

Allelopathic Effects of Aqueous Leaf and Bark Extracts of *Myrica esculenta* on Germination and Seedling Growth of Traditional Agricultural Crops under Laboratory and Nursery Conditions

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Abstract

Agroforestry systems are widely recognized for enhancing agricultural productivity and ecosystem sustainability in the Himalayan region; however, successful tree–crop integration depends on the compatibility between component species. This study evaluated the allelopathic effects of aqueous leaf and bark extracts of *Myrica esculenta* Buch.-Ham. ex D. Don on seed germination, seedling growth, and biomass production of five traditional Himalayan crops (*Eleusine coracana*, *Setaria italica*, *Amaranthus caudatus*, *Vigna umbellata*, and *Panicum miliaceum*) under laboratory and nursery conditions. A completely randomized design with four treatments (control, 5%, 7%, and 9% aqueous extracts) and five replications was adopted. Germination, growth, and biomass parameters were analysed using one-way ANOVA followed by Duncan's Multiple Range Test ($P \leq 0.05$), while Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were employed to evaluate multivariate treatment responses. The results revealed significant concentration-dependent allelopathic effects, with leaf extracts exhibiting greater phytotoxicity than bark extracts. Under laboratory conditions, leaf extracts reduced germination by 32.91% in *E. coracana*, 18.34% in *S. italica*, and 11.18% in *A. caudatus*, whereas bark extracts caused maximum inhibition in *A. caudatus* (21.52%). In nursery experiments, *E. coracana* was the most susceptible species, showing mean germination inhibition of 19.87% and 38.68% under leaf and bark extracts, respectively. Radicle growth was generally more sensitive than plumule growth, while low extract concentrations occasionally stimulated seedling growth, indicating hormetic responses. PCA showed that the first two principal components explained 72.9% of the total variation (PC1 = 46.9%; PC2 = 26.0%), and HCA clearly distinguished control from extract-treated groups. Overall, *M. esculenta* exhibits significant allelopathic potential, particularly through its leaves, with crop responses varying among species. The findings provide valuable insights into tree–crop compatibility and support the selection of suitable crop combinations for sustainable agroforestry systems in the Garhwal Himalaya.

1. INTRODUCTION

Agroforestry systems are recognized as one of the most sustainable land-use strategies for improving agricultural productivity while maintaining ecological integrity, particularly in fragile mountain ecosystems such as the Himalaya (Keprate et al., 2024; Ghimire et al., 2024; Singh et al., 2024). By integrating trees with agricultural crops, these systems enhance biodiversity, improve soil fertility, regulate soil moisture, reduce erosion, increase carbon sequestration, and provide multiple ecosystem services, including fuelwood, fodder, timber, fruits, and medicinal products (Jose, 2009; Udawatta et al., 2021). However, the success of agroforestry largely depends on the compatibility between tree and crop species, which is influenced by several ecological interactions, including competition for resources and allelopathy (Valino et al., 2023).

Allelopathy refers to the direct or indirect effects of secondary metabolites produced by one plant on the germination, growth, physiology, and development of neighbouring plants (Shadab et al., 2026). Allelochemicals are released into the environment through leaf litter decomposition, root exudation, volatilization, stem flow, and leaching from aerial plant parts. These compounds include phenolic acids, flavonoids, tannins, alkaloids, terpenoids, coumarins, and quinones, which may influence seed germination, cell division, enzyme activity, membrane permeability, nutrient uptake, photosynthesis, respiration, and biomass accumulation (Maturi et al., 2026). The magnitude of allelopathic effects depends on plant species, plant organs, concentration of allelochemicals, environmental conditions, and the sensitivity of the recipient species. Although inhibitory effects are commonly reported, low concentrations of allelochemicals may stimulate plant growth through hormesis, demonstrating the concentration-dependent nature of allelopathic interactions (Xu et al., 2023; Zambelli et al., 2025).

Myrica esculenta Buch.-Ham. ex D. Don (family Myricaceae), commonly known as Kaafal, is an economically and ecologically important multipurpose tree species of the mid-Himalayan region (Kaur, et al., 2026). It naturally occurs between approximately 900 and 2,100 m above sea level and is widely distributed across Uttarakhand, Himachal Pradesh, Nepal, and Bhutan (Sharma et al., 2026). The species is highly valued for its edible fruits, medicinal bark, fuelwood, fodder, and its ecological role in stabilizing fragile mountain ecosystems (Ahmad et al., 2026; Singh et al., 2025; Gusain and Khanduri, 2016). Phytochemical investigations have demonstrated that different plant parts contain appreciable quantities of phenolic compounds, flavonoids, tannins, glycosides, triterpenoids, and other bioactive constituents possessing antioxidant, antimicrobial, anti-inflammatory, and pharmacological activities (Raniga, et al., 2025; Sharma et al., 2026). Since phenolic compounds and flavonoids are well-

known allelochemicals, the species is expected to influence neighbouring vegetation through biochemical interactions, although this aspect remains poorly understood.

Traditional farming systems in the Garhwal Himalaya cultivate crops such as *Eleusine coracana* (Finger millet), *Setaria italica* (Foxtail millet), *Amaranthus caudatus* (Grain amaranth), *Vigna umbellata* (Rice bean), and *Panicum miliaceum* (Proso millet) in association with naturally growing or deliberately retained tree species (Rawat et al., 2025; Singh et al., 2025). These traditional crop–tree combinations contribute significantly to household food security, nutritional diversity, and livelihood resilience. However, maintaining crop productivity depends on selecting tree species that exhibit minimal adverse effects on associated crops. Previous investigations have demonstrated significant allelopathic influences of several agroforestry tree species, including *Quercus leucotrichophora*, *Celtis australis*, *Grewia optiva*, and *Ficus* Species on the germination and early seedling growth of agricultural crops (Sharma, et al., 2025; Satapathy et al., 2022). These studies highlight that tree-derived allelochemicals may either suppress or stimulate crop establishment depending on species composition and extract concentration.

Research Gap

Despite extensive investigations on the nutritional, medicinal, phytochemical, and pharmacological properties of *M. esculenta* (Kabra et al., 2019), comparatively little information is available regarding its allelopathic influence on traditional Himalayan agricultural crops. Furthermore, studies simultaneously comparing aqueous leaf and bark extracts across multiple concentrations under both laboratory and nursery conditions are lacking. Such information is essential for understanding tree–crop compatibility and for designing sustainable agroforestry systems that maximize productivity while minimizing negative biochemical interactions.

Therefore, the present study was undertaken to evaluate the allelopathic effects of aqueous leaf and bark extracts of *Myrica esculenta* at different concentrations on seed germination, seedling growth, and biomass production of selected traditional Himalayan agricultural crops under laboratory and nursery conditions. Specifically, the study aimed to (i) Compare the allelopathic potential of leaf and bark extracts, (ii) Assess concentration-dependent responses of different crop species, and (iii) Identify compatible crop species suitable for integration with *M. esculenta* in Himalayan agroforestry systems. The findings are expected to improve understanding of tree–crop interactions and provide scientific evidence for developing ecologically compatible and sustainable agroforestry practices in the Garhwal Himalaya.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Department of Forest Biology and Tree Improvement, College of Forestry, V.C.S.G. Uttarakhand University of Horticulture and Forestry (VCSG UUHF), Ranichauri Campus, Tehri Garhwal, Uttarakhand, India (30°18'N, 78°24'E; approximately 1,800 m above mean sea level). The region experiences a temperate climate with an average annual rainfall of 1,400–1,800 mm, primarily received during the southwest monsoon (June–September). The mean annual temperature ranges from 8°C in winter to 28°C in summer. Laboratory experiments were carried out under controlled environmental conditions, whereas nursery experiments were conducted in the university nursery during the growing season.

2.2 Collection and Identification of Plant Material

Fresh leaves and bark of *M. esculenta* Buch.-Ham. ex D. Don were collected during the active growing season (April–May) from healthy, mature trees growing naturally in the Garhwal Himalaya, Uttarakhand, India. Plant samples were collected from at least ten randomly selected trees to minimize individual tree variation. The species was identified and authenticated by taxonomists of the Department of Forest Biology and Tree Improvement, VCSG UUHF. Voucher specimens were deposited in the departmental herbarium for future reference.

