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Enhancing Seed Germination and Seedling Establishment in High-Value Plants Using Natural Medicinal Plant Extracts as Biostimulants

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ABSTRACT

The establishment of a uniform and vigorous seedling stand is a critical bottleneck in the commercial cultivation of high-value plants, such as medicinal and industrial crops. Relying on synthetic chemicals to enhance germination often raises concerns regarding cost, environmental toxicity, and sustainability. This study investigated the efficacy of natural plant-derived biostimulants as a sustainable alternative to improve seed germination and seedling establishment. A factorial experiment was conducted in a completely randomized design with three replications. Treatments included hydro-alcoholic extracts of four medicinal plants—thyme (*Thymus daenensis*), marjoram (*Satureja hortensis*), rosemary (*Rosmarinus officinalis*), and peppermint (*Mentha piperita*)—applied at concentrations of 10 and 20 mL L^{-1} as seed priming agents to six high-value species: *Echinacea purpurea*, *Digitalis purpurea*, *Osteospermum ecklonis*, *Dianthus caryophyllus*, *Antirrhinum majus*, and *Zinnia elegans*. Key metrics measured were germination percentage (GP), mean germination time (MGT), germination rate index (GRI), seedling vigor index (SVI), and seedling establishment rate. Analysis of variance indicated significant main effects of extract type and plant species, as well as their interaction ($p<0.01$), on most germination and seedling growth parameters. Notably, peppermint extract at 10 mL L^{-1} significantly enhanced GP and SVI across most species, except for *Osteospermum*, where thyme extract (10 mL L^{-1}) was most effective. The results demonstrate that specific plant extracts can effectively reduce mean germination time and increase seedling uniformity and robustness. This research provides evidence that targeted seed priming with natural plant extracts can optimize the early growth phase, leading to more synchronized germination and stronger seedling stands. These findings offer a practical, eco-friendly strategy to increase propagation efficiency, reduce seedling production costs, and improve crop uniformity in commercial nurseries and large-scale cultivation of medicinal and industrial plants.

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1. Introduction

Greenhouse products in Iran are categorized into vegetables, ornamental plants, medicinal plants, and fruits (Arjmandian *et al.*, 2015). In recent decades, greenhouse production of plant seedlings has rapidly increased due to numerous advantages, such as enhanced production efficiency, off-season cultivation, high product quality, low water consumption, and employment generation (Ahmed *et al.*, 2024). Plants are a rich source of various natural compounds with diverse biological activities (Kafi *et al.*, 2026). Many plants possess significant medicinal value, and naturally occurring compounds extracted from them exhibit properties such as growth regulation, herbicidal and pesticidal effects, as well as allelopathic and toxic activities (Khamare *et al.*, 2022). Historically, various plant parts and their extracts have been widely used for their rich phytochemical composition, broad availability, ease of use, relatively low toxicity, and diverse biological activities (Michalak, 2023). It has been reported that natural plant extracts derived from leaves, seeds, roots, and fruits containing antioxidants

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and hormones can impact physiological processes (Norani *et al*., 2026; Khamare *et al*., 2022; Rezvanypour and Hatamzadeh, 2016). Some extracts from plant species also exhibit effective antimicrobial activity (Pinto *et al*., 2010; Álvarez-Martínez *et al*., 2021) and can reduce plant diseases (Abdel-Monaim *et al*., 2011). The positive effects of medicinal plant extracts on the growth and performance of treated plants have been documented, though research results on their role as growth stimulants or inhibitors vary across studies (Rezvanypour and Hatamzadeh, 2016). In some instances, a particular compound may act as a growth stimulant for one plant species, while serving as a growth inhibitor for others or under different conditions (Rezvanypour and Hatamzadeh, 2016).

Beyond their protective effects against pests and various diseases, multiple researchers have highlighted the impact of plant extracts on seed germination and growth of different crops. Germination is one of the most critical stages in plant development. In this context, Mutlu and Atici (2009) reported that aqueous extracts from the roots and leaves of *Nepeta meyeri* Benth affected seed germination and seedling growth in several crops, including barley, wheat, canola, safflower, and sunflower. They also demonstrated the species-specific nature of allelopathic effects, finding that extracts from *Tecomella undulata* (Sam.) enhanced seed germination in tall fescue but had no adverse impact on purslane or amaranth germination.

Zhao et al. (2022) reported that the seed germination rate of bamboo decreased with increasing concentrations of aqueous sesame extract. Their findings indicated that the mean germination time of bamboo seeds increased as extract concentration rose, suggesting that the sesame extract delayed the germination process. Researchers reported that extracts of *Conyza bonariensis* and *Richardia brasiliensis* increased the height of lettuce seedlings (da Silva *et al*., 2024). Fiaz et al. (2018) reported that *Moringa oleirifera* extract was applied as seed priming in *Celosia cristata* L. to evaluate its effectiveness for germination under different salinity levels. Seaweed extract has been shown to improve traits such as germination rate, early seed establishment, and crop yield (Mughunth *et al*., 2024). Seaweed extracts stimulate plant growth by providing growth hormones, vitamins, and essential nutrients (Fe, K, P, N) (Bajguz and Piotrowska-Niczyporuk, 2013). Researchers have noted that treatments with seaweed extract have a particularly pronounced stimulatory effect on plant growth during the early developmental stages (Rayorath *et al*., 2008).

