Research Article

Effect of Allelopathic Trees on the Morphological Features of Rice (*Oryza sativa*)

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Abstract | The present study was conducted to evaluate the allelopathic effects of selected tree species on seed germination and morphological traits of *Oryza sativa*. Allelopathy is an important ecological mechanism influencing crop performance, particularly in rice-based agroecosystems where interactions with surrounding vegetation may affect growth and yield. In this study, aqueous extracts prepared from the stems, roots, and leaves of Ficus carica, Ailanthus altissima, and *Eucalyptus lanceolatus* were applied at three concentrations (5 g, 10 g, and 15 g) and a control treatment to assess their inhibitory potential. The results showed that allelopathic effects increased with concentration, with the highest inhibition observed at 15 g treatments. Radicle and plumule growth were significantly reduced across all treatments, indicating strong suppression during early seedling development. Leaf extracts exhibited comparatively weaker effects on leaf length and leaf width, whereas stem and root extracts, particularly from *Ailanthus altissima* and Eucalyptus lanceolatus, significantly reduced these traits. Furthermore, extracts from *Ficus carica* and *Eucalyptus lanceolatus* markedly reduced grain number, spikelet number, and 100-grain weight, indicating a substantial negative impact on yield-related parameters. Differences among plant parts suggest variation in the concentration and activity of allelochemicals, such as phenolics and other secondary metabolites. Correlation analysis revealed that radicle length was positively and significantly correlated with plumule length, plant height, leaf length, leaf number, leaf width, grain number, spikelet number, and 100-grain weight. Plumule length also showed significant positive correlations with plant height, leaf width, grain number, spikelet number, and grain weight, while its relationship with leaf length and leaf number was non-significant. Principal Component Analysis (PCA) further supported these findings by clearly separating high-concentration treatments from control conditions, with growth and yield traits contributing most strongly to the observed variation. Overall, the findings demonstrate that allelopathic tree species significantly suppress rice growth and productivity in a concentration-dependent manner. These results highlight the importance of managing tree–crop interactions and provide valuable insights for improving sustainable rice cultivation practices.

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Keywords | Allelopathy, Allelochemicals, *Oryza sativa*; rice, Germination inhibition, Morphological traits, Plant–plant interactions, Growth suppression, Principal component analysis (PCA)

Introduction

The genus *Oryza* L. belongs to the tribe Oryzeae, family Poaceae, and subfamily Oryzoideae. It comprises two cultivated species, *Oryza sativa* L. and *Oryza glaberrima*, along with approximately 20 wild species distributed across tropical and subtropical regions (Rice, 1984; Yang, 2006; Khatri *et al*., 2020). Among these, *Oryza sativa* (Asian rice) is the most economically important species and serves as a staple food for more than half of the global population (Arnon, 1949; Swain and Hillis, 1959; Mann, 1987; Erida *et al*., 2023). It is an annual grass that can grow up to 1 m in height and is well adapted to a wide range of environmental conditions, including flooded and waterlogged habitats (Ismail and Kumar, 1996; Kohli *et al*., 1997; Subhan *et al*., 2025). The plant consists of an erect stem with nodes bearing leaves, and grains are produced on panicles that arch downward (Vitousek and Walker, 1989). The grain, particularly the endosperm, represents the most economically valuable component for human consumption (Mizutani, 1999; Yang, 2006; Ullah *et al*., 2025a). Rice is one of the most important cereal crops worldwide and is a primary food source for a significant portion of the human population (Hiscox and Israelstam, 1979; Malik and Husain, 2007). It can be cultivated across diverse agroecological conditions, ranging from upland systems to lowland flooded environments, and from humid to relatively dry climates. Globally, rice, maize, and wheat together contribute approximately 49% of total caloric intake, with rice alone accounting for about 23% (Kohli and Rani, 1994; Batish *et al*., 2002a). Despite its importance, rice production faces several constraints, particularly in developing countries such as Pakistan, where environmental and agronomic challenges significantly limit crop yield and productivity (Stachon and Zimdahl, 1980; Ullah *et al*., 2025b). One of the major challenges affecting crop production is environmental pollution resulting from the excessive and improper use of synthetic fertilizers and pesticides (Batish et al., 2002b). Chemical weed control has become increasingly common in modern agriculture; however, overuse of these inputs leads to soil degradation, water contamination, and adverse effects on human and animal health (Quayyum *et al*., 2000). The accumulation of nitrates and other agrochemicals contributes to eutrophication and environmental imbalance (Xuan *et al*., 2004). These concerns have prompted increasing interest in sustainable and eco-friendly alternatives for crop management. Allelopathy has emerged as an important ecological mechanism that can influence plant growth and crop productivity. The term allelopathy is derived from the Greek words "allelo" (mutual) and "pathy" (suffering), and it was first introduced by Hans Molisch to describe biochemical interactions among plants (Xuan *et al*., 2005; Ullah *et al*., 2025c). It refers to the direct or indirect effects of one plant on another through the release of chemical compounds into the environment (Khan *et al*., 2018a; Poudel *et al*., 2019). These compounds, known as allelochemicals, are secondary metabolites produced by plants, algae, bacteria, and fungi, which can affect seed germination, growth, and survival of neighboring plants (Javaid *et al*., 2006). Depending on their nature and concentration, allelochemicals may exert either inhibitory or stimulatory effects on target organisms, influencing physiological and developmental processes (Niu *et al*., 2007; Khan *et al*., 2018b). In agricultural systems, allelopathy plays a crucial role in plant–plant interactions, particularly in crop–weed and crop–tree relationships (Poudel *et al*., 2019). Many plant species, including both native and invasive weeds, release allelochemicals that can significantly affect seed germination and crop growth (Khatri *et al*., 2020). Weeds are a major constraint in agricultural production, especially in Asia, where they compete with crops for nutrients, water, and light (Xuan *et al*., 2004). In addition, allelochemicals released by these plants can further suppress crop development by inhibiting germination and early seedling growth (Wang *et al*., 2011). Therefore, understanding allelopathic interactions is essential for developing sustainable weed management strategies and improving crop productivity (Poudel *et al*., 2019; Khan *et al*., 2018a). Therefore, the present study aims to investigate the allelopathic effects of selected tree species on the germination and morphological traits of *Oryza sativa* under controlled conditions. Specifically, this study (i) evaluates the inhibitory effects of aqueous extracts derived from different plant parts (root, stem, and leaves) at varying concentrations (5 g, 10 g, and 15 g) on seed germination and early seedling growth, (ii) assesses the impact of allelopathic treatments on key morphological and yield-related traits, including plant height, leaf characteristics, grain number, spikelet number, and 100-grain weight, (iii) examines the relationships among growth and yield traits using correlation analysis, and (iv) identifies the major sources of variation among treatments through Principal Component Analysis (PCA). By integrating morphological and statistical analyses, this study provides insights into the role of allelopathy in influencing rice growth and offers a scientific basis for sustainable crop management and agroecosystem improvement.