The collected plant materials were washed thoroughly with running tap water followed by distilled water to remove dust and debris. The samples were shade-dried at room temperature (25 ± 2°C) for approximately 15 days until constant weight and

subsequently ground into a fine powder using a laboratory grinder. The powdered samples were stored in airtight polyethylene containers at 4°C until extraction.

2.3 Preparation of Aqueous Extracts

Aqueous extracts of leaf and bark were prepared separately following a modified cold extraction method. Briefly, 100 g of dried powdered material was mixed with 1 L of distilled water (10% w/v) and kept at room temperature ($25 \pm 2^\circ\text{C}$) for 24 h with intermittent shaking. The mixture was filtered first through double-layered muslin cloth and subsequently through Whatman No. 1 filter paper.

The obtained filtrate was considered the stock extract (10%). Working solutions of 5%, 7%, and 9% concentrations were prepared by appropriate dilution with distilled water. Fresh extracts were prepared immediately before each experiment to avoid degradation of allelochemicals. The pH of the extracts ranged between 5.8 and 6.5.

2.4 Experimental Plant Species

Five important traditional agricultural crops commonly cultivated in the Garhwal Himalaya were selected as test species:

- *Eleusine coracana* (L.) Gaertn.
- *Setaria italica* (L.) P. Beauv.
- *Amaranthus caudatus* L.
- *Vigna umbellata* (Thunb.) Ohwi & H. Ohashi
- *Panicum miliaceum* L.

Uniform, healthy, and disease-free seeds were procured from authenticated local sources and stored under ambient laboratory conditions until use.

2.5 Laboratory Bioassay

The laboratory experiment was conducted using a Completely Randomized Design (CRD) consisting of four treatments (Control, 5%, 7%, and 9%) with five replications.

Twenty surface-sterilized seeds of each crop were placed in sterilized 90-mm Petri dishes lined with two layers of Whatman No. 1 filter paper. Seeds were surface sterilized with 1% sodium hypochlorite solution for two minutes and thoroughly rinsed with sterile distilled water.

Each Petri dish received 10 mL of the respective aqueous extract, whereas distilled water was used for the control treatment.

The Petri dishes were incubated at $25 \pm 2^\circ\text{C}$ with a 12 h light/12 h dark photoperiod and approximately 70% relative humidity.

Moisture was maintained by adding the corresponding extract whenever required. Germination was recorded daily for 21 days. A seed was considered germinated when the radicle protruded at least 2 mm.

At the completion of the experiment, ten randomly selected seedlings from each replication were used for recording plumule length, radicle length, fresh biomass, and dry biomass.

2.6 Nursery Experiment

The nursery experiment was conducted under open nursery conditions using a Completely Randomized Design with five replications.

Plastic pots (25 cm × 20 cm) were filled with a sterilized potting mixture consisting of soil, sand, and well-decomposed farmyard manure (2:1:1, v/v/v). Twenty seeds were sown per pot at a depth of approximately 2 cm.

Immediately after sowing, each pot received the designated aqueous extract treatment (5%, 7%, or 9%), while distilled water served as the control. Subsequent irrigation with the corresponding treatment solution was carried out at regular intervals to maintain adequate soil moisture throughout the experiment.

Seed germination was monitored daily for 21 days. Forty-five days after sowing, ten randomly selected seedlings from each replication were carefully uprooted for recording root length, shoot length, fresh biomass, and oven-dry biomass.

2.7 Measurement of Growth Parameters

Shoot, root, plumule, and radicle lengths were measured using a graduated ruler with an accuracy of 1 mm. Fresh biomass was measured immediately after harvesting using a digital analytical balance (0.001 g precision). Dry biomass was determined after oven-drying the plant material at $70 \pm 2^\circ\text{C}$ for 48 h until constant weight.

2.8 Germination Percentage

Germination percentage was calculated using the following formula:

$$\text{Germination Percentage (\%)} = \frac{\text{Number of germinated seeds}}{\text{Total Number of Seed Sown}} \times 100$$

2.9 Seedling Vigour Index

Seedling Vigour Index (SVI) was calculated according to **Abdul-Baki and Anderson (1973)** using the following formula:

$$\text{SVI} = \text{Germination Percentage (\%)} \times \text{Total Seedling Length (cm)}$$

The experiment followed a Completely Randomized Design (CRD). Data were expressed as mean $\pm$ standard deviation (SD). Prior to analysis, data were examined for normality using the Shapiro–Wilk test and homogeneity of variances using Levene's test. One-way analysis of variance (ANOVA) was performed separately for each crop and treatment to determine the effects of extract concentration on germination and seedling growth parameters. When significant differences were detected, treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% significance level ($P \leq 0.05$). Statistical analyses were carried out using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA), and graphical representations were prepared using GraphPad Prism 9.0 and Microsoft Excel 2021.

3. RESULTS

3.1 Laboratory Bioassay

3.1.1 Effect of *Myrica esculenta* Leaf and Bark Extracts on Seed Germination

The aqueous extracts of *Myrica esculenta* exhibited marked, concentration-dependent allelopathic effects on the germination of all five test crops, although the magnitude of inhibition varied with plant part, extract concentration, and crop species (Table 1). Leaf extracts generally produced stronger inhibitory effects than bark extracts, indicating a higher phytotoxic potential of the foliage. Among the crops tested, *Eleusine coracana* was the most susceptible to leaf extracts, with mean germination inhibition of 32.91%, followed by *Setaria italica* (18.34%), *Panicum miliaceum* (14.28%), *Vigna umbellata* (12.93%), and *Amaranthus caudatus* (11.18%). The maximum inhibition under leaf treatment was recorded in *E. coracana* at 7% extract concentration (38.75%), whereas *V. umbellata* exhibited comparatively lower inhibition (4.70%) at 5% concentration. Bark extracts also significantly reduced germination in most crops, with the greatest average inhibition observed in *Amaranthus caudatus* (21.52%), followed by *S. italica* (21.14%), *E. coracana* (20.39%), and *V. umbellata* (15.29%). In contrast, *P. miliaceum* showed a slight overall stimulation (+ 2.25%) under bark extracts, primarily due to enhanced germination at 5% (+ 21.62%) and 7% (+ 9.45%) concentrations, suggesting a hormetic response at lower extract levels. Overall, the findings demonstrate that *M. esculenta* possesses significant allelopathic activity, with leaf extracts exerting greater inhibitory effects than bark extracts,

while species-specific sensitivity and occasional stimulatory responses highlight the complexity of allelopathic interactions under laboratory conditions (Table 1).

Table 1
Effect of aqueous leaf and bark extract of *M. esculenta* on germination percent of test crops under laboratory condition

Treatments	Test crops				
Leaf	Eleusine coracana	Setaria italica	Amaranthus caudatus	Vigna umbellata	Panicum miliaceum
Control	80 ± 6.12	89 ± 6.52	95 ± 4.47	85 ± 5.48	91 ± 3.74
5%	51 ± 8.94 -36.25	78 ± 7.58 -12.35	80 ± 8.37 -15.78	81 ± 7.35 -4.70	83 ± 5.70 - 8.79
7%	49 ± 9.62 -38.75	67 ± 7.58 -24.71	77 ± 8.12 -18.94	73 ± 6.00 -14.11	76 ± 4.18 -16.48
9%	61 ± 11.40 - 23.75	73 ± 11.51 -17.97	79 ± 13.19 -16.84	68 ± 8.72 -20.00	75 ± 7.91 -17.58
Mean	53.66 ± 9.98 -32.91	72.66 ± 8.89 -18.34	78.66 ± 9.89 -11.18	74 ± 7.35 -12.93	78 ± 5.93 -14.28
Bark					
Control	67 ± 18.23	93 ± 4.47	96 ± 3.74	85 ± 4.48	74 ± 5.00
5%	50 ± 7.42 -25.37	77 ± 9.75 -17.20	90 ± 5.10 - 6.25	75 ± 10.49 -11.76	90 ± 5.10 +21.62
7%	61 ± 10.84 -8.95	69 ± 11.40 -25.80	74 ± 4.90 - 22. 91	69 ± 8.60 -18.82	81 ± 8.00 +9.45
9%	49 ± 8.22 -26.86	74 ± 13.42 -20.43	69 ± 11.58 -28.12	72 ± 5.48 -15.29	56 ± 4.78 -24.32
Mean	53 ± 8.82 - 20.39	73.33 ± 11.52 -21.14	75.33 ± 7.19 -21.52	72 ± 8.19 -15.29	73 ± 5.96 +2.25

(Plus and minus signs depict % stimulation (+) and % inhibition (-) in percent germination of crops as compared to their respective control).