Treatment with *Moringa oleifera* leaf extract has been shown to enhance seed germination and improve growth in various crops under both normal and stress conditions (Nouman *et al*., 2012; Yasmeen *et al*., 2012; Yasmeen *et al*., 2013). Similarly, extracts from *Aloe vera* L. and henna plants have been found to improve the growth and chemical composition of *Schefflera arboricola* (Zulfiqar *et al*., 2020). Moosavi et al. (2009) reported that seeds primed with extracts exhibited significantly higher germination percentage, faster germination rate, improved root length, and enhanced seed vigor. Application of aqueous chia extract at different concentrations significantly increased lettuce seed germination compared to controls (Erhatić *et al*., 2023).

Improvements in the morphological traits of various horticultural plants, including daffodil, geranium, and freesia, have also been reported with the use of certain plant extracts, such as garlic (El-Sayed *et al*., 2015). The use of various chemicals to promote seed germination and seedling production often results in toxic and hazardous effects. Moreover, the continuous application of synthetic chemicals is generally not environmentally sustainable and can be costly (Paulikienė *et al*., 2025). Consequently, the exploration and use of safe, effective, and biodegradable natural materials, like plant extracts, have gained considerable importance in recent decades for improved crop production, enhanced germination, and seedling growth (Zulfiqar *et al*., 2020). However, the mechanisms by which plant extracts promote plant growth are not yet fully understood.

In a study, researchers examined the aqueous extracts of rosemary, peppermint, thyme, and savory plants through liquid chromatography (LC-MS) and reported a number of their important compounds that play a role in plant growth and development. In peppermint: compounds such as caffeic acid, rosmarinic acid, catechin, and eriocitrin; in rosemary: compounds such as retinol, rosmannol, carnosol, and ursolic acid; in savory: luteolin, apigenin, and naringenin; and in thyme: methyl jasmonate, carvacrol, and thymol (Ghorbanpour and Hammaren, 2025). Therefore, this study aimed to evaluate the efficacy of aqueous extracts from thyme, marjoram, rosemary, and peppermint as natural biostimulants for seed priming. Specifically, we sought to determine their effects on key germination parameters and seedling vigor metrics in six selected plant species with established commercial value in medicinal and horticultural industries. The overarching goal was to identify effective, sustainable, and cost-effective alternatives to synthetic chemicals that can enhance propagation efficiency and improve seedling stand uniformity in commercial nursery production and large-scale cultivation.

2. Materials and methods

A factorial experiment based on a completely randomized design was conducted to investigate the effects of various plant extracts on the germination characteristics of seeds and seedlings of six species with horticultural and medicinal value: *Echinacea purpurea*, *Digitalis purpurea*, *Osteospermum ecklonis*, *Dianthus caryophyllus*, *Antirrhinum majus*, and *Zinnia elegans*. This design included four treatments (two concentrations), six seed species (Table 1), and three replications, carried out in 2023 at the Ornamental Plant Innovation Greenhouse Complex in Gorgan.

Table 1. Characteristics of plants from which seeds were used

Scientific name	Cultivar	Family	Flower color	Important part	Water requirement	Propagation method
Echinacea purpurea	Purple Coneflower	Asteraceae	Purple	Flower	Low	Seed
Digitalis purpurea	Excelsior	Plantaginaceae	Pink	Flower	Moderate	Seed
Osteospermum ecklonis	Dondo	Asteraceae	Pink	Flower	Low	Seed
Dianthus chinensis	Tiny Rubies	Caryophyllaceae	Pink	Flower	Moderate	Seed/ cutting
Antirrhinum majus	Legend	Plantaginaceae	Yellow	Flower	Moderate	Seed
Zinia elegans	Magellan Coral	Asteraceae	Red	Flower	Low	Seed

The duration of the experimental period was the same for all plants, which was eighty days from planting to the establishment of the seedlings. The plant seeds were sourced from Pakan-bazr Company, Isfahan, Iran. The characteristics of the plants used for seed pre-treatment are provided in Table 2.

Table 2. Characteristics of medicinal plants used in the study

No.	Local name	Scientific name	Family	Part used for extract
1	Peppermint	*Mentha piperita*	Lamiaceae	Leaves
2	Thyme	*Thymus vulgaris*	Lamiaceae	Leaves
3	Rosemary	*Rosmarinus officinalis*	Lamiaceae	Leaves
4	Savory	*Satureja hortensis*	Lamiaceae	Leaves

2.1. Preparation of plant extracts

The powdered leaves of peppermint, thyme, rosemary, and savory were mixed in a 1:10 ratio (100 g of powdered peppermint, thyme, rosemary, and savory to 900 mL of distilled water) and shaken for 24 hours at 1600 rpm in a shaker to extract the compounds. The upper phase of the mixture was then used for the experiment (Babarabie, 2019). Powdered leaves were purchased from Noavaran Mehrgol Golestan Company (Gorgan, Iran).