Materials and Methods

Experimental site

The study was conducted in the Department of Botany (Allelopathy, Conservation, and Plant Systematics), Hazara University, Mansehra, Pakistan. Both laboratory and field experiments were carried out from May 2021 to September 2021 under controlled and natural environmental conditions (Khan *et al*., 2018c).

Collection of plant material

Fresh leaves, stems, and roots of selected allelopathic tree species (Ficus carica, Ailanthus altissima, and Eucalyptus lanceolatus) were collected from District Shangla, Khyber Pakhtunkhwa, Pakistan. Only healthy and disease-free plant parts were selected. The collected materials were washed with distilled water to remove dust and debris and then shade-dried at room temperature. The dried plant materials were ground into fine powder using a mechanical grinder and stored separately for further analysis (Khan *et al*., 2024).

Preparation of aqueous extracts

Aqueous extracts were prepared by soaking powdered plant materials (leaves, stems, and roots separately) at concentrations of 5%, 10%, and 15% (w/v) in distilled water for 24 hours at room temperature (Khan *et al*., 2025). The extracts were filtered using Whatman No. 1 filter paper, and the final volume was adjusted to 100 mL. These concentrations were selected to evaluate dose-dependent allelopathic effects (low, medium, and high concentrations). Distilled water was used as a control treatment, and fresh extracts were prepared before each experiment (Asif *et al*., 2025).

Germination experiment

The germination experiment was conducted under laboratory conditions using a Completely Randomized Design (CRD). Ten healthy seeds of *Oryza sativa* were placed in Petri dishes lined with two layers of Whatman filter paper (Sajid *et al*., 2023). Each Petri dish received 10 mL of the respective extract (5%, 10%, and 15%) to maintain moisture, while distilled water was used as a control (Khan et al., 2016). All Petri dishes were incubated in darkness at 25 °C for 10 days. Moisture levels were maintained by adding extract solution as required. After the incubation period, the following parameters were recorded (Shakir *et al*., 2023a):

- Radicle length (cm)
- Plumule length (cm)

Field experiment

The field experiment was conducted using a Randomized Complete Block Design (RCBD) at Hazara University, Mansehra. The field was divided into plots with adequate spacing to avoid treatment interference (Shakir *et al*., 2023b). Rice seeds were sown uniformly across all plots. For each treatment, 150 g of powdered plant material (roots, stems, and leaves of Ficus carica, Ailanthus altissima, and Eucalyptus lanceolatus) was applied separately to designated rows, while untreated rows served as a control (Saifullah *et al*., 2025). Three plants from each plot were randomly selected at different growth stages. The following morphological and yield-related traits were recorded:

- Plant height (cm)
- Leaf length (cm)
- Leaf width (cm)
- Number of leaves per plant
- Number of grains per plant
- Spikelet number per plant
- 100-grain weight (g)

Statistical analysis

All data were analyzed using SPSS software (IBM SPSS Statistics, version XX). Analysis of variance (ANOVA) was performed to determine significant differences among treatments. Mean comparisons were conducted using the Least Significant Difference (LSD) test at a 5% probability level ($p \leq 0.05$). Pearson correlation analysis was performed to evaluate the relationships among growth and yield-related traits. In addition, Principal Component Analysis (PCA) was conducted using R software (version 3.4.0) to identify major sources of variation and to assess the overall impact of allelopathic treatments on rice growth. The PCA results were visualized using appropriate graphical packages to illustrate trait contributions and treatment separation.

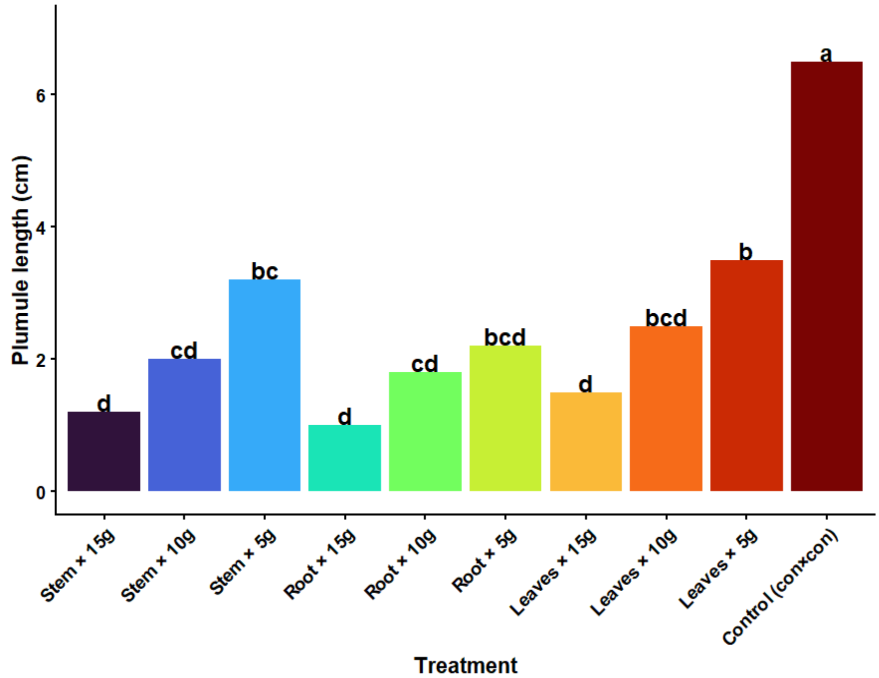

Figure 1: *Effects of Ficus carica on Oryza sativa plumule length*

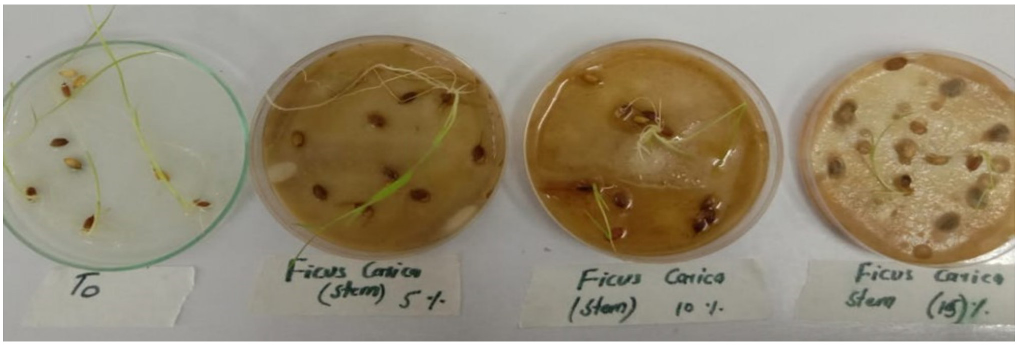

Plate 1: *Allelopathic effect of 5% 10% 15% aqueous extract of Ficus carica stem on radicle and plumule length of Oryza sativa*

