table 6). No significant differences were observed among these treatments ($P \leq 0.05$), indicating similar efficacy in enhancing seedling vigor.

Table 6. *Mean GRI and SVI of capsicum (Capsicum annuum L.) under the treatment combinations grouped within the best-performing clusters, identified from hierarchical cluster analysis of GRI and SVI. Highlighted treatments are the top-performing priming treatments that were common to the best-performing clusters for both GRI and SVI.*

		GRI	
Cluster No.	**Treatment Combination**	**Treatment**	**Mean GRI**
4	CU_5_24	Cow urine, 5%, 24 h	56.11 ± 4.26[a]
4	CU_10_12	Cow urine, 10%, 12 h	57.78 ± 4.33[a]
4	CU_10_24	Cow urine, 10%, 24 h	58.73 ± 4.33[a]
4	CU_20_12	Cow urine, 20%, 12 h	56.67 ± 4.26[a]
4	MD_10_12	Moringa Dry Extract, 10%, 12 h	57.74 ± 4.29[a]
4	MD_10_24	Moringa Dry Extract, 10%, 24 h	56.76 ± 4.24[a]
4	MF_12	Moringa Fresh extract, 12 h	57.01 ± 4.23[a]
4	S_10_12	Sucrose solution, 10%, 12 h	57.98 ± 4.18[a]
4	S_10_24	Sucrose solution, 10%, 24 h	57.77 ± 3.96[a]
4	P_2_6	Potassium nitrate solution, 2%, 6 h	58.73 ± 3.64[a]
4	R_1st_24	Rice husk solid matrix conditioning, 1st treatment, 24 h	55.72 ± 2.83[a]

Cluster No.	Treatment Combination	GRI SVI Treatment	Mean SVI
2	CU_10_12	Cow urine, 10%, 12 h	595.17 ± 116.06[a]
2	CU_10_24	Cow urine, 10%, 24 h	643.64 ± 114.54[a]
2	CU_20_12	Cow urine, 20%, 12 h	630.36 ± 110.18[a]
2	CO_100_12	Coconut water, 100%, 12 h	566.67 ± 105.79[a]
2	S_5_24	Sucrose solution, 5%, 12 h	598.12 ± 104.15[a]
2	S_10_12	Sucrose solution, 10%, 12 h	543.60 ± 100.38[a]
2	R_1st_12	Rice husk solid matrix conditioning, 1st treatment, 12 h	573.15 ± 98.97[a]

Comparative assessment of the best-performing clusters for both GRI and SVI identified four treatment combinations that consistently promoted superior germination and seedling vigor. These common treatments were cow urine at 10% for 12 and 24 h, cow urine at 20% for 12 h, and sucrose solution at 10% for 12 h, which are highlighted in Table 6.

Importantly, organic priming agents such as cow urine offer a cost-effective, accessible, and environmentally sustainable alternative to chemical primers, making them particularly suitable for smallholder and rural agricultural systems.

Cow urine is a complex biological fluid composed of approximately 95% water, 2.5% urea, and 2.5% various salts, hormones, enzymes, and minerals [40]. These constituents together provide a rich source of nutrients and bioactive compounds that can stimulate early seed metabolic activity and improve germination performance.

In the present study, priming using cow urine increased germination percentage and seedling vigor in *Capsicum annuum* compared with the control and several other organic treatments. These improvements may be attributed, at least in part, to the availability of urea-derived nitrogen and other biologically active constituents that promote seed metabolism and support early seedling establishment [40].

Comparable findings have been reported by Shivamurthy and Patil [22], who observed that cow urine-treated seeds exhibited significantly higher growth and yield compared to untreated seeds. Their results support the present study's observation that cow urine priming enhances both physiological and morphological growth parameters in *Capsicum* seedlings. The presence of essential micro and macronutrients, along with plant growth regulators, likely facilitated improved photosynthetic activity and biomass accumulation during the initial stages of development.

Overall, the findings suggest that cow urine can serve as a cost-effective and eco-friendly organic primer that enhances germination and early growth in capsicum. Its wide availability and low cost make it particularly advantageous for resource-limited farmers seeking sustainable ways to enhance seed performance and crop establishment.