2.2. Planting and treatment methods

After the plant extracts were prepared, the seeds were soaked in the extracts for 20 minutes before planting. Thirty millilitres of the desired extract at the specified concentrations were placed in each container, in which the seeds were soaked. Standard culture trays with 105 wells were used to culture the seeds. From the beginning to the end of the experiment, the seeds and then the seedlings were placed in a greenhouse environment with a temperature of 26±5 degrees Celsius and a humidity of 70±5 percent until the end of the experiment.

2.3. Analysis of essential elements in plant extracts

The essential elements present in the extracts, used after being dried by a freeze-dryer, were sent to Dr. Makhzari's Water and Soil Laboratory (located in Kordkooy, Golestan Province, Iran). The results are reported in Table 3.

Table 3. Elements in the leaves of the plants used for the experiment (according to the laboratory results of Mahzari, Kordkooy, Golestan, Iran, 2024)

Analyzed Components	Unit	Rosemary	Peppermint	Thyme	Marjoram
Nitrogen	%	1.7	1.3	1.1	1.1
Phosphorus	%	0.61	0.55	0.48	0.33
Potassium	%	2.5	2.7	2.2	2.3
Calcium	%	4.8	2.6	2.4	2.7
Magnesium	%	0.6	0.5	0.5	0.4
Copper	ppm	11.3	11.1	10.4	10.6
Iron	ppm	82.3	63.7	59.9	61.2
Manganese	ppm	29.7	30.3	33.8	34.4
Zinc	ppm	20.7	18.6	18.3	16.9
Boron	ppm	33.1	31.5	29.6	28.1

2.4. Application of treatments

In this experiment, the treatments included peppermint, rosemary, thyme, and savory extracts at concentrations of 10 and 20 mL per liter. Distilled water was used as the control. Seeds were planted in a growth medium consisting of peat moss and perlite in a 1:1 volume ratio. In each tray, 100 seeds were sown.

2.5. Measured traits

The number of germinated seeds was recorded daily throughout the experiment. Germination characteristics, including germination percentage (GP), mean germination time (MGT), coefficient of velocity of germination (CVG), germination index (GI), mean daily germination (MDG), and seed vigor index (SVI), were calculated using Equations 1-6, respectively. Germination percentage (GP) was calculated according to Riis et al. (1995):

$$GP = \frac{N}{N_1} \quad (1)$$

Where N is the total number of germinated seeds at the end of the experiment, and N_1 is the total number of seeds sown. Mean germination time (MGT) was calculated according to Ellis and Roberts (1981):

$$MGT = \frac{(n \times d)}{N} \quad (2)$$

Where n is the number of seeds germinated on each day, d is the number of days from the start of the experiment, and N is the total number of seeds that germinated by the end of the experiment. The mean germination rate was determined according to Jones and Sanders (1987):

$$CVG = \frac{(N_1 + N_2 + \cdots N_i \times 100)}{N_1 \times T_1 + N_2 \times T_2 + \cdots N_i \times T_i} \quad (3)$$

Where N_i is the number of seeds germinated on day i and T_i is the number of days from sowing to day i. The germination index (GI) was calculated according to AOSA (1993):

$$G_i = \frac{N_i}{D_i} \quad (4)$$

where N_i is the number of seeds germinated on day i and D_i is the corresponding day of counting. Mean daily germination (MDG) was calculated as:

$$MGD = \frac{GP}{ND} \quad (5)$$

where GP is the final germination percentage, and ND is the duration of the experiment (days). Seed vigor index (SVI) was calculated according to Agrawal (2003):

$$\text{Seed vigor index} = \text{Seedling length} \times \text{Final germination percentage} \quad (6)$$

The seedling establishment percentage was calculated two weeks after transplanting and transferring the seedlings to pots. The number of healthy and surviving seedlings was counted and expressed as a percentage. Finally, seedling length was measured using a caliper, and the total number of leaves was counted.

2.6. Statistical analysis

The data obtained from the experiment were analyzed using the statistical design and SAS software, and Duncan's test was used for comparing the means at the significance level of 0.05

3. Results and discussion

3.1. Seed germination traits

The results of variance analysis showed that the individual effects of extract and plant species (except for the effect of extract on mean germination and germination rate) and their interaction were significant at the 1% level for all seed germination traits (Table 4).

Table 4. Analysis of variance (ANOVA) of the effects of plant extracts on germination indices of the plant seeds

SOV	df	GP	MGT	GRI	GI	MDG	SVI
Extract (E)	8	679.9^{**}	0.63^{*}	1.34^{ns}	0.04^{**}	2.46^{**}	107182^{**}
Plant type (P)	5	2122.4^{**}	397.9^{**}	0.01^{**}	0.59^{**}	126.4^{**}	3261632^{**}
E × P	53	590.2^{**}	38.45^{**}	0.002^{**}	0.07^{**}	13.55^{**}	351530^{**}
Error	148	121.4	0.38	0.009	0.006	0.49	101.81
CV (%)	-	3.92	14.94	3.28	6.57	3.23	10.18

GP: Germination Percentage; MGT: Mean Germination Time; GRI: Mean Germination Rate Coefficient; GI: Germination Index; MDG: Mean Daily Germination Percentage; SVI: Seed Vigor Index. *, **: Significant difference at the 5 and 1 percent levels, respectively. ^{ns}: Not significant.