Table 1: *Analysis of variance for effects of allelopathic plants (leaves, stem, root) at different levels of concentration (5g, 10g, 15g) on radical and plumule length*

Effects		**Radical**		**Plumule**	
Species	DF	F	P	F	P
Ficus carica	9	20.9024	<.0001	22.3926	<.0001
Ailanthus altissima	9	22.2857	<.0001	15.7656	<.0001
Eucalyptus lanceolatus	9	13.0701	<.0001	12.6882	<.0001

Note: *DF stands for degrees of freedom, P stands for probability values, and F stands for the ratio of two variances.*

Results

The results demonstrated that aqueous extracts of selected allelopathic tree species significantly influenced germination, growth, and yield-related traits of *Oryza sativa*, with effects varying depending on plant part and extract concentration (Jhariya *et al*., 2022).

Laboratory experiment: allelopathic effects on radicle and plumule length of Oryza sativa

effect of Ficus carica on radicle and plumule length

Ficus carica showed significant effects ($p \leq 0.05$) on radicle and plumule growth of *Oryza sativa* (Table 1). The maximum radicle and plumule lengths were recorded in the control treatment, followed by the leaf extract at a 5 g concentration. A gradual reduction in both parameters was observed with increasing extract concentration. The minimum plumule length (0.83 ± 0.16 cm) was recorded under stem and root extracts at 15 g concentration (Plate 1), while the lowest radicle length (1.5 ± 0.5 cm) was also observed under root and stem extracts at the same concentration (Plate 2).

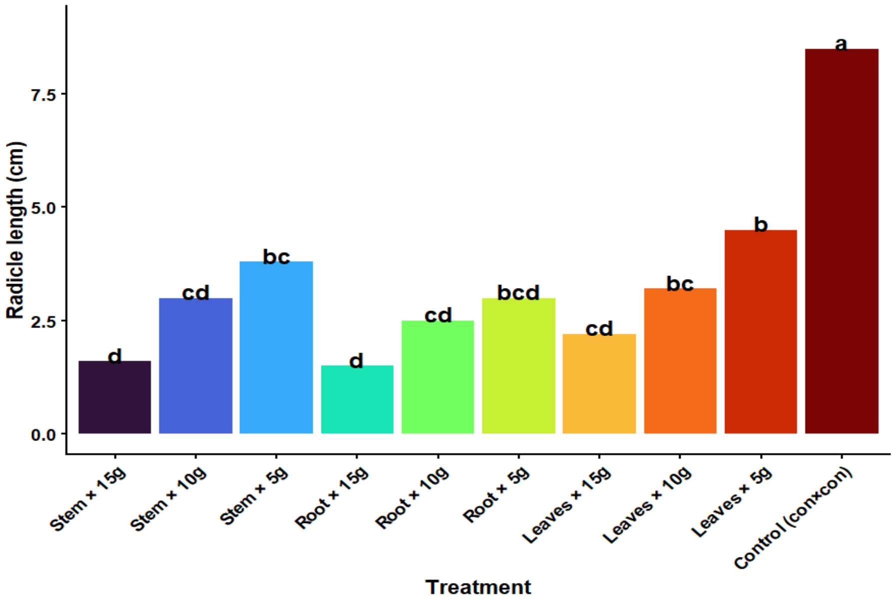

Figure 2: *Effects of Ficus carica on Oryza sativa radical length*

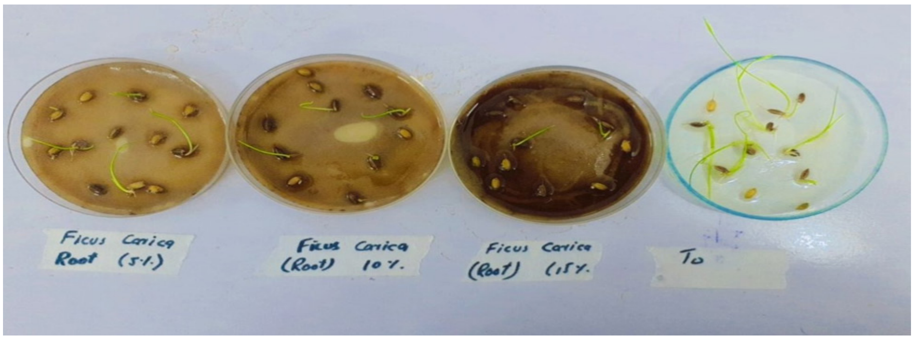

Plate 2: *Allelopathic effect of 5% 10% 15% aqueous extract of Ficus carica root on radicle and plumule length of Oryza sativa*

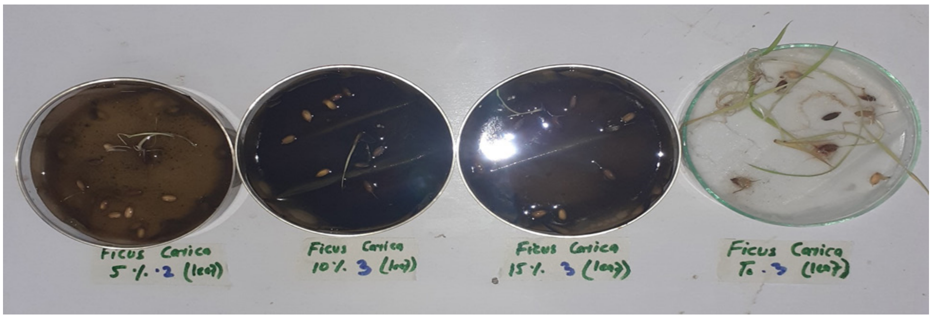

Plate 3: *Allelopathic effect of 5% 10% 15% aqueous extract of Ficus carica leaves on radicle and plumule length of Oryza sativa*

Among the different plant parts, stem and root extracts exhibited stronger inhibitory effects compared to leaf extracts. Overall, *Ficus carica* extracts demonstrated a concentration-dependent inhibitory effect, with the highest suppression observed at 15 g concentration across all plant parts (Plate 3; Figure 1 and Figure 2).