3.1.2 Effect of *Myrica esculenta* Leaf and Bark Extracts on Seedling Growth

Radicle and plumule growth of the test crops responded differently to the aqueous leaf and bark extracts of *Myrica esculenta*, indicating species-specific and organ-specific allelopathic effects (Table 2). In general, leaf extracts exerted a stronger inhibitory effect on radicle elongation than on plumule growth. The greatest inhibition of radicle length under leaf extracts was observed in *Eleusine coracana* (mean inhibition 31.72%), followed by *Vigna umbellata* (29.35%), whereas *Amaranthus caudatus* showed the least reduction (7.03%). Conversely, plumule growth was less affected and even stimulated in some species. Mean plumule length increased in *Eleusine coracana* (+ 7.48%), *Setaria italica* (+ 3.27%), *Vigna umbellata* (+ 22.18%), and *Panicum miliaceum* (+ 2.31%), while a slight inhibition was recorded only in *Amaranthus caudatus* (11.59%). Under bark extract treatments, contrasting responses were evident. Bark extracts markedly promoted the plumule and radicle growth of *Setaria italica* (16.61% and 34.24%), *Amaranthus caudatus* (35.64% and 34.32%), and *Panicum miliaceum* (5.04% and 14.77%), whereas

Eleusine coracana exhibited reduced plumule growth (9.29%) despite enhanced radicle elongation (+ 11.21%). The strongest inhibitory effect of bark extract was recorded on the plumule of *Vigna umbellata* (19.97%), particularly at 9% concentration, where plumule length declined by 64.18% relative to the control. These findings demonstrate that the allelopathic influence of *M. esculenta* varies considerably with plant part, extract concentration, crop species, and seedling organ, with radicle growth generally being more sensitive than plumule growth and low extract concentrations occasionally producing stimulatory (hormetic) effects (Table 2).

Table 2

Effect of aqueous leaf and bark extract of *M. esculenta* on radicle and plumule length of test crops under laboratory condition.

Treatments	Test crops									
	<i>Eleusine coracana</i>		<i>Setaria italica</i>		<i>Amaranthus caudatus</i>		<i>Vigna umbellata</i>		<i>Panicum miliaceum</i>	
Leaf	Plumule (cm)	Radicle (cm)	Plumule (cm)	Radicle (cm)	Plumule (cm)	Radicle (cm)	Plumule (cm)	Radicle (cm)	Plumule (cm)	Radicle (cm)
Control	2.42 ± 0.35	3.12 ± 0.52	4.99 ± 0.80	4.67 ± 0.43	3.62 ± 0.17	2.92 ± 0.21	3.52 ± 0.40	2.99 ± 0.27	3.02 ± 0.9	3.04 ± 1.45
5%	2.77 ± 0.11 +14.46	2.13 ± 0.10 -31.73	5.32 ± 0.16 + 6.61	5.14 ± 0.24 + 10.06	2.87 ± 0.88 -20.71	2.87 ± 0.36 -1.71	2.07 ± 0.49 -41.19	2.45 ± 0.41 -17.72	3.08 ± 0.4 +1.98	4.29 ± 0.43 + 41.11
7%	2.79 ± 0.12 +15.28	2.01 ± 0.09 -35.57	5.02 ± 0.29 +0.60	4.96 ± 0.44 +6.20	3.12 ± 0.20 -13.81	2.44 ± 0.14 -16.43	2.82 ± 0.16 -19.88	2.24 ± 0.58 -25.08	3.05 ± 1.0 +0.99	2.02 ± 0.43 -33.55
9%	2.23 ± 0.15 -7.85	2.25 ± 0.04 - 27.88	5.12 ± 0.57 + 2.60	4.31 ± 0.31 -7.49	3.61 ± 0.31 - 0.27	2.97 ± 0.27 +1.71	2.57 ± 0.34 -26.98	2.28 ± 0.31 - 23.74	3.02 ± 0.5 0.00	2.65 ± 0.33 -12.82
Mean	2.59 ± 0.12 +7.48	2.13 ± 0.07 -31.72	5.15 ± 0.34 +3.27	4.80 ± 0.33 + 2.92	3.2 ± 0.46 -11.59	2.76 ± 0.25 -7.03	2.48 ± 0.33 -29.35	2.32 ± 0.43 +22.18	3.05 ± 0.6 +2.31	3.04 ± 0.39 -1.75
Bark										
Control	3.80 ± 0.28	3.12 ± 0.12	3.41 ± 0.29	2.93 ± 0.33	1.73 ± 0.12	2.37 ± 0.10	2.82 ± 0.43	2.91 ± 0.16	2.91 ± 1.5	4.01 ± 1.22
5%	3.57 ± 0.53 -6.05	3.66 ± 0.47 + 17.30	3.81 ± 0.22 + 11.73	4.03 ± 0.27 + 37.54	2.58 ± 0.36 + 49.13	3.79 ± 0.17 +44.72	3.68 ± 0.37 + 30.49	2.18 ± 0.57 -25.08	1.91 ± 0.6 -34.36	4.18 ± 0.32 + 4.23
7%	3.55 ± 2.88 - 6.57	3.11 ± 0.16 -0.32	4.12 ± 0.43 + 28.73	3.79 ± 0.42 +29.35	2.13 ± 0.28 +23.12	4.32 ± 0.37 +58.24	2.08 ± 0.24 -26.24	2.55 ± 0.24 -12.37	2.61 ± 0.9 -10.30	2.74 ± 0.32 31.67
9%	3.22 ± 0.40 -15.26	3.64 ± 0.40 +16.66	3.73 ± 0.21 +9.38	3.98 ± 0.45 +35.83	2.33 ± 0.59 + 34.68	2.37 ± 0.10 0.00	1.01 ± 0.43 -64.18	3.82 ± 0.14 +31.27	2.92 ± 0.4 +0.34	3.18 ± 0.24 -20.69
Mean	3.44 ± 1.27 -9.29	3.47 ± 0.34 +11.21	3.88 ± 0.29 + 16.61	3.93 ± 0.38 +34.24	2.34 ± 0.41 + 35.64	3.49 ± 0.21 +34.32	2.25 0.34 -19.97	2.85 0.31 +2.06	2.48 ± 0.3 -14.77	3.36 ± 0.29 +5.04

(Plus and minus signs depict % stimulation (+) and % inhibition (-) in precent germination of crops as compared to their respective control)

3.1.3 Effect of *Myrica esculenta* Leaf and Bark Extracts on Root Dry Weight

The aqueous leaf and bark extracts of *Myrica esculenta* significantly influenced the germination of all five test crops under nursery conditions, with the degree of inhibition varying among crop species, extract type, and concentration (Table 3). Overall, leaf extracts produced greater inhibitory effects than bark extracts in most crops, although species-specific responses were evident.

Among the leaf extract treatments, *Eleusine coracana* was the most susceptible, exhibiting the greatest reduction in germination, with a mean inhibition of 19.87% (from 64% in the control to a mean of 51.33%), while the maximum inhibition (37.50%) occurred at the 7% concentration. Germination of *Vigna umbellata* was also markedly reduced, with a mean inhibition of 26.63%, reaching a maximum reduction of 30.66% at the 9% concentration. Moderate inhibition was observed in *Panicum miliaceum* (mean 18.74%), whereas *Amaranthus caudatus* and *Setaria italica* were comparatively less affected, showing mean reductions of 13.82% and 12.15%, respectively. In general, increasing extract concentration resulted in greater inhibition, with the 9% leaf extract causing the most pronounced suppression in most species (Table 3).