3.1.1. Germination percentage

Based on the results in Table 5, the highest germination percentage was observed for the following treatments: rosemary extract at 10 mL L^{-1} in carnation, rosemary extract at 20 mL L^{-1} in digitalis and snapdragon, peppermint extract at 10 mL L^{-1} in digitalis, zinnia, and carnation, peppermint extract at 20 mL L^{-1} in zinnia, thyme extract at 10 mL L^{-1} in zinnia, and savory extract at 10 and 20 mL L^{-1} in zinnia. The lowest germination percentage was observed for thyme extract at 20 mL L^{-1} and savory extract at 10 and 20 mL L^{-1} in digitalis.

3.1.2. Mean germination time

The highest mean germination time was recorded for rosemary extract at 10 mL L^{-1} in echinacea, while the lowest mean germination time was observed for all treatments at various concentrations and the control in zinnia (Table 5).

3.1.3. Mean germination rate coefficient

The highest germination rate was observed for all treatments at various concentrations and the control in zinnia. In contrast, the lowest germination rate was found for thyme extract at 10 mL L^{-1} in *Osteospermum* and savory extract at 10 mL L^{-1} in *Osteospermum* (Table 4).

3.1.4. Germination index

The highest germination index was observed for rosemary extract at 10 mL L^{-1} in carnation, while the lowest germination index was recorded for savory extract at 20 mL L^{-1} in *Osteospermum* (Table 6).

3.1.5. Mean daily germination

The highest mean daily germination percentage was observed for peppermint extract at 10 mL L^{-1} in zinnia, thyme extract at 10 mL L^{-1} in zinnia, and savory extract at 10 mL L^{-1} in zinnia, while the lowest value for this index was recorded for rosemary extract at 20 mL L^{-1} and the control in Echinacea (Table 6).

3.1.6. Seed vigor index

Additionally, the highest seed vigor index was observed for thyme extract at 10 mL L^{-1} in zinnia, while the lowest seed vigor index was found for thyme extract at 20 mL L^{-1} in digitalis and savory extract at 10 and 20 mL L^{-1} in digitalis (Table 6).

Table 5. Mean comparison of the effects of plant extracts on germination indices of some plant seeds

Trait	Plant extracts	Echinacea	Digitalis	*Osteospermum*	Carnation	Snapdragon	Zinnia
Germination percentage (%)	R10	90.00^{bcd}	83.33^{cde}	76.67^{def}	100.00^{a}	86.67^{bcd}	96.67^{a}
	R20	66.67^{ghi}	100.00^{a}	76.67^{def}	90.00^{bcd}	100.00^{a}	83.33^{cde}
	M10	90.00^{bcd}	100.00^{a}	70.00^{fgh}	100.00^{a}	96.67^{a}	100.00^{a}
	M20	80.00^{def}	76.67^{def}	73.33^{efg}	83.33^{cde}	96.67^{a}	100.00^{a}
	T10	83.33^{cde}	73.33^{efg}	90.00^{bcd}	96.67^{a}	93.33^{bc}	100.00^{a}
	T20	80.00^{def}	56.67^{j}	76.67^{def}	76.67^{def}	76.67^{def}	96.67^{a}
	S10	76.67^{def}	56.67^{j}	86.67^{bcd}	93.33^{bc}	96.67^{a}	100.00^{a}
	S20	80.00^{def}	56.67^{j}	63.35^{hij}	70.00^{fgh}	76.67^{def}	100.00^{a}
	C	64.67^{ghij}	80.00^{def}	65.00^{ghij}	93.33^{bc}	81.67^{cde}	98.33^{a}
Mean germination time (days)	R10	17.75^{a}	10.02^{l}	15.91^{efghi}	11.66^{k}	16.04^{efgh}	7.76^{n}
	R20	16.52^{cde}	10.02^{l}	15.79^{fghi}	11.68^{k}	15.87^{efghi}	7.59^{n}
	M10	17.27^{ab}	10.16^{l}	15.71^{fghi}	11.79^{k}	16.01^{efgh}	7.46^{n}
	M20	17.31^{ab}	10.04^{l}	16.95^{bc}	11.78^{k}	15.70^{fghi}	7.17^{n}
	T10	14.06^{j}	10.07^{l}	16.98^{bc}	12.15^{k}	16.87^{bcd}	7.31^{n}
	T20	16.20^{efg}	10.00^{l}	16.31^{def}	11.75^{k}	15.58^{ghi}	7.23^{n}
	S10	17.10^{bc}	9.96^{l}	17.28^{ab}	11.61^{k}	16.00^{efgh}	7.75^{n}
	S20	16.02^{efgh}	9.76^{l}	15.28^{i}	11.743^{k}	16.12^{efg}	7.26^{n}
	C	16.53^{cde}	9.17^{m}	15.41^{hi}	11.78^{k}	15.89^{efghi}	7.33^{n}
Mean germination rate coefficient	R10	0.07^{defg}	0.09^{bcd}	0.06^{hijk}	0.08^{cdef}	0.06^{hijk}	0.12^{a}
	R20	0.08^{cdef}	0.09^{bcd}	0.06^{hijk}	0.08^{cdef}	0.063^{hijk}	0.13^{a}
	M10	0.08^{cdef}	0.09^{bcd}	0.06^{hijk}	0.08^{cdef}	0.06^{hijk}	0.13^{a}
	M20	0.08^{cdef}	0.09^{bcd}	0.06^{hijk}	0.08^{cdef}	0.06^{hijk}	0.13^{a}
	T10	0.09^{bcd}	0.09^{bcd}	0.05^{jk}	0.08^{def}	0.06^{hijk}	0.13^{a}
	T20	0.07^{defgh}	0.100^{b}	0.06^{hijk}	0.08^{cdef}	0.05^{jk}	0.13^{a}
	S10	0.07^{defgh}	0.100^{b}	0.05^{jk}	0.08^{cdef}	0.06^{hijk}	0.13^{a}
	S20	0.09^{bcd}	0.10^{b}	0.06^{hijk}	0.08^{cdef}	0.06^{hijk}	0.12^{a}
	C	0.07^{defgh}	0.09^{bcd}	0.07^{defgh}	0.08^{cdef}	0.06^{hijk}	0.13^{a}