Tomato

The dendrograms from the hierarchical cluster analysis of tomato (*Solanum lycopersicum* L.) based on mean GRI (Fig. 5) and mean SVI (Fig. 6) are presented below, showing the grouping of treatment combinations based on their comparative germination and seedling vigor performances.

Hierarchical cluster analysis of tomato treatment combinations based on mean GRI (Fig. 5) and mean SVI (Fig. 6) grouped the treatments into eight distinct clusters (Fig. 5; G1-G8 and Fig. 6; S1-S8) at an average linkage distance of 0.25.

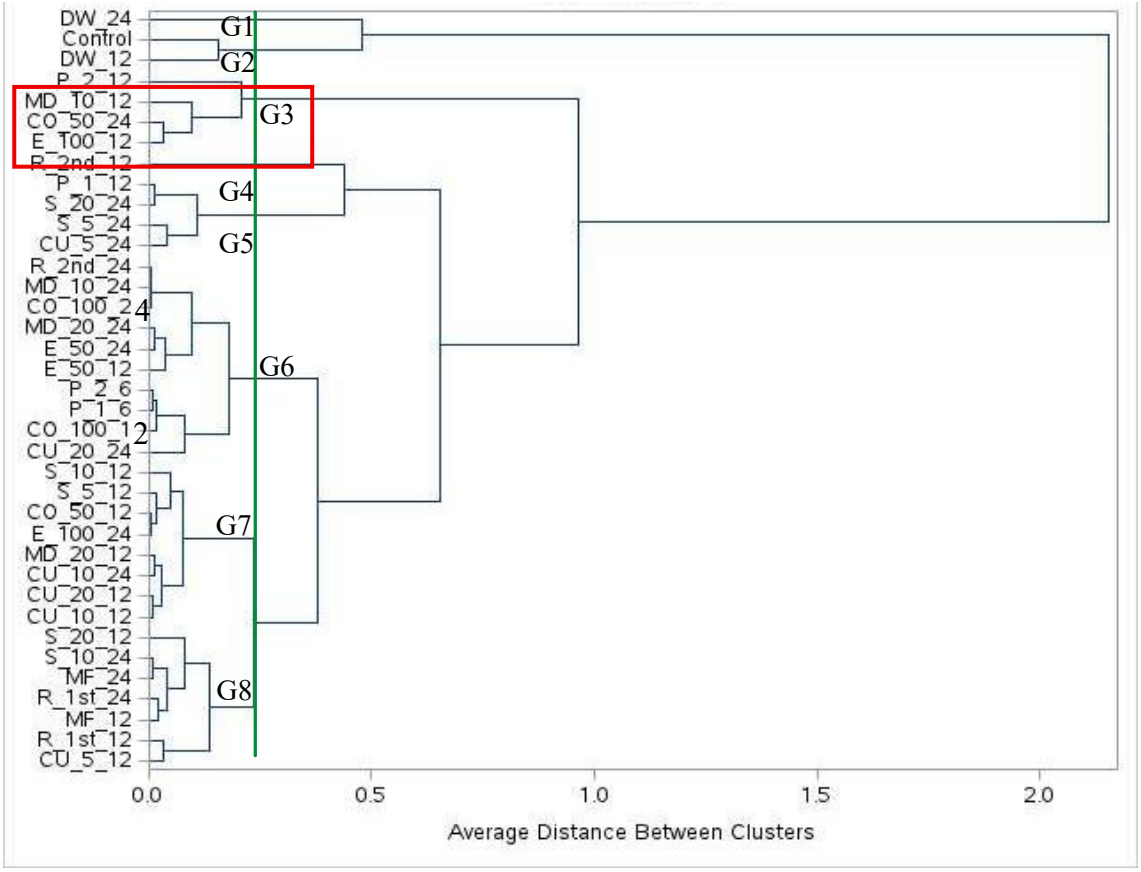


Fig. 5. *Hierarchical dendrogram illustrating the clustering of 37 priming treatment combinations for Tomato (Solanum lycopersicum L.) based on mean GRI values. Clusters were generated using hierarchical cluster analysis to depict the similarity among treatments in terms of germination performance, with shorter linkage distances indicating greater similarity.*