Effect of Ailanthus altissima on radicle and plumule length

Ailanthus altissima exhibited significant effects ($p \leq 0.05$) on radicle and plumule growth of *Oryza sativa* (Table 1). The maximum plumule and radicle lengths (7 ± 0.57 cm and 9 ± 0.57 cm, respectively) were recorded in the control treatment (distilled water), followed by the leaf extract at a 5 g concentration (Plate 4). A progressive reduction in growth parameters was observed with increasing extract concentration. The minimum plumule length (1.5 ± 0.28 cm) was recorded under root extract at 15 g concentration, followed by stem extract at the

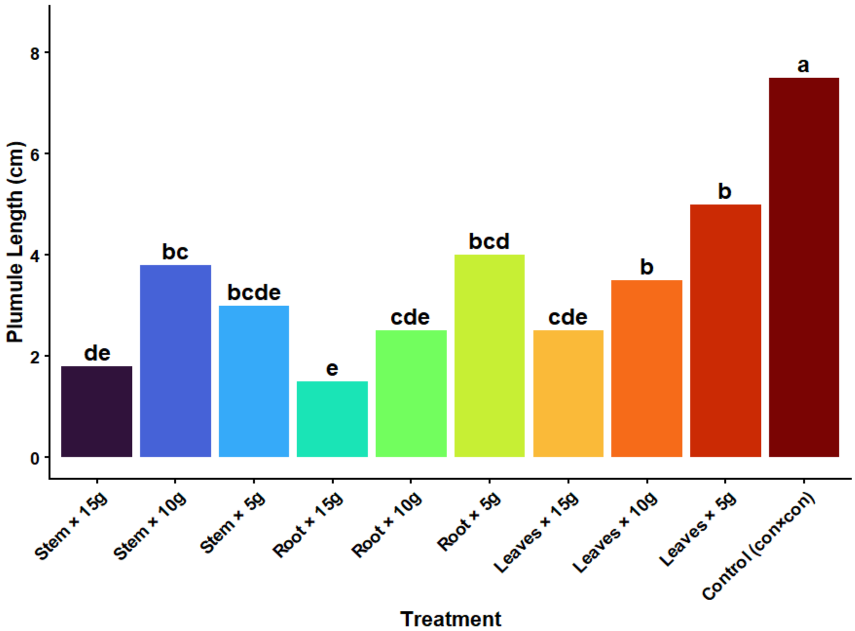

Figure 3: *Effects of Ailanthus altissima on Oryza sativa plumule length*

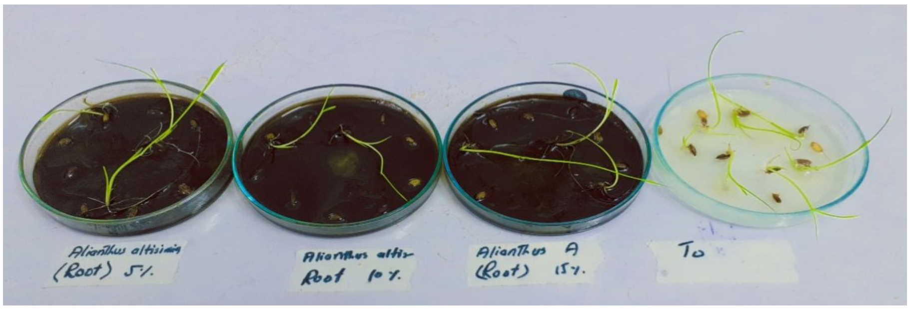

Plate 4: *Allelopathic effect of 5% 10% 15% aqueous extract of Ailanthus altissima root on radicle and plumule length of Oryza sativa*

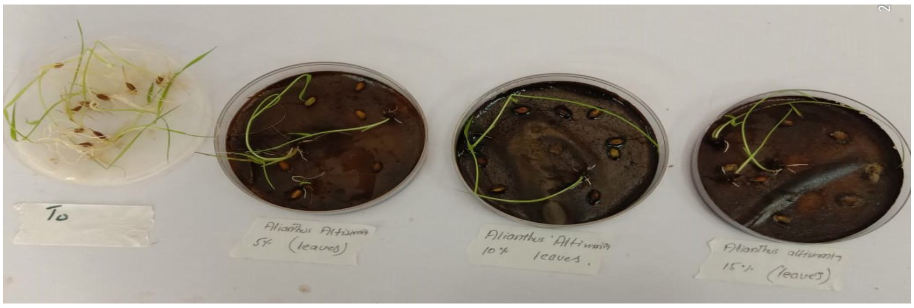

Plate 5: *Allelopathic effect of 5% 10% 15% aqueous extract of Ailanthus altissima leaves on radicle and plumule length of Oryza sativa*

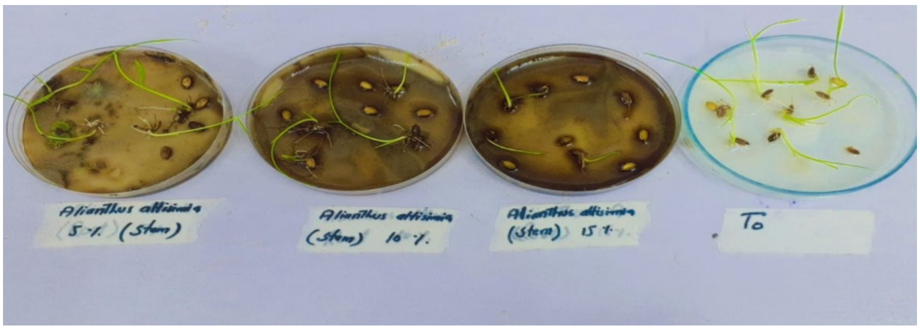

Plate 6: *Allelopathic effect of 5% 10% 15% aqueous extract of Ailanthus altissima stem on radicle and plumule length of Oryza sativa*

same concentration (Plate 5). Similarly, the lowest radicle length (2.5 ± 0.28 cm) was observed under root extract at 15 g concentration, followed by stem extract (Plate 6). Among the different plant parts, root extracts showed the strongest inhibitory effects, followed by stem extracts, while leaf extracts exhibited comparatively lower inhibition. Overall, *Ailanthus altissima* extracts demonstrated a clear concentration-dependent inhibitory effect, with the highest suppression of radicle and plumule growth observed at 15 g concentration (Figure 3 and Figure 4).