Letters (a, b, c, etc.) indicate statistical differences. Different letters represent significant differences at P≤0.05.

Table 6. Mean comparison of the effect of plant extracts on seed germination indices of some plants

Trait	Plant extracts	Echinacea	Digitalis	*Osteospermum*	Carnation	Snapdragon	Zinnia
Seed germination index	R10	0.15^{wxy}	0.38^{klm}	0.19^{rstuvw}	0.66^{a}	0.47^{ghi}	0.43^{hijkl}
	R20	0.15^{wxy}	0.47^{fghi}	0.17^{vwx}	0.55^{cd}	0.62^{ab}	0.28^{opq}
	M10	0.30^{nop}	0.36^{lmn}	0.27^{opq}	0.61^{abc}	0.63^{ab}	0.52^{defg}
	M20	0.14^{wxy}	0.33^{mno}	0.16^{vwxy}	0.48^{efghi}	0.61^{abc}	0.48^{efghi}
	T10	0.25^{pqr}	0.30^{nop}	0.23^{qrstu}	0.53^{de}	0.53^{de}	0.46^{ghi}
	T20	0.25^{pqrs}	0.18^{uvw}	0.13^{wxy}	0.47^{hij}	0.33^{mno}	0.34^{mn}
	S10	0.19^{rstuvw}	0.24^{pqrst}	0.19^{rstuvw}	0.37^{klm}	0.58^{bcd}	0.53^{def}
	S20	0.20^{rstuvw}	0.24^{pqrst}	0.10^{y}	0.30^{nop}	0.39^{ijklmn}	0.41^{hijkl}
	C	0.15^{wxy}	0.34^{mno}	0.11^{xy}	0.58^{bcd}	0.43^{hijk}	0.47^{efghi}
Mean daily germination	R10	1.72^{xy}	4.22^{jk}	2.76^{qrst}	5.00^{fgh}	3.17^{opq}	7.66^{c}
	R20	1.48^{y}	5.33^{f}	2.63^{stu}	4.37^{ij}	4.12^{jk}	6.33^{d}
	M10	2.59^{stu}	4.88^{gh}	2.38^{tuvw}	5.83^{e}	3.96^{jklm}	9.00^{a}
	M20	2.22^{uvw}	3.77^{klm}	2.53^{stuv}	3.29^{nop}	3.96^{jklm}	8.00^{bc}
	T10	2.34^{tuvw}	3.55^{mno}	3.33^{nop}	5.20^{fg}	3.65^{lmn}	9.33^{a}
	T20	2.22^{uvw}	2.44^{tuvw}	2.69^{rst}	4.16^{jk}	2.69^{rst}	7.66^{c}
	S10	2.09^{vwx}	2.47^{tuvw}	3.17^{opq}	3.12^{opqr}	3.96^{jklm}	9.00^{a}
	S20	2.22^{uvw}	2.44^{tuvw}	2.06^{wx}	3.12^{opqr}	2.69^{rst}	8.33^{b}
	C	1.63^{y}	4.05^{jkl}	2.22^{uvw}	4.68^{hi}	2.93^{pqrs}	8.16^{b}
Seed vigor index	R10	280.00^{z}	206.66^{z}	566.66^{n}	506.66^{p}	666.66^{l}	1150^{f}
	R20	326.66^{x}	276.66^{z}	566.66^{n}	480.00^{q}	693.33^{k}	950.0^{g}
	M10	490.00^{q}	406.66^{uv}	426.66^{st}	580.00^{n}	833.33^{h}	1350^{b}
	M20	420.00^{tu}	323.33^{x}	400.00^{v}	440.00^{rs}	666.66^{l}	1200^{e}
	T10	443.33^{rs}	416.66^{tuv}	840.00^{h}	710.00^{j}	610.00^{m}	1400^{a}
	T20	480.00^{q}	190.00^{z}	453.33^{r}	740.00^{i}	566.66^{n}	1150^{f}
	S10	283.33^{z}	190.00^{z}	533.33^{o}	446.66^{r}	833.33^{h}	1350^{b}
	S20	300.00^{y}	190.00^{z}	346.66^{w}	420.00^{tu}	566.66^{n}	1250^{c}
	C	100.00^{z}	204.00^{z}	446.66^{r}	532.33^{o}	608.33^{m}	1225^{d}