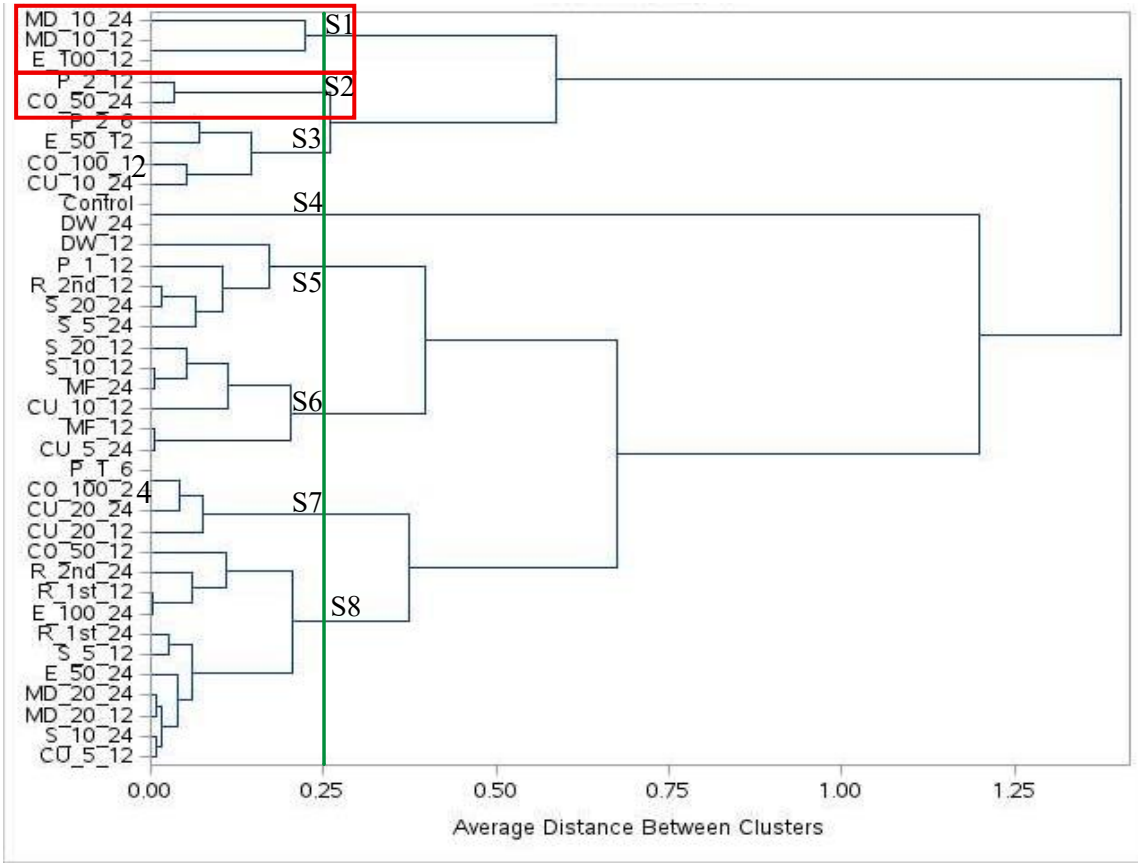


Fig. 6. *Hierarchical dendrogram illustrating the clustering of 37 priming treatment combinations for Tomato (Solanum lycopersicum L.) based on mean Seedling Vigor Index (SVI) values. The dendrogram was generated using hierarchical cluster analysis to depict similarities among treatments in terms of seedling vigor, where shorter linkage distances indicate higher similarity in performance.*

Based on Duncan's multiple range test, the clusters with the highest mean values for GRI and SVI were identified as the best-performing clusters. For tomato, cluster G3 demonstrated the highest mean GRI (53.41) (Table 7), whereas cluster S1 had the highest mean SVI (751.76) followed by cluster S2 (642.43). These clusters are highlighted in Table 7 and outlined in Fig. 5 (GRI) and Fig. 6 (SVI). The best-performing clusters were selected for further analysis and discussion in the subsequent sections.