Effect of Eucalyptus lanceolatus on radicle and plumule length

Eucalyptus lanceolatus showed significant effects ($p \leq 0.05$) on radicle and plumule growth of *Oryza sativa* (Table 1). The maximum plumule and radicle lengths (3.16 ± 0.16 cm and 5.66 ± 0.33 cm, respectively) were recorded in the control treatment, followed by leaf extract at 5 g concentration (Plate 7). A strong inhibitory effect was observed with increasing extract concentration. No seed germination was recorded under the stem extract at 15 g concentration (Plate 8), indicating complete inhibition. Similarly, no plumule emergence was observed at a stem extract concentration of 10 g, while radicle growth was minimal (0.33 ± 0.33 cm). The minimum plumule length (0.66 ± 0.33 cm) was recorded under root extract at both 10 g and 15 g concentrations (Plate 9). Among the different plant parts, stem

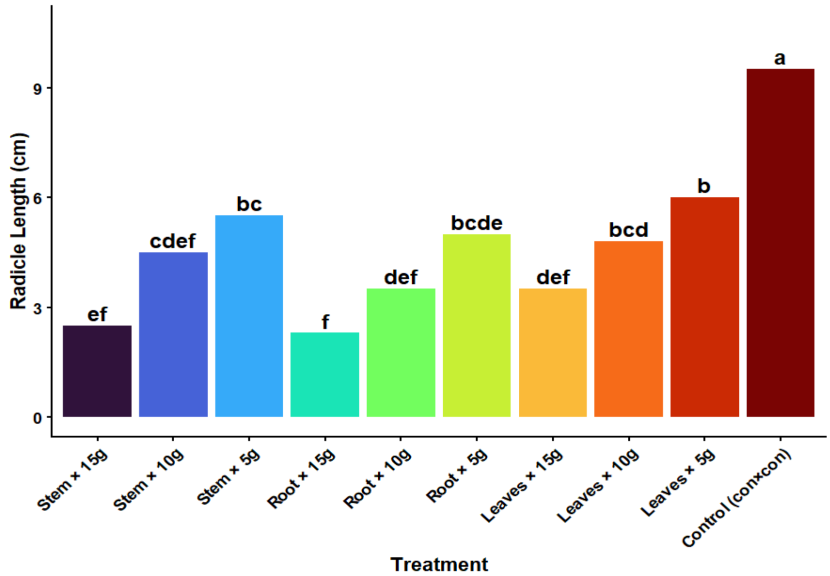

Figure 4: *Effects of Ailanthus altissima on Oryza sativa radical length*

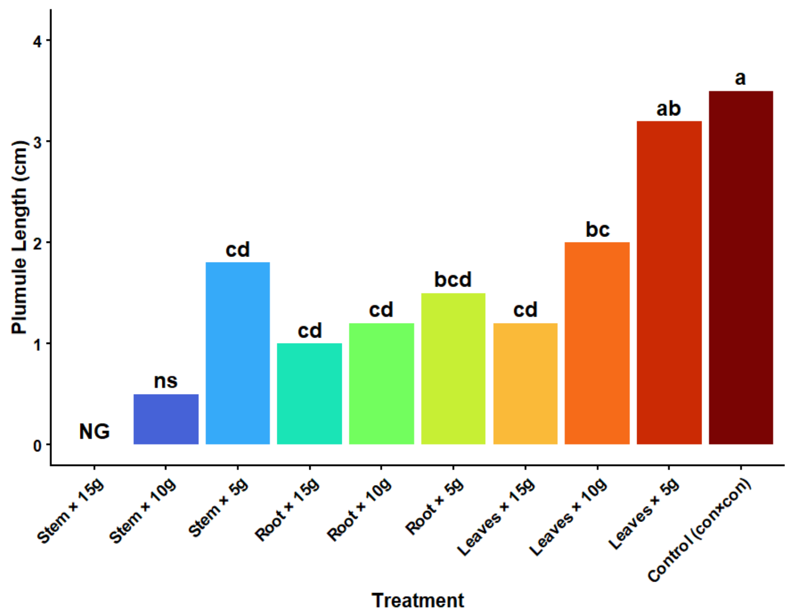

Figure 5: *Effects of Eucalyptus lanceolatus on Oryza sativa plumule length*

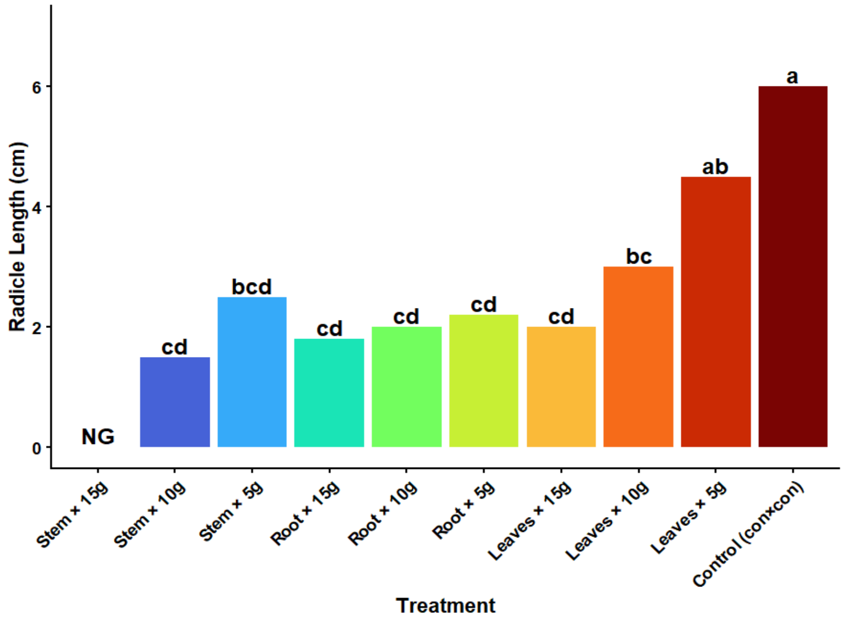

Figure 6: *Effects of Eucalyptus lanceolatus on Oryza sativa radical length*

Plate 7: *Allelopathic effect of 5% 10% 15% aqueous extract of Eucalyptus lanceolatus leaves on radicle and plumule length of Oryza sativa*

Plate 8: *Allelopathic effect of 5% 10% 15% aqueous extract of Eucalyptus lanceolatus root on radicle and plumule length of Oryza sativa*

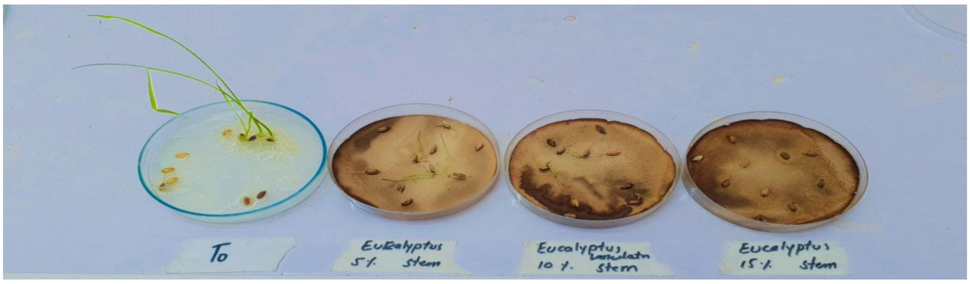

Plate 9: *Allelopathic effect of 5% 10% 15% aqueous extract of Eucalyptus lanceolatus stem on radicle and plumule length of Oryza sativa*

extracts exhibited the strongest inhibitory effects, followed by root extracts, while leaf extracts showed comparatively weaker inhibition. Overall, *Eucalyptus lanceolatus* extracts demonstrated a pronounced concentration-dependent inhibitory effect, with 10 g and 15 g concentrations causing severe suppression of germination and seedling growth compared to the 5 g concentration (Figure 5 and Figure 6).