Bark extracts also inhibited seed germination under nursery conditions, although their effects differed among crops. *Eleusine coracana* again exhibited the highest sensitivity, recording a mean germination inhibition of 38.68%, with the maximum reduction (45.83%) observed at the 7% concentration. *Vigna umbellata* showed substantial inhibition, with a mean reduction of 24.64%, while *Setaria italica* displayed moderate inhibition (16.29%). In contrast, *Amaranthus caudatus* was the least affected by bark extracts, with an average inhibition of only 10.72%, and germination at the 9% concentration remained comparable to the control, indicating complete recovery (0% inhibition). *Panicum miliaceum* exhibited moderate sensitivity, with a mean inhibition of 11.26%. (Table 3).

Table 3

Effect of aqueous leaf and bark extract of *M. esculenta* on germination percent of test crops under nursery condition

Treatments	Test crops				
	<i>Eleusine coracana</i>	<i>Setaria italica</i>	<i>Amaranthus caudatus</i>	<i>Vigna umbellata</i>	<i>Panicum miliaceum</i>
Leaf					
Control	64 ± 12.94	85 ± 5.00	94 ± 4.18	75 ± 6.12	96 ± 4.18
5%	44 ± 4.18 -31.25	75 ± 3.54 -11.76	86 ± 4.18 -8.51	56 ± 8.22 -25.33	87 ± 5.70 -10.41
7%	40 ± 8.66 -37.5	76 ± 7.42 -10.58	83 ± 5.70 -11.70	57 ± 10.37 -24.00	84 ± 9.60 -12.5
9%	46 ± 8.22 -28.12	73 ± 2.74 -14.11	74 ± 4.18 -21.27	52 ± 10.37 -30.66	64 ± 12.94 -33.33
Mean	51.33 ± 7.02 -96.87	74.66 ± 4.56 -12.15	81 ± 4.68 -13.82	55 ± 9.65 -26.63	78.33 ± 9.41 -18.74
Bark					
Control	72 ± 5.70	90 ± 3.54	95 ± 3.54	96 ± 4.00	71 ± 8.94
5%	53 ± 8.37 -26.38	78 ± 9.08 -13.33	77 ± 2.74 -18.94	70 ± 14.14 -27.08	41 ± 4.18 -27.08
7%	39 ± 2.24 -45.83	80 ± 5.00 -11.11	82 ± 2.74 -13.68	73 ± 4.47 -23.95	61 ± 8.94 -23.95
9%	41 ± 4.18 -43.05	68 ± 7.58 -24.44	95 ± 5.00 0.00	74 ± 4.18 -22.91	57 ± 11.51 -22.91
Mean	44.33 ± 4.93 -38.68	75.33 ± 7.22 -16.29	84.66 ± 3.49 -10.72	72.33 ± 7.59 -24.64	53 ± 4.92 -11.26

(Plus and minus signs depict % stimulation (+) and % inhibition (-) in percent germination of crops as compared to their respective control).

3.2 Nursery (Pot) Experiment

3.2.1 Effect on Seed Germination

The aqueous leaf and bark extracts of *Myrica esculenta* significantly affected the shoot and root growth of all test crops under nursery conditions, with the magnitude of response varying among species and extract concentrations (Table 4). Overall, leaf extracts caused greater inhibition than bark extracts, and the inhibitory effect generally increased with increasing extract concentration.

Under leaf extract treatments, *Eleusine coracana* showed the highest reduction in shoot length (mean inhibition 21.97%), followed by *Panicum miliaceum* (12.85%) and *Vigna umbellata* (11.34%). Root growth was comparatively less affected, although the greatest inhibition was observed in *Vigna umbellata* (11.42%), while *Eleusine coracana* exhibited a slight stimulation (+ 0.87%). The maximum reduction in shoot and root growth was generally recorded at the 9% extract concentration.

Bark extracts also reduced seedling growth, with *Vigna umbellata* showing the greatest inhibition in shoot length (29.06%), followed by *Eleusine coracana* (24.42%). Root length was most affected in *Eleusine coracana* (16.44%) and *Vigna umbellata* (14.87%). In contrast, slight stimulation of shoot and root growth was observed in *Amaranthus caudatus* (+ 1.03% and + 3.55%) and *Panicum miliaceum* root length (+ 5.69%).

Overall, the results indicate that *M. esculenta* extracts inhibited seedling growth under nursery conditions, with leaf extracts exhibiting stronger allelopathic effects than bark extracts, while *Eleusine coracana* and *Vigna umbellata* were the most sensitive species (Table 4).

Table 4

Effect of aqueous leaf and bark extract of *M. esculenta* on root and shoot length of test crops under nursery condition.

Treatments	Test crops									
	<i>Eleusine coracana</i>		<i>Setaria italica</i>		<i>Amaranthus caudatus</i>		<i>Vigna umbellata</i>		<i>Panicum miliaceum</i>	
Leaf	Shoot length (cm)	Root length (cm)	Shoot length (cm)	Root length (cm)	Shoot length (cm)	Root length (cm)	Shoot length (cm)	Root length (cm)	Shoot length (cm)	Root length (cm)
Control	18.90 ± 0.86	3.43 ± 0.90	19.58 ± 0.90	4.09 ± 2.01	19.98 ± 1.00	3.58 ± 0.21	22.86 ± 1.92	4.23 ± 0.13	22.81 ± 1.29	4.09 ± 0.21
5%	16.16 ± 1.46	3.63 ± 0.47	16.40 ± 0.80	3.74 ± 0.30 - 1.55	17.24 ± 1.81	3.82 ± 1.06 + 6.70	21.14 ± 0.77	3.99 ± 0.50	21.84 ± 1.72	3.94 ± 0.21
	-14.49	5.83	-16.24		-13.71		-7.52	-5.67	-4.25	-3.66
7%	14.21 ± 1.86	3.41 ± 0.30	19.28 ± 0.91	3.95 ± 0.23	17.67 ± 1.29 - 11.56	3.40 ± 0.27	22.74 ± 3.50	3.93 ± 0.30	20.78 ± 1.37	4.00 ± 0.40
	-24.81	-0.58	-1.53	-3.42		-5.02	-0.52	-7.09	-8.89	-2.20
9%	13.87 ± 3.87	3.34 ± 0.17	20.4 ± 2.11 + 4.18	3.38 ± 0.32	13.61 ± 2.93	2.72 ± 0.35	20.91 ± 2.36	3.31 ± 0.67	17.01 ± 1.33	4.09 ± 0.23
	-26.61	-2.62		-17.35	-31.88	-24.02	-8.53	-21.51	-25.42	0.00
Mean	14.74 ± 2.39	3.46 ± 0.31	18.79 ± 1.27	3.69 ± 0.28	16.17 ± 2.01	3.31 ± 0.56	21.59 ± 2.21	3.74 ± 0.49	19.87 ± 1.47	4.01 ± 0.28
	-21.97	+ 0.87	-4.53	-7.44	-11.34	-7.44	- 5.52	-11.42	-12.85	-1.95
Bark										
Control	20.41 ± 1.42	3.69 ± 0.97	21.05 ± 1.85	4.32 ± 0.50	18.05 ± 1.36	2.91 ± 0.23	20.41 ± 1.51	3.72 ± 0.98	21.79 ± 1.46	3.86 ± 0.34
5%	17.01 ± 0.68	2.87 ± 0.16	19.64 ± 0.97	4.33 ± 0.28 + 0.23	18.14 ± 1.83 + 0.55	2.63 ± 2.29	17.67 ± 0.39	2.86 ± 0.16	22.43 ± 0.89 + 2.93	4.20 ± 0.23 + 8.80
	-16.65	-22.22	-6.69			-9.62	-13.42	-23.11		
7%	15.75 ± 1.38	2.81 ± 0.10 + 23.84	19.78 ± 0.44	4.43 ± 0.51 + 2.54	18.18 ± 1.42 + 0.72	3.02 ± 0.12 + 3.78	15.75 ± 1.38	2.81 ± 0.10	20.29 ± 0.33	4.14 ± 0.33 + 7.25
	-22.83		-6.03				-19.33	-24.46	-6.88	
9%	13.51 ± 1.09	1.81 ± 0.10	17.66 ± 1.40	3.39 ± 0.48	17.72 ± 1.08 + 1.82	2.77 ± 0.11	13.52 ± 1.09	3.83 ± 0.36 + 2.95	17.86 ± 1.10	3.90 ± 0.23 + 1.03
	-33.80	-50.94	-16.10	-21.52		-4.81	-54.43		-18.03	
Mean	15.42 ± 1.05	2.83 ± 0.12	19.02 ± 0.93	4.05 ± 0.42	18.01 ± 1.44 +	2.80 ± 0.84	15.64 ± 0.95	3.16 ± 0.20	20.19 ± 0.77	4.08 ± 0.26 + 5.69
	-24.42	-16.44	-9.60	-6.25	1.03	-3.55	-29.06	-14.87	-7.32	