Table 7. *Cluster-wise means of GRI and SVI for Tomato (Solanum lycopersicum L.) derived from hierarchical cluster analysis, with statistical grouping based on Duncan's multiple range test. Within each parameter, cluster means followed by different letters indicate significant differences at P ≤ 0.05 (GRI: R^2 = 0.99, SVI: R^2 = 0.96).*

Cluster No.	Cluster Mean
GRI	
G3	53.41[a]
G6	46.27[b]
G7	43.39[c]
G8	40.77[d]
G5	37.79[e]
G4	32.63[f]
G2 (with control)	20.88[g]
G1	15.32[h]
SVI	
S1	751.76[a]
S2	642.43[b]
S3	574.23[c]
S7	458.60[d]
S8	360.02[e]
S5	263.74[f]
S6	160.03[g]
S4 (with control)	85.25[h]

The best-performing treatment combinations for tomato, based on mean GRI (cluster G3), are presented in Table 8. These treatments included eggshell-vinegar extract (100%, soaked for 12 h), coconut water (50%, soaked for 24 h), moringa dry extract (10%, soaked for 12 h), and potassium nitrate (2%, soaked for 12 h). Statistical analysis indicated no significant differences among these treatments ($P \leq 0.05$), suggesting comparable effectiveness in promoting seed germination.

For seedling vigor, the best performing treatment combinations included in cluster S1 were eggshell-vinegar extract (100%, for 12 h) and moringa dry extract (10%, for 12 h and 24 h). The second-best performing cluster, S2, included coconut water (50%, for 24 h) and potassium nitrate (2%, for 12 h) (Table 8). No significant differences were observed among treatments within each cluster ($P \leq 0.05$), indicating similar effectiveness in enhancing seedling growth.

Table 8. *Mean GRI and mean SVI of tomato (Solanum lycopersicum L.) treatment combinations within the best-performing clusters, selected from hierarchical cluster analysis based on GRI and SVI. Highlighted treatments represent the top-performing*

priming agents that are common to both GRI and SVI best-performing clusters, consistently enhancing germination and seedling vigor.

		GRI	
Cluster No.	**Treatment Combination**	**Treatment**	**Mean GRI**
G3	E_100_12	Eggshell-vinegar extract,100%, 12 h	54.57 ± 4.89[a]
G3	CO_50_24	Coconut water, 50%, 24 h	54.21 ± 4.58[a]
G3	MD_10_12	Moringa Dry Extract, 10%, 12 h	53.26 ± 4.23[a]
G3	P_2_12	Potassium nitrate, 2%, 12 h	51.60 ± 3.89[a]
		SVI	
Cluster No.	**Treatment Combination**	**Treatment**	**Mean SVI**
S1	E_100_12	Egg shell and vinegar extract,100%, 12 h	731.29 ± 186.27[a]
S1	MD_10_12	Moringa Dry Extract, 10%, 12 h	731.44 ± 179.26[a]
S1	MD_10_24	Moringa Dry Extract, 10%, 24 h	792.52 ± 170.90[a]
S2	CO_50_24	Coconut water, 50%, 24 h	647.00 ± 156.05[a]
S2	P_2_12	Potassium nitrate, 2%, 12 h	637.85 ± 149.29[a]

Comparative evaluation of the best-performing clusters for both GRI and SVI identified four treatment combinations that consistently improved both germination and seedling vigor: eggshell-vinegar extract (100%, for 12 h), coconut water (50%, for 24 h), moringa dry extract (10%, for 12 h), and potassium nitrate (2%, for 12 h), which are highlighted in Table 8. These treatments were common to the top-performing clusters for both parameters. Potassium nitrate (KNO_3) has been widely reported as an effective chemical priming agent for tomato seeds. Ali et al. [41] demonstrated that priming tomato seeds of two tomato cultivars with 0.75% KNO_3 significantly enhanced seedling establishment, vigor, and key physiological and biochemical attributes under both growth chamber and greenhouse conditions. The beneficial effects of KNO_3 priming in tomato have been attributed to its role in activating nitrate reductase activity, which facilitates the production of nitrite and nitric oxide. These signaling molecules contribute to dormancy alleviation and promote faster and more uniform germination [17]. The positive response of KNO_3-primed tomato seeds observed in the present study is therefore consistent with earlier findings, confirming its effectiveness in improving germination and early seedling performance.