Letters (a, b, c, etc.) indicate statistical differences. Different letters represent significant differences at P≤0.05.

3.2. Seedling traits

The results of variance analysis showed that the effects of extract and plant species, as well as their interaction, were significant at the 1% level for all seedling traits, including seedling length, seedling establishment percentage, and number of leaves (Table 7).

Table 7. Analysis of variance (ANOVA) for the effects of plant extracts on seedling traits of some plants

SOV	df	Seedling length	Establishment percentage	Number of leaves
Extract (E)	8	4.82^{**}	1057.59^{**}	1.72^{**}
Plant type (P)	5	433.85^{**}	5800.72^{**}	565.86^{**}
E × P	53	45.31^{**}	1356.32^{**}	54.44^{**}
Error	148	1.90	542.86	0.44
CV (%)	-	1.22	23.51	4.76

**: Significant difference at the 1% level.

3.2.1. Seedling length

Based on the mean comparison results, the highest seedling length was observed in all treatments at various concentrations in the zinnia plant, while the shortest seedling length was seen in the 20 mL L^{-1} thyme extract treatment in the digitalis plant species.

3.2.2. Establishment percentage

The highest seedling establishment percentage was obtained from the rosemary extract treatments at 10 and 20 mL L^{-1} in zinnia and carnation, peppermint extract treatments at 10 and 20 mL L^{-1} in zinnia, thyme and savory extracts at 10 mL L^{-1} in zinnia, and the control group. The lowest seedling establishment percentage was recorded for the peppermint extract at 20 mL L^{-1} in digitalis.

3.2.3. Number of leaves

The highest leaf number was observed in the rosemary extract at 20 mL L^{-1} in snapdragon, while the lowest leaf count was observed in the savory extract at 20 mL L^{-1} in digitalis (Table 8).

The results of this study showed that the plant extracts used affected the germination traits and seedling growth of the plant species. Most of the plant extracts did not show any adverse effects on seed germination. Seed germination is one of the critical biological stages that determines the successful establishment and final performance of plants (Reed *et al.*, 2022). Various reports confirm the stimulating and inhibitory effects of essential oils and plant extracts on seed germination and plant growth, which supports our findings (Semerdjieva *et al.*, 2022; Mirmostafaee *et al.*, 2020). In this regard, Chiang et al. (2003) stated that the positive effect of plant extracts on seed germination traits is due to the different chemical compounds found in these plants. Chemical compounds (secondary metabolites) can influence seed germination and plant performance, and depending on the type and concentration of secondary metabolites in different plant extracts, plant responses vary. In fact, the type of metabolites can play a crucial role in stimulating or inhibiting seed germination and other seedling traits.

Table 8. Mean comparison of the effect of plant extracts on the measured traits of seedlings of some plants.