(Plus and minus signs depict % stimulation (+) and % inhibition (-) in percent germination of crops as compared to their respective control)

3.2.2 Effect on Seedling Growth (Shoot and Root Length)

The aqueous leaf and bark extracts of *Myrica esculenta* significantly influenced the root dry weight of the test crops under laboratory conditions, with responses varying among species and extract concentrations (Table 5). Under leaf extract treatments, root dry weight was markedly enhanced in *Vigna umbellata* (mean stimulation 47.61%), followed by a slight

increase in *Eleusine coracana* (+ 8.93%). In contrast, *Setaria italica*, *Panicum miliaceum*, and *Amaranthus caudatus* showed mean reductions of 33.33%, 25.00%, and 22.22%, respectively. The highest stimulation was observed in *V. umbellata* at 9% concentration (+ 80.95%).

Under bark extract treatments, *Vigna umbellata* also exhibited the greatest increase in root dry weight (mean + 18.83%), whereas *Setaria italica* (-5.53%), *Panicum miliaceum* (-11.11%), and *Eleusine coracana* (-16.66%) recorded reductions. *Amaranthus caudatus* showed no overall change in root dry weight. Overall, the results indicate that leaf extracts produced stronger effects than bark extracts, with both stimulatory and inhibitory responses depending on crop species and extract concentration (Table 5).

Table 5
Effect of aqueous leaf and bark extract of *M. esculenta* on root dry weight root of test crops under laboratory condition.

Treatments	Test crops				
Leaf	Eleusine coracana	Setaria italica	Amaranthus caudatus	Vigna umbellata	Panicum miliaceum
Control	0.07 ± 0.05	0.08 ± 0.04	0.06 ± 0.02	0.21 ± 0.01	0.08 ± 0.01
5%	0.09 ± 0.08 + 28.57	0.05 ± 0.05 -37.5	0.07 ± 0.03 -16.66	0.27 ± 0.01 + 28.57	0.07 ± 0.02 -12.5
7%	0.06 ± 0.03 -14.28	0.04 ± 0.05 -50.00	0.09 ± 0.06 + 50.00	0.28 ± 0.03 + 33.33	0.07 ± 0.02 -12.5
9%	0.08 ± 0.06 + 12.5	0.07 ± 0.04 -12.5	0.05 ± 0.06 -16.66	0.38 ± 0.05 + 80.95	0.08 ± 0.02 0.00
Mean	0.07 ± 0.05 + 8.93	0.05 ± 0.046 - 33.33	0.07 ± 0.05 -22.22	0.31 ± 0.03 + 47.61	0.06 ± 0.02 -25.00
Bark					
Control	0.08 ± 0.06	0.06 ± 0.06	0.07 ± 0.03	0.23 ± 0.02	0.06 ± 0.02
5%	0.09 ± 0.04 + 12.5	0.08 ± 0.03 + 33.00	0.09 ± 0.02 + 28.57	0.25 ± 0.08 + 8.69	0.06 ± 0.03 0.00
7%	0.05 ± 0.06 -37.5	0.04 ± 0.04 -33.3	0.07 ± 0.03 0.00	0.27 ± 0.02 + 17.39	0.06 ± 0.06 0.00
9%	0.08 ± 0.05 0.00	0.05 ± 0.03 -16.66	0.03 ± 0.06 -28.57	0.30 ± 0.05 + 30.43	0.04 ± 0.07 -33.33
Mean	0.04 ± 0.03 -16.66	0.05 ± 0.03 -5.53	0.07 ± 0.03 0.00	0.27 ± 0.05 + 18.83	0.05 ± 0.05 -11.11

(Plus, and minus signs depict % stimulation (+) and % inhibition (-) in percent germination of crops as compared to their respective control.)

3.2.3 Effect on Shoot Dry Weight

The aqueous leaf and bark extracts of *Myrica esculenta* produced variable effects on the shoot dry weight of the test crops under laboratory conditions, with responses differing among species and extract concentrations (Table 6). Under leaf extract

treatments, shoot dry weight was markedly reduced in Eleusine coracana (mean inhibition 76.71%) and Panicum miliaceum (1.39%), whereas stimulation was observed in Vigna umbellata (19.62%), Amaranthus caudatus (17.58%), and Setaria italica (9.09%). The greatest inhibition was recorded in E. coracana at 9% concentration (83.68%).

Under bark extract treatments, shoot dry weight increased in Eleusine coracana (28.87%), Setaria italica (15.74%), and Vigna umbellata (11.99%), while Amaranthus caudatus (23.50%) and Panicum miliaceum (39.39%) showed overall reductions. The maximum inhibition was observed in A. caudatus at 5% concentration (77.67%), whereas the highest stimulation occurred in Setaria italica at 7% concentration (+ 86.11%). Overall, the response of shoot dry weight to *M. esculenta* extracts was species-specific, with both inhibitory and stimulatory effects depending on the plant part and extract concentration (Table 6).

Table 6
Effect of aqueous leaf and bark extract of *M. esculenta* on shoot dry weight of test crops under nursery condition

Treatments	Test crops				
Leaf	<i>Eleusine coracana</i>	<i>Setaria italica</i>	<i>Amaranthus caudatus</i>	<i>Vigna umbellata</i>	<i>Panicum miliaceum</i>
Control	1.9 ± 0.04	0.33 ± 0.75	0.28 ± 0.48	1.36 ± 0.08	0.24 ± 0.45
5%	0.32 ± 0.25 -83.15	0.31 ± 0.36 -6.06	0.29 ± 0.73 + 3.57	2.1 ± 0.08 + 28.83	0.17 ± 0.29 -29.16
7%	0.33 ± 0.20 -63.33	0.40 ± 0.47 + 21.21	0.45 ± 0.77 + 60.71	1.37 ± 0.05 + 15.95	0.21 ± 0.39 - 12.5
9%	0.31 ± 0.12 -83.68	0.33 ± 0.39 0.00	0.25 ± 0.36 -10.71	1.4 ± 0.07 + 14.11	0.19 ± 0.03 -20.83
Mean	0.32 ± 0.19 -76.71	0.34 ± 0.039 + 9.09	0.33 ± 0.62 + 17.58	1.62 ± 0.06 + 19.62	0.19 ± 0.23 -1.39
Bark					
Control	0.32 ± 0.07	0.36 ± 0.92	1.12 ± 0.11	1.5 ± 0.07	0.33 ± 0.31
5%	0.41 ± 0.22 + 28.12	0.25 ± 0.77 -30.55	0.25 ± 0.11 - 77.67	1.22 ± 0.22 18.66	0.16 ± 0.18 -51.51
7%	0.36 ± 0.53 + 12.5	0.67 ± 0.56 + 86.11	1.32 ± 0.47 -15.15	1.5 ± 0.53 0.00	0.25 ± 0.34 -24.24
9%	0.4 ± 0.07 + 25	0.33 ± 0.75 -8.33	1.37 ± 0.38 + 22.32	1.24 ± 0.07 -17.33	0.19 ± 0.08 -42.42
Mean	0.39 ± 0.27 + 28.87	0.41 ± 0.69 + 15.74	0.98 ± 0.32 -23.5	1.32 ± 0.27 + 11.99	0.2 ± 0.2 -39.39

(plus and minus signs depict % stimulation (+) and % inhibition (-) in percent germination of crops as compared to their respective control.)

3.3 Multivariate Analysis

3.3.1 Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed to evaluate the multivariate response of crop–treatment combinations based on germination percentage, plumule length, radicle length, and root dry weight. The first two principal components

explained 72.9% of the total variation, with PC1 accounting for 46.9% and PC2 for 26.0%. The PCA score plot revealed a clear separation among treatments, indicating substantial variation in crop responses to leaf and bark extracts. Control treatments were generally associated with higher germination and seedling growth, whereas leaf and bark extract treatments exhibited greater dispersion, reflecting differential allelopathic effects. The partial overlap among treatment groups suggests species-specific responses to the extracts, with some crop–treatment combinations exhibiting similar growth characteristics despite different treatments. Overall, the PCA effectively distinguished treatment-induced variation and demonstrated the influence of allelopathic extracts on seed germination and early seedling development.

3.3.2 Hierarchical Cluster Analysis (HCA)

Hierarchical cluster analysis (HCA) based on standardized germination percentage, plumule length, radicle length, and root dry weight grouped the crop–treatment combinations into distinct clusters according to their overall response. The dendrogram revealed clear variation in allelopathic effects among treatments, with control treatments generally separated from extract-treated samples due to their higher germination and better seedling growth. Leaf extract treatments showed greater dispersion, indicating stronger inhibitory effects, whereas bark extract treatments exhibited intermediate responses. The clustering pattern also demonstrated species-specific sensitivity to the extracts, confirming differential tolerance among the test crops. Overall, the HCA supported the PCA results by highlighting the multivariate relationships among germination and seedling growth traits under different allelopathic treatments (Fig. 2).

4. DISCUSSION

4.1 Concentration-Dependent Allelopathic Effects of *Myrica esculenta*

The present investigation clearly demonstrated that the allelopathic effects of aqueous leaf and bark extracts of *M. esculenta* were concentration dependent. In general, increasing extract concentration from 5% to 9% progressively reduced germination percentage, radicle and plumule growth, shoot and root development, and biomass accumulation in most of the tested Himalayan crops. Such concentration-dependent inhibition is a characteristic feature of allelopathic interactions and reflects the increasing availability of phytotoxic secondary metabolites released from plant tissues (Xu et al., 2023). Phenolic acids, flavonoids, tannins, terpenoids, and other water-soluble compounds are known to interfere with membrane permeability, enzyme activity, hormonal balance, nutrient uptake, respiration, and cell division, ultimately reducing seed germination and seedling growth (Wang et al., 2025; Lal and Biswas, 2023).

Although inhibitory responses predominated, slight stimulation of certain growth parameters was observed at lower extract concentrations (5%), particularly in some crop species. This phenomenon is consistent with the concept of hormesis, where low concentrations of biologically active compounds stimulate physiological processes, whereas higher concentrations become inhibitory (Misra et al., 2023; Rahman et al., 2023). Mild stimulation may result from activation of antioxidant defence systems, enhanced metabolic activity, or temporary improvement in nutrient mobilization before toxic thresholds are exceeded. Similar biphasic responses have been reported in several allelopathic investigations involving agroforestry tree species and agricultural crops, suggesting that the biological activity of allelochemicals depends largely on their concentration and the sensitivity of the recipient species (Xu et al., 2023).

The overall findings agree with previous studies on agroforestry tree species, including *Ficus auriculata*, *Ficus semicordata*, *Grewia optiva*, *Morus alba*, and other Himalayan trees, where increasing concentrations of aqueous extracts significantly inhibited seed germination and early seedling development. Therefore, the present study confirms that *M. esculenta* possesses measurable allelopathic potential capable of influencing neighbouring agricultural crops under both laboratory and nursery conditions.

4.2 Differential Allelopathic Activity of Leaf and Bark Extracts

A consistent observation throughout the present study was that leaf extracts generally produced stronger inhibitory effects than bark extracts for most germination and seedling growth parameters (Silva Souza et al., 2025; Burns et al., 2012). This

suggests that leaves constitute the primary source of phytotoxic compounds in *M. esculenta*. Leaves are metabolically more active than bark tissues and accumulate higher concentrations of phenolic compounds, flavonoids, tannins, and other secondary metabolites involved in plant defence against herbivores, pathogens, and environmental stress (Kousar et al., 2026).

Phenolic compounds are widely recognized as major allelochemicals capable of suppressing seed germination through inhibition of α -amylase activity, disruption of protein synthesis, reduction of ATP production, and impairment of cell elongation. Flavonoids may alter auxin transport and oxidative metabolism, whereas hydrolysable and condensed tannins interfere with nutrient availability and enzyme function. Because these compounds are readily leached from fresh or decomposing leaves during rainfall, leaf litter often represents the principal pathway through which allelochemicals enter the soil in natural ecosystems (Jabran and Farooq et al., 2012).

The stronger phytotoxicity of leaf extracts observed in this study is consistent with phytochemical reports indicating that *M. esculenta* leaves contain abundant phenolics, flavonoids, tannins, glycosides, and triterpenoids possessing considerable biological activity. Previous reviews on the phytochemistry of *M. esculenta* have similarly reported higher concentrations of bioactive compounds in leaves than in woody tissues, thereby supporting the greater inhibitory effects observed in the present investigation (Sharma et al., 2026).

4.3 Species-Specific Responses of Traditional Himalayan Crops

Marked variation in allelopathic sensitivity was observed among the five traditional Himalayan crops. *Eleusine coracana* consistently exhibited the greatest reduction in germination and seedling growth, whereas *Amaranthus caudatus* generally showed the highest tolerance to both leaf and bark extracts. These differences indicate that crop species respond differently to the same allelochemicals due to inherent physiological, biochemical, and genetic characteristics (Yamawo, 2026; Shahmohammadi et al., 2026).

The greater sensitivity of *E. coracana* may be attributed to rapid uptake of water-soluble allelochemicals during germination, limited detoxification capacity, and greater susceptibility of root meristematic tissues to phenolic toxicity (John and Sarada, 2012). Since root tissues are the first organs exposed to allelochemicals, inhibition of root elongation can subsequently restrict water absorption, mineral uptake, and shoot development. The pronounced inhibition of radicle growth observed in this study supports this explanation (Dawood, 2018).

Conversely, the comparatively higher tolerance of *A. caudatus* may be associated with efficient antioxidant defence systems, enhanced detoxification mechanisms, maintenance of membrane integrity, or reduced permeability to phytotoxic compounds (Wahid et al., 2009). Amaranth species are well known for their adaptability to stressful environmental conditions and possess strong antioxidant metabolism, which may help mitigate oxidative damage induced by allelochemicals. Such physiological resilience probably contributed to the comparatively lower inhibition observed across most growth parameters (Kumar et al., 2025).

These species-specific responses have important ecological implications because they indicate that tree–crop compatibility in agroforestry systems depends not only on the allelopathic potential of the tree species but also on the inherent tolerance of the associated crops.

4.4 Laboratory versus Nursery Responses

Although similar inhibitory trends were observed under laboratory and nursery conditions, the magnitude of allelopathic effects differed between the two experimental environments. Laboratory bioassays generally produced stronger and more consistent responses because seeds were exposed directly to aqueous extracts under controlled environmental conditions without interference from soil processes. In contrast, nursery experiments represented a more realistic growing environment where soil properties influenced the availability and persistence of allelochemicals.

Several mechanisms may explain the comparatively moderated responses under nursery conditions. Soil colloids and organic matter can adsorb phenolic compounds, thereby reducing their bioavailability to germinating seeds (Uwihanganye et al., 2025). Furthermore, soil microorganisms are capable of degrading or transforming many allelochemicals into less toxic metabolites,

thereby decreasing their inhibitory effects over time. Continuous leaching, dilution through irrigation, and natural chemical degradation may further reduce phytotoxicity under pot conditions (Poudyal and Cregg, 2019).

These findings emphasize that laboratory bioassays are highly suitable for identifying allelopathic potential, whereas nursery experiments provide a more realistic assessment of tree–crop interactions. Consequently, integrating results from both experimental approaches offers a stronger basis for predicting field performance than relying on laboratory experiments alone.

4.5 Implications for Himalayan Agroforestry Systems

The present findings have important implications for designing sustainable agroforestry systems in the Himalayan region. Since *Myrica esculenta* exhibited measurable allelopathic activity, careful selection of compatible intercrops is essential to minimize negative interactions and maintain crop productivity. Based on the present study, *Amaranthus caudatus* demonstrated the highest tolerance to aqueous extracts and therefore appears to be a suitable companion crop for integration with *M. esculenta*. *Panicum miliaceum* and *Setaria italica* exhibited intermediate tolerance, whereas *Eleusine coracana* was consistently the most sensitive species and may experience reduced establishment when grown in close association with mature *M. esculenta* trees.

The results also suggest that management practices such as periodic removal of excessive leaf litter, wider tree spacing, strategic pruning, and selection of tolerant crop species could reduce the accumulation of allelochemicals in the cropping zone. Such management interventions may improve crop performance while retaining the ecological and economic benefits of *M. esculenta*, including fruit production, medicinal value, biodiversity conservation, carbon sequestration, and soil stabilization. Therefore, understanding allelopathic interactions is essential for optimizing tree–crop compatibility and promoting climate-resilient agroforestry systems in the Garhwal Himalaya.

4.6 Limitations and Future Research

Despite providing valuable insights into the allelopathic potential of *M. esculenta*, the present study has certain limitations. The experiments employed aqueous extracts prepared under controlled laboratory conditions, which may not fully represent the gradual release, transformation, and persistence of allelochemicals under natural field conditions. In natural ecosystems, concentrations of allelochemicals fluctuate depending on rainfall, litter decomposition, soil characteristics, microbial activity, and seasonal environmental conditions.

Furthermore, the study did not identify or quantify the individual phytotoxic compounds responsible for the observed inhibitory effects. Advanced analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC–MS), or liquid chromatography–mass spectrometry (LC–MS) should be employed in future investigations to characterize the specific allelochemicals involved. Additional studies should also evaluate physiological and biochemical responses, including antioxidant enzyme activity, chlorophyll content, photosynthetic efficiency, oxidative stress markers, and nutrient uptake, to better understand the mechanisms underlying crop tolerance.

Finally, long-term field experiments under established agroforestry systems are required to validate the laboratory and nursery findings under natural environmental conditions. Such investigations will improve understanding of seasonal dynamics, litter decomposition, soil microbial interactions, and long-term tree–crop compatibility, thereby facilitating the development of scientifically sound recommendations for sustainable Himalayan agroforestry systems.

5. CONCLUSION

The present study demonstrated that aqueous leaf and bark extracts of *Myrica esculenta* exert significant concentration-dependent allelopathic effects on the germination and early seedling growth of traditional Himalayan agricultural crops under both laboratory and nursery conditions. In general, increasing extract concentration resulted in greater inhibition of germination, seedling growth, and biomass accumulation, although slight stimulatory responses at lower concentrations suggested a hormetic effect. Leaf extracts consistently exhibited stronger phytotoxicity than bark extracts, indicating a higher abundance of bioactive allelochemicals in the leaves. Among the test crops, *Eleusine coracana* was the most sensitive,

whereas *Amaranthus caudatus* showed the highest tolerance, highlighting species-specific differences in allelopathic response. These findings provide valuable information for selecting compatible intercrops in *M. esculenta*-based agroforestry systems. Further phytochemical characterization and long-term field studies are recommended to identify the responsible allelochemicals and validate these interactions under natural environmental conditions.

Declarations

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Author Contributions

Conceptualization: R. S. Bali; Methodology: Deepti Granthi, R. S. Bali, and Naresh Singh; Investigation: Deepti Granthi, C. S. Dhanai, B. S. Butola, and Tara Singh Mehra; Data curation: Deepti Granthi and Naresh Singh; Formal analysis: Naresh Singh; Writing—original draft preparation: Deepti Granthi and Naresh Singh; Writing—review and editing: R. S. Bali, Arvind Bijalwan, C. S. Dhanai, B. S. Butola, and Tara Singh Mehra; Supervision: R. S. Bali. All authors have read and approved the final manuscript.

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no competing interests.

Ethics and consent to participate

The leaf and bark material of *Myrica esculenta* used in this study was collected from the research field of the College of Forestry, Ranichauri, VCSG Uttarakhand University of Horticulture and Forestry, Uttarakhand, India, for academic and research purposes. The plant material was collected from the institutional research area and was not collected from protected forest areas, private farmland, or any external site. The collection and use of the plant material were undertaken in accordance with applicable institutional guidelines and relevant regulations.

The plant material was identified as *Myrica esculenta* by Dr. R. S. Bali, Assistant Professor, Department of Forest Biology and Tree Improvement (FBTI), College of Forestry, Ranichauri, VCSG Uttarakhand University of Horticulture and Forestry, Uttarakhand, India. A representative voucher specimen of the collected material has been deposited and maintained in the Department of Forest Biology and Tree Improvement (FBTI), College of Forestry, Ranichauri, VCSG Uttarakhand University of Horticulture and Forestry, Uttarakhand, India, under voucher/deposition number UUHF-FBTI-0003.

Permission for collection of the plant material was obtained from the Dean, College of Forestry, Ranichauri. The collection was undertaken within the institutional research field for academic and research purposes.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

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Figures

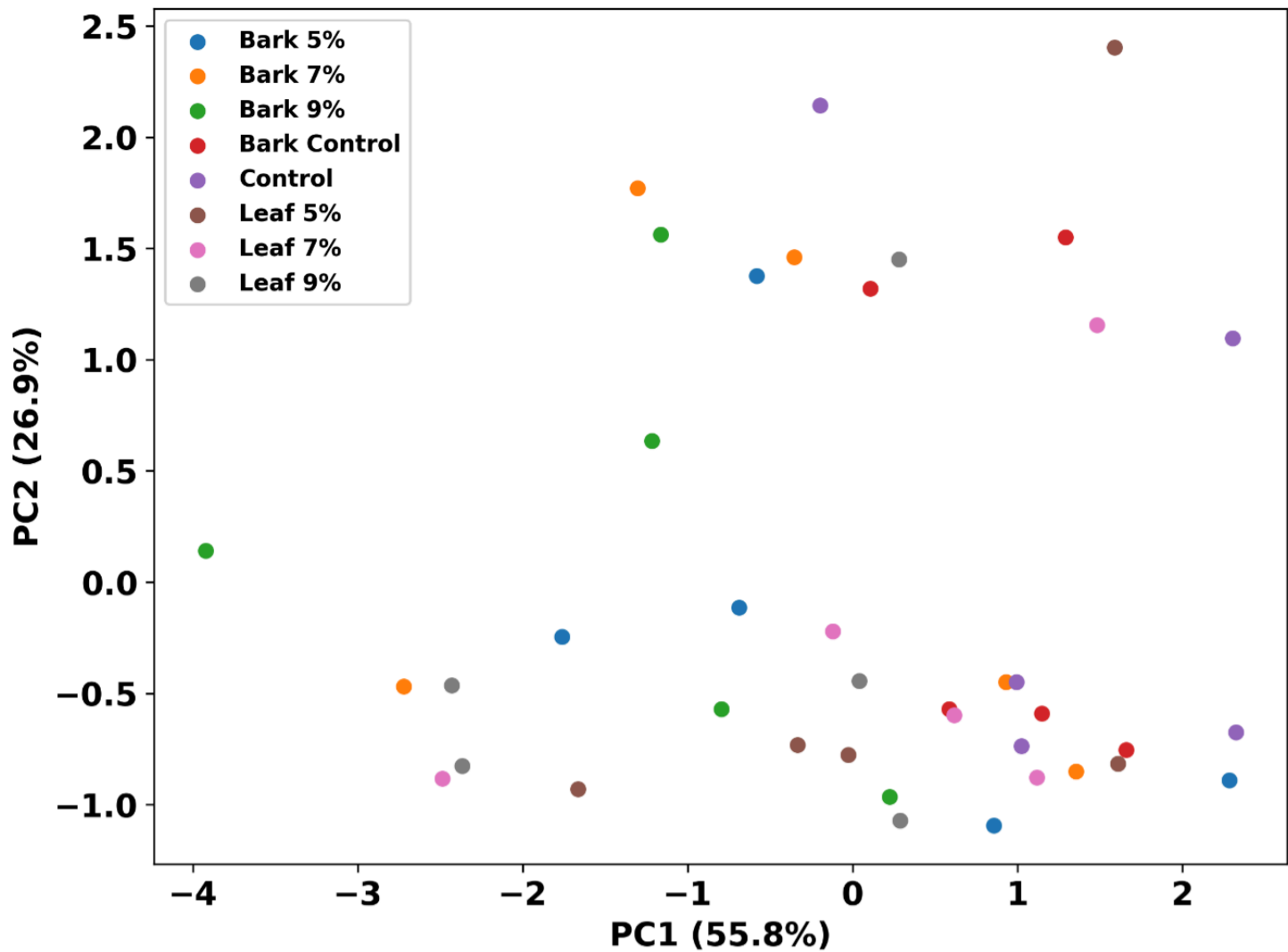


Figure 1

PCA score plot of crop-treatment combinations based on germination and seedling growth traits.

Hierarchical Cluster Analysis (Ward's Method)

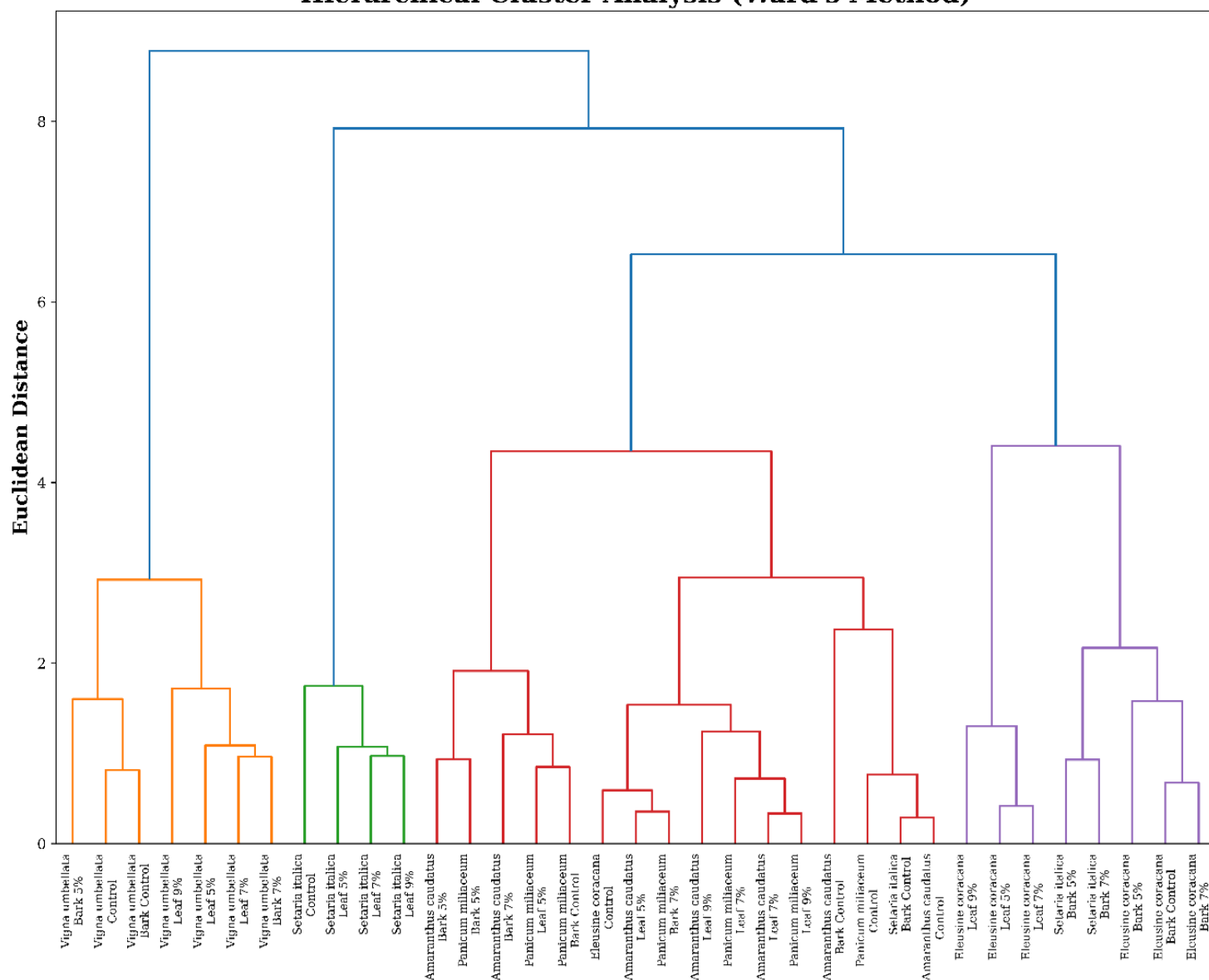


Figure 2

Hierarchical cluster analysis (Ward's method, Euclidean distance) illustrating the similarity among crop–treatment combinations based on germination percentage, plumule length, radicle length, and root dry weight.

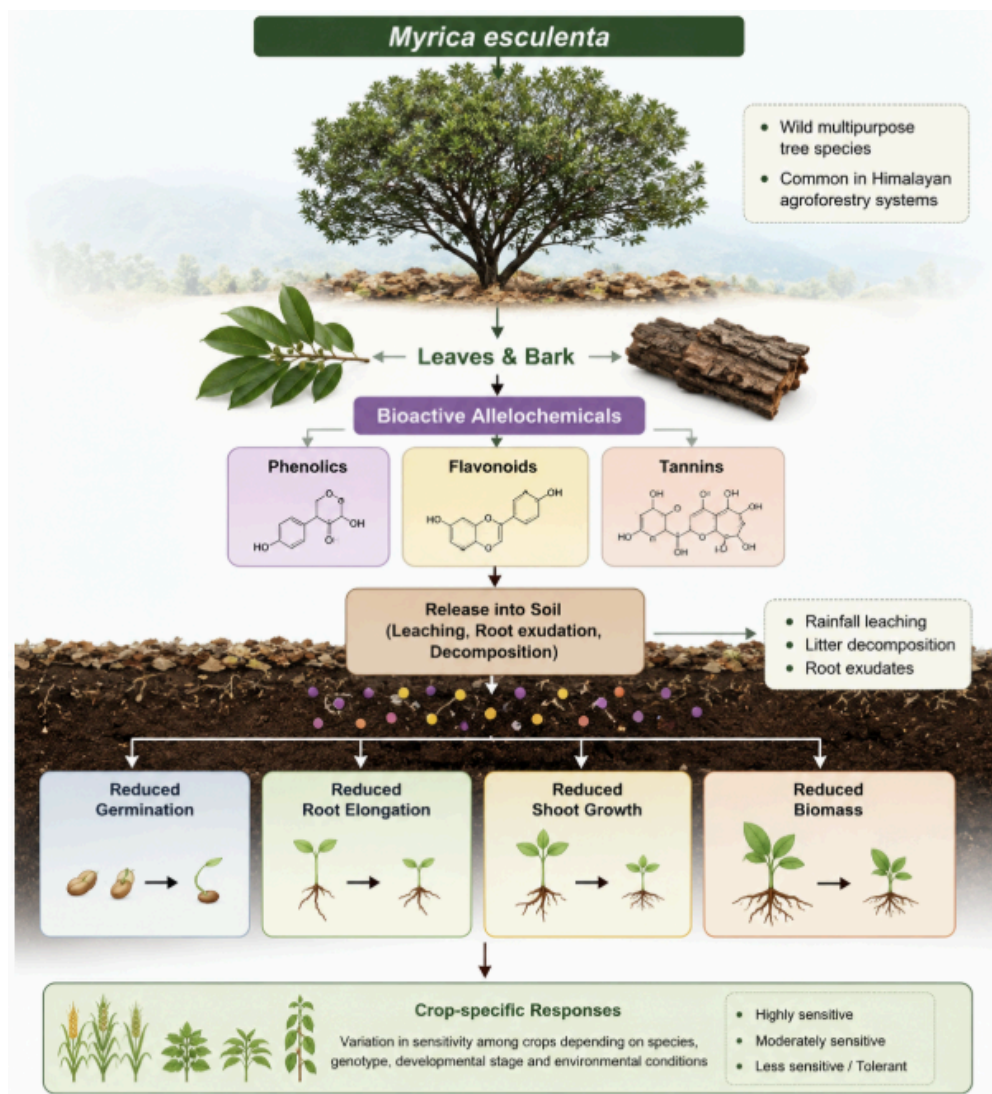


Figure 3

Schematic representation of the allelopathic effects of *M. esculenta* on traditional Himalayan crops