Notably, organic primers such as eggshell-vinegar solution, coconut water, and moringa dry leaf extract provide affordable, readily available, and environmentally friendly alternatives to chemical primers such as potassium nitrate. Their low cost and ease of access make them especially well suited for smallholder and resource-limited farming systems. Given that all these primers performed equally well, farmers can select any of them according to availability and convenience to improve germination and early seedling development in tomato. To explain the consistent improvements observed across these organic primers, the underlying physiological and biochemical mechanisms responsible for their effects are discussed below.

Crushed eggshells primarily contain calcium in the form of insoluble calcium carbonate. When combined with a weak acid, such as acetic acid (vinegar), a chemical reaction occurs that converts the calcium into a water-soluble, plant-available form [42]. This conversion enhances the bioavailability of calcium, which can play an important role in seed germination and early seedling development. The presence of readily available

calcium in eggshell-vinegar extract may therefore underpin the improved germination rates, seedling vigor, and overall growth performance observed in seeds treated with this organic priming agent. Calcium plays a critical physiological role in seed germination and seedling development: it stabilizes cell membranes, modulates enzyme activities, enhances mobilization of seed reserves, and influences root and shoot differentiation [43]. Although specific studies on eggshell-vinegar priming of tomato seeds are scarce, analogous research on calcium-based priming (e.g., $CaCl_2$) in other species has demonstrated improved germination speed, higher seedling vigor, reduced mean germination time and improved root/shoot growth [44, 43]. Therefore, the observed superiority of the eggshell and vinegar treatment in this study can be attributed mechanistically to enhanced calcium and phosphorous supply, improved early metabolic activation, and possibly improved cell wall integrity and nutrient uptake in the incipient seedling.

Among natural plant-based bio-stimulants, *Moringa oleifera* leaf extract is recognized for its richness in antioxidants, macro- and micronutrients, vitamins, and phytohormones such as cytokinins and potassium [14, 45, 46]. In the present study, priming tomato seeds with moringa dry leaf extract significantly enhanced germination and seedling vigor compared to the control and other priming treatments. These findings are consistent with Dunsin [14], who reported improved germination rate, seedling vigor, and biomass accumulation in maize following moringa leaf extract priming.

The superior performance of moringa-primed seeds may be attributed to accelerated mobilization of seed reserves, enhanced enzymatic activity, and improved root and shoot development [23, 24]. Afzal et al. [23] further observed that such priming reduces mean germination time and increases germination percentage, germination index, and seedling biomass, likely owing to higher amylase activity, soluble sugar content, and chlorophyll accumulation. Overall, these physiological enhancements facilitate early seedling establishment, improved photosynthetic efficiency, and robust seedling growth, supporting the effectiveness of moringa leaf extract as a natural, cost-effective priming agent for tomato.

CONCLUSION

The present study demonstrated that seed priming significantly improved germination and early seedling growth of chilli (*Capsicum annuum* L.), capsicum (*Capsicum annuum* L.), and tomato (*Solanum lycopersicum* L.) within the Solanaceae family. Both organic priming agents (cow urine, coconut water, moringa leaf extract, and eggshell-vinegar extract) and chemical primers (KNO_3 and sucrose solution) produced comparable enhancements in germination performance and seedling vigor across all three crops, indicating that selected organic alternatives can perform on par with conventional chemical treatments.

Crop-specific responses revealed that coconut water (50%, for 12 h or 24 h) and sucrose solution (20%, 12 h) were most effective for chilli, while cow urine (10%, for 12 h or 24 h; 20%, for 12 h) and sucrose solution (10%, 12 h) enhanced capsicum performance. In tomato, eggshell–vinegar extract (100%, 12 h), coconut water (50%, 24 h), moringa dry leaf extract (10%, 12 h), and potassium nitrate (2%, 12 h) were identified as superior treatments.

Overall, the findings highlight the potential of organic priming agents as low-cost, accessible, and environmentally sustainable substitutes for chemical primers, particularly suitable for smallholder farming systems.

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