Trait	Plant extracts	Echinacea	Digitalis	*Osteospermum*	Carnation	Snapdragon	Zinnia
Seedling length	R10	6.00^{ghi}	1.33^{o}	8.00^{def}	6.00^{ghi}	10.00^{c}	15.00^{a}
	R20	7.00^{efgh}	3.66^{jklm}	10.00^{c}	7.33^{efg}	8.00^{def}	15.00^{a}
	M10	7.00^{efgh}	4.33^{ijkl}	8.00^{def}	8.66^{cde}	10.00^{c}	15.00^{a}
	M20	7.00^{efgh}	4.33^{ijkl}	8.00^{def}	4.66^{ijkl}	8.00^{def}	15.00^{a}
	T10	7.00^{efgh}	5.33^{hij}	12.00^{b}	8.66^{cde}	8.00^{def}	15.00^{a}
	T20	8.00^{def}	2.33^{mno}	8.00^{def}	7.00^{efgh}	10.00^{c}	15.00^{a}
	S10	4.33^{ijkl}	1.66^{no}	8.00^{def}	8.33^{cdef}	10.00^{c}	15.00^{a}
	S20	5.00^{ijk}	1.00^{o}	8.00^{def}	8.00^{def}	10.00^{c}	15.00^{a}
	C	3.00^{lmn}	4.58^{ijkl}	9.50^{cd}	6.66^{fgh}	10.00^{c}	15.00^{a}
Seedling establishment (%)	R10	43.33^{ef}	85.00^{abc}	50.00^{bcdef}	8.33^{cdef}	91.66^{ab}	100.00^{a}
	R20	66.66^{abcdef}	50.00^{bcdef}	38.33^{ef}	100.00^{a}	75.00^{abcde}	83.33^{abcd}
	M10	83.33^{abcd}	75.00^{abcde}	63.33^{abcdef}	91.66^{ab}	91.66^{ab}	100.00^{a}
	M20	58.33^{abcdef}	25.00^{f}	45.66^{cdef}	50.00^{bcdef}	50.00^{bcdef}	100.00^{a}
	T10	75.00^{abcde}	75.00^{abcde}	88.33^{ab}	91.66^{ab}	75.00^{abcde}	100.00^{a}
	T20	58.33^{abcdef}	56.00^{bcdef}	91.33^{ab}	55.00^{bcdef}	58.33^{abcdef}	66.66^{abcde}
	S10	66.66^{abcde}	70.00^{abcde}	65.33^{abcdef}	83.33^{abcd}	91.66^{ab}	100.00^{a}
	S20	41.66^{def}	73.33^{abcde}	50.00^{bcdef}	83.33^{abcd}	73.33^{abcde}	100.00^{a}
	C	65.41^{abcdef}	66.25^{abcdef}	73.33^{abcde}	72.91	66.66^{abcde}	100.00^{a}
Number of seedling leaves	R10	3.33^{j}	3.00^{jk}	5.00^{hi}	12.00^{c}	14.00^{b}	7.33^{e}
	R20	3.00^{jk}	5.00^{hi}	5.33^{hi}	12.00^{c}	15.33^{a}	6.67^{ef}
	M10	3.33^{j}	5.00^{hi}	4.67^{hi}	12.00^{c}	14.00^{b}	7.33^{e}
	M20	3.33^{j}	3.00^{jk}	4.67^{hi}	12.00^{c}	14.00^{b}	6.67^{ef}
	T10	3.00^{jk}	5.00^{hi}	4.67^{hi}	12.00^{c}	14.00^{b}	7.33^{e}
	T20	3.00^{jk}	3.33^{j}	5.00^{hi}	12.00^{c}	14.00^{b}	6.67^{ef}
	S10	3.00^{jk}	3.00^{jk}	5.00^{hi}	12.00^{c}	14.00^{b}	7.00^{e}
	S20	3.33^{j}	2.00^{l}	4.33^{i}	12.00^{c}	14.00^{b}	6.00^{fg}
	C	3.00^{jk}	2.33^{kl}	4.67^{hi}	10.00^{d}	14.00^{b}	7.00^{e}

Letters (a, b, c, etc.) indicate statistical differences. Different letters represent significant differences at $P \leq 0.05$.

The research by Girase et al. (2019) showed that priming *Abelmoschus esculentus* seeds with *Albizia amara* extract increased traits such as germination percentage, germination rate, seed vigor index, seedling length, and root and stem length. It has been reported that maize seeds treated with rosemary leaf extract had a higher germination percentage compared to the control group (Panuccio *et al*., 2018).

Rosemary extract contains biologically active compounds, terpenoids, antioxidant activity, and high amounts of flavonoids and phenolic compounds, including limonene, a-pinene, 3-carene, 6-camphenol, Exo-fenchol, cinnamic acid, retinol, 3-cyclohexene-1-methanol, ß-Caryophyllene (BCP), luteolin, rosmarinic acid, rosmarinol, rosmanol, and carnoso, which enhance seed germination and other plant growth parameters (Koriesh *et al*., 2018; Farooq and Koul, 2020).

Sarika et al. (2013) reported that priming French bean seeds with extracts of various plants improved seed quality, seedling length, and dry weight, which in turn enhanced seed vigor index, germination rate, and mean germination time (Rai *et al*., 2021).

Researchers reported that different concentrations of extracts from 25 different plants, including peppermint, increased germination rate, germination percentage, seedling length, and seedling weight of wheat seeds. They also reported that lower concentrations of these extracts showed 100% germination, while higher concentrations of certain plant extracts exhibited inhibitory effects, resulting in decreased germination rate (Yadav *et al*., 2024). The researchers stated that seed priming increases seed metabolism, which in turn accelerates germination and seedling emergence.

Seed vigor index is also an important variable that determines the competitive ability of a plant species. Research results showed that different concentrations of oleander extract reduced the seed vigor index of Italian chicory (Uslu *et al*., 2018). A 50% concentration of thyme extract decreased the germination duration (increased germination rate) in lily bulbs (Babarbie, 2019). Researchers also found a strong negative correlation between germination rate and mean germination time (Alencar *et al*., 2015; Lozano-Isla *et al*., 2018).

Bingöl and Battal (2017) reported that priming purslane and maize seeds with sage extract resulted in different effects on germination rate. The increased germination rate was due to the increased metabolism and cell division in the embryo meristem of the seeds as a result of priming, leading to faster germination and more seedling emergence (Ashraf *et al*., 2008).