Effect of allelopathic plants on morphological parameters of Oryza sativa

Analysis of variance for the effect of allelopathic plants on morphological traits of Oryza sativa

One-way analysis of variance (ANOVA) revealed that plant height, leaf length, and leaf width of *Oryza sativa* were significantly ($p \leq 0.05$) affected by the application of leaf, stem, and root powders of Ficus carica, Ailanthus altissima, Eucalyptus lanceolatus, Melia azedarach, and Morus alba (Table 2). These results indicate that allelopathic treatments had a pronounced influence on key vegetative growth parameters. In contrast, the number of leaves did not show a significant response ($p > 0.05$) to the allelopathic treatments, suggesting that this trait is less sensitive to allelochemical effects compared to other morphological characteristics.

Plant height and number of leaves

The plant height of *Oryza sativa* was significantly ($p \leq 0.05$) reduced by the application of allelopathic plant part powders compared to the control treatment.

Effect of Ailanthus altissima on plant height

The plant height of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Ailanthus altissima* (Figure 7). The highest plant height (approximately 90 cm) was recorded in the control treatment, which was significantly greater than all allelopathic treatments.

Among the treated groups, leaf, root, and stem powders resulted in a marked reduction in plant height, with values ranging between approximately 55 and 58 cm. However, no significant differences were observed among these plant parts, as indicated by the same significance group (b). Overall, all parts of *Ailanthus altissima* exhibited a strong inhibitory effect on plant height compared to the control, indicating its pronounced allelopathic potential under field conditions Table 1.

Effect of Eucalyptus lanceolatus on plant height

The plant height of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Eucalyptus lanceolatus* (Figure 8). The highest plant height (approximately 90 cm) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem powders resulted in a marked reduction in plant height, with values ranging between approximately 52 and 56 cm. However, no significant differences were observed among these plant parts, as indicated by the same significance group (b). Overall, all parts of *Eucalyptus lanceolatus* exhibited a strong inhibitory effect on plant height compared

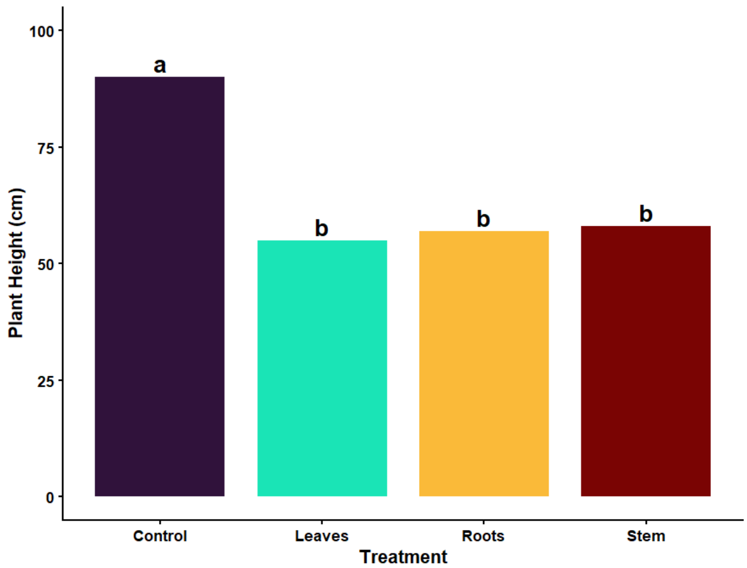

Figure 7: *Effect of different plant parts (leaves, roots, and stems) of Ailanthus altissima on the plant height (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test. The control represents plants grown without allelopathic treatment.*

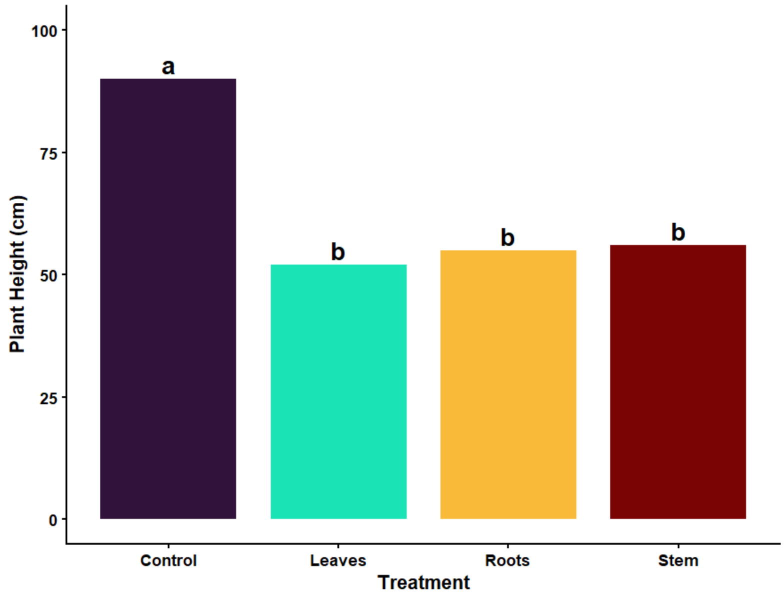

Figure 8: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on the plant height (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test. The control represents plants grown without allelopathic treatment.*

Table 2: *Analysis of variance for the effects of allelopathic plants (leaves, stem, root), on Oryza sativa morphology*

Effects		**Plant height**		**Leaves No.**		**Leaf Length**		**Leaf width**	
	DF	F	P	F	P	F	P	F	P
Ficus carica	3	80.8033	<.0001	1.1111	0.359	37.9007	<.0001	41.6389	<.0001
Ailanthus altissima	3	151.9351	<.0001	0.3478	0.7909	73.6646	<.0001	32.8588	<.0001
Eucalyptus lanceolatus	3	219.4824	<.0001	1.3061	0.2894	214.6037	<.0001	70.902	<.0001
Melia azedarach	3	237.7944	<.0001	0.386	0.7638	121.2504	<.0001	43.2653	<.0001
Morus alba	3	108.112	<.0001	0.1	0.9594	26.1287	<.0001	51.2401	<.0001

Note: *DF stands for degrees of freedom, P stands for probability values, and F stands for the ratio of two variances.*

to the control, indicating its pronounced allelopathic potential under field conditions Table 1.

Effect of Ficus carica on plant height

Plant height of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Ficus carica* (Figure 9). The highest plant height (approximately 88–90 cm) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf powder resulted in the greatest reduction in plant height (~55 cm), followed by root and stem powders (~62–64 cm). Significant differences were observed among plant parts, with leaf treatment showing the strongest inhibitory effect (group c), while root and stem treatments exhibited moderate inhibition (group b). Overall, *Ficus carica* showed a strong allelopathic effect on plant height, with leaf extracts exerting the strongest inhibitory influence compared to other plant parts Table 1.

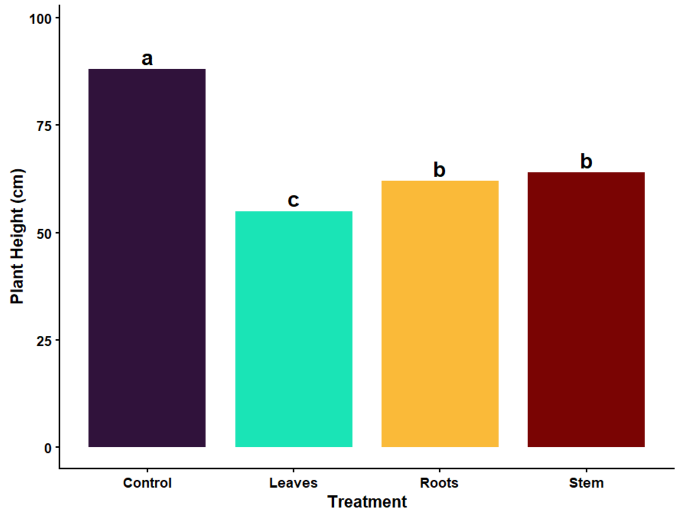

Figure 9: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on the plant height (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test. The control represents plants grown without allelopathic treatment.*

Effect of melia azedarach on plant height

The plant height of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Melia azedarach* (Figure 10). The highest plant height (approximately 90 cm) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, root powder resulted in the greatest reduction in plant height (~50 cm), followed by stem (~60 cm) and leaf (~65 cm) treatments. Significant differences were observed among plant parts, as indicated by distinct significance groups (b, c, and d), with root treatment showing the strongest inhibitory effect. Overall, *Melia azedarach* exhibited a strong allelopathic effect on plant height, with root extracts exerting the strongest inhibitory influence compared to leaf and stem treatments.

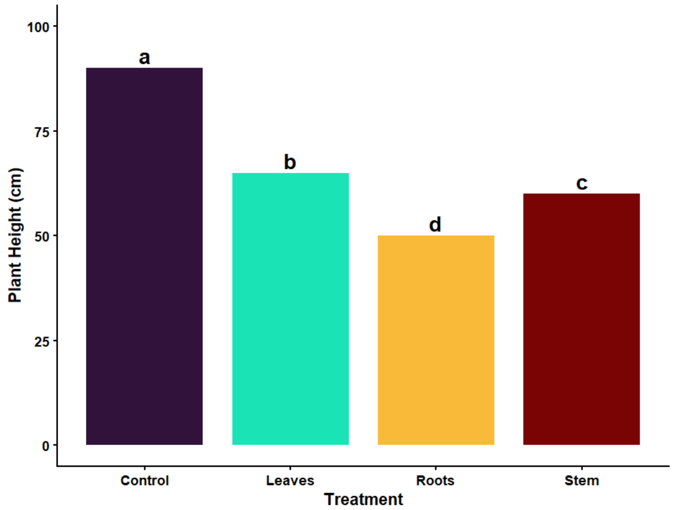

Figure 10: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on the plant height (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at $p \leq 0.05$ based on the LSD test. The control represents plants grown without allelopathic treatment.*

Effect of allelopathic plants on the number of leaves

The number of leaves of *Oryza sativa* was not significantly affected ($p > 0.05$) by the application of different allelopathic plant parts compared to the control treatment (Figure 10). Although slight variations were observed among treatments, these differences were not statistically significant.

Effect of Ailanthus altissima on the number of leaves

The number of leaves of *Oryza sativa* was not significantly affected ($p > 0.05$) by different parts of *Ailanthus altissima* (Figure 11). The control and all treatments (leaves, roots, and stems) showed nearly similar values, ranging from 3 to 3.5 leaves per plant. No significant differences were observed among treatments, as indicated by the same statistical group (a). These results suggest that the number of leaves is relatively insensitive to the allelopathic effects of *Ailanthus altissima* Table 2.

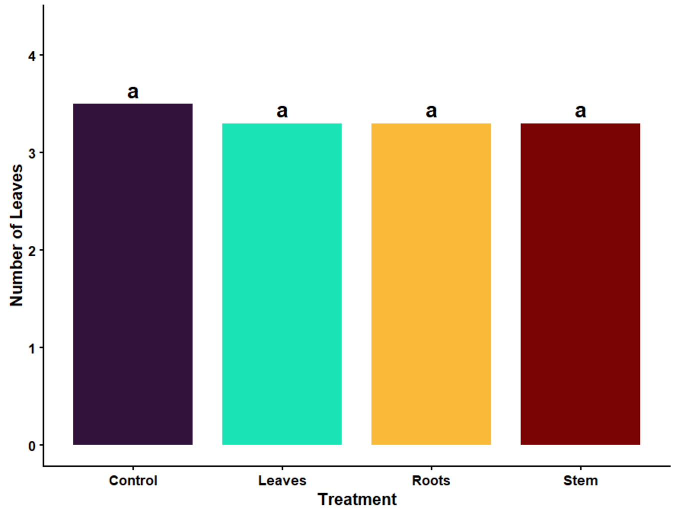

Figure 11: *Effect of different plant parts (leaves, roots, and stems) of Ailanthus altissima on the number of leaves of Oryza sativa. Bars represent mean values ± standard error. Same letters above bars indicate non-significant differences at $p > 0.05$ based on the LSD test.*

Effect of Eucalyptus lanceolatus on the number of leaves

The number of leaves of *Oryza sativa* was not significantly affected ($p > 0.05$) by different parts of *Eucalyptus lanceolatus* (Figure 12). The control and all treatments (leaves, roots, and stems) exhibited nearly similar values, with only minor variations among treatments. No significant differences were observed among the plant parts, as all treatments belonged to the same statistical group (a). These results indicate that the number of leaves is not sensitive to the allelopathic effects of *Eucalyptus lanceolatus* Table 2.

Effect of Ficus carica on the number of leaves

The number of leaves of *Oryza sativa* was not significantly affected ($p > 0.05$) by different parts of *Ficus carica* (Figure 13). The control and all treatments (leaves, roots, and stems) showed nearly similar values, with only slight variations among treatments. No significant differences were observed among the plant parts, as all treatments belonged to the same statistical group (a). These results indicate that the number of leaves is not influenced by the allelopathic effects of *Ficus carica* Table 2.

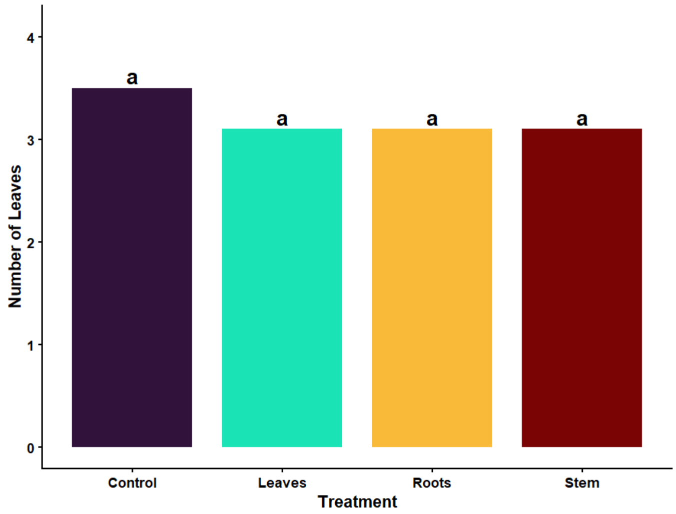

Figure 12: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on the number of leaves of Oryza sativa. Bars represent mean values ± standard error. Same letters above bars indicate non-significant differences at p > 0.05 based on the LSD test.*

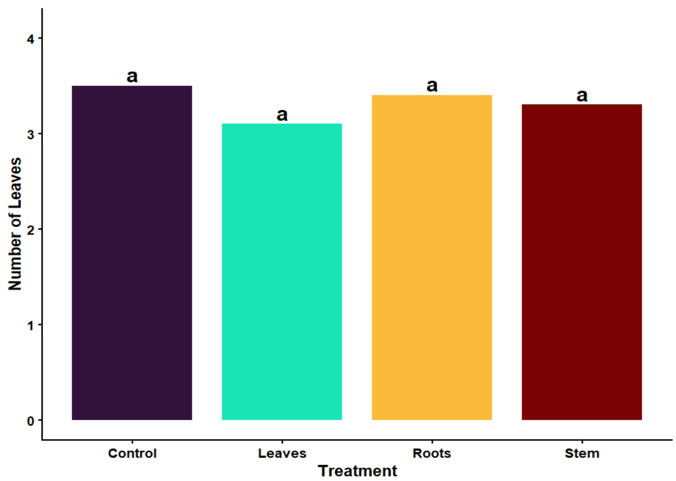

Figure 13: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on the number of leaves of Oryza sativa. Bars represent mean values ± standard error. Same letters above bars indicate non-significant differences at p > 0.05 based on the LSD test.*

Effect of Melia azedarach on the number of leaves

The number of leaves of *Oryza sativa* was not significantly affected (p > 0.05) by different parts of *Melia azedarach* (Figure 14). The control and all treatments (leaves, roots, and stem) exhibited nearly similar values, with only slight variations among treatments. No significant differences were observed among the plant parts, as all treatments belonged to the same statistical group (a). These results indicate that the number of leaves is not influenced by the allelopathic effects of *Melia azedarach* Table 2.

Effect of allelopathic plants on leaf length

Leaf length of *Oryza sativa* was significantly affected (p ≤ 0.05) by different allelopathic plant species and their respective parts compared to the control treatment.

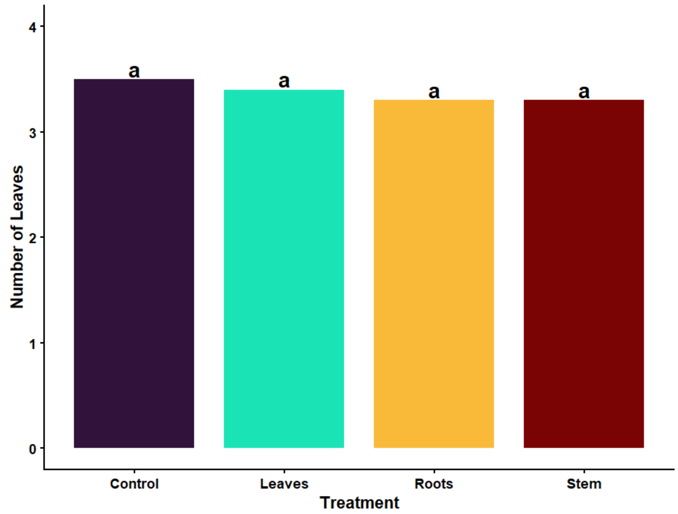

Figure 14: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on the number of leaves of Oryza sativa. Bars represent mean values ± standard error. Same letters above bars indicate non-significant differences at p > 0.05 based on the LSD test.*

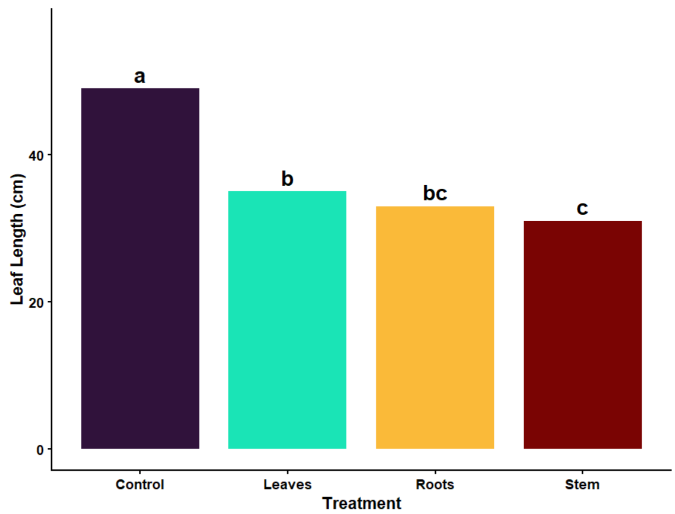

Figure 15: *Effect of different plant parts (leaves, roots, and stem) of Ailanthus altissima on leaf length (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on LSD test.*

Effect of Ailanthus altissima on leaf length

Leaf length of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Ailanthus altissima* (Figure 15). The maximum leaf length (approximately 45 cm) was recorded in the control treatment, which was significantly higher than all allelopathic treatments. Among the