The germination-stimulating compounds found in these plant extracts can induce earlier cell cycle activities, thus speeding up the emergence and growth of the radicle and hypocotyl in germinating seeds. This results in faster germination of treated seeds (Jain and Van Staden, 2007). Our experimental results suggest the presence of growth regulators in the extracts, along with regulatory and growth-promoting activities of the medicinal plant extracts for germination, growth, and seedling development across all species used.

The results from the analysis of variance (Table 6) showed that the individual effects of plant extracts and plant species, as well as their interactions, were significant at the 1% level for all measured seedling traits.

The results of this study indicate the positive impact of the plant extracts used on the post-germination traits of the seedlings in the species tested. The application of the extracts at all concentrations had a positive and significant effect on post-germination traits (seedling length, seedling establishment percentage, and leaf count). This effect is probably due to compounds such as secondary metabolites present in the extracts.

Medicinal plant extracts are rich in plant hormones and growth regulators such as auxins, cytokinins, gibberellins, and phenolic compounds, which are used to stimulate and improve plant growth, enhancing the performance and quality of cultivated products (Iqbal *et al*., 2020). Many researchers believe that the phenolic compounds found in medicinal plant extracts have bio-stimulatory effects on plants (Kisiriko *et al*., 2021), and through balancing hormonal activities, they improve physiological functions such as plant height, root length, and germination (De Klerk *et al*., 2011).

Plant metabolites can have either positive or negative effects on growth and development processes. Aloe vera extract has been widely recognized as a natural plant biostimulant that can enhance seed germination, vegetative growth, nutrient uptake, and tolerance to abiotic stress in various crops (Baličević *et al*., 2018). Supporting the role of plant extracts in enhancing crop performance, Altaee (2019) documented that licorice extract promoted stem elongation in narcissus, a finding relevant for bulb production systems. In a more direct agricultural context, Prabha et al. (2016) demonstrated that seed priming with extracts of *Vinca*, *Chlorophytum*, and *Azadirachta* plants improved seedling vigor, reduced mortality, and increased establishment rates in tomato, an economically vital vegetable crop (Prabha *et al*., 2016).

Research findings have indicated that the growth and vigor of maize seedlings improved with the use of medicinal plant extracts (Basra *et al*., 2011), which aligns with our results. The study by Babarebi (2019) showed that high concentrations of thyme extract significantly reduced the stem length and spike length of lily plants. However, Yasin et al. (2012) reported that the extract of Salsola leaves and roots reduced the growth of aerial parts and the establishment of wheat seeds by 13%, which contradicts our results.

Mozdzen et al. (2019) reported that a 1% concentration of aqueous peppermint leaf extract stimulated the growth of bean and maize seedlings. The use of Moringa root and leaf extracts improved seedling emergence and growth characteristics of sunflower plants, a result attributed to plant hormones that stimulate growth and development (Iqbal *et al*., 2020). According to Nerlekar et al. (2021), the application of 30 and 50% concentrations of extracts from *Hydrilla verticillata* and *Eichhornia crassipes* increased the growth of aerial parts and the leaf count in pea and maize plants.

According to the authors, some compounds in plant extracts, such as phenolic compounds, phytohormones (e.g., gibberellins), flavonoids, and other secondary metabolites, have a significant effect on seedling growth (Singh *et al*., 2024). Growth-promoting hormones in these extracts enhance cell division, proliferation, and cell enlargement, thereby boosting growth and increasing the plant's length and leaf count. Another study showed that increasing the concentration of thyme and savory extracts resulted in a decrease and an increase in the number of leaves in lily plants, respectively, which suggests different effects of these plant extracts on the growth of lilies. Additionally, the varying effects of different extracts and their differences in growth traits, such as leaf number, may be due to their biochemical contents and compounds (Babarebie, 2019). Treatment with Aloe vera leaf extract also increased the number of leaves in poplar trees (El-Sherif, 2017). Researchers have noted that medicinal plant leaves not only serve as good sources of mineral nutrients such as potassium, calcium, magnesium, and vitamin C but also contain zeatin, one of the most active cytokinins, which plays a role in accelerating cell division. This, in turn, helps improve seedling emergence traits and subsequently boosts the growth components of the plant (Batool *et al*., 2020). Therefore, the use of medicinal plant extracts as priming agents can significantly enhance plant performance.

4. Conclusion

Recently, extracts of medicinal plants have gained attention due to their high content of phytohormones, antioxidants, amino acids, and macro and micronutrients. According to various reports, these plant extracts are natural, cost-effective, accessible, sustainable, and environmentally friendly biostimulants that can improve growth traits and productivity of various crops. In our study, successful results were obtained, highlighting the importance of seed priming with medicinal plant extracts. This research demonstrated the positive potential of different plant extracts as natural biostimulants and their beneficial effects on germination and post-germination traits of various plant species. Our findings revealed that medicinal plant extracts had a positive impact on growth indicators such as seedling emergence and growth, indicating their potential for broader agricultural applications using these bioactive compounds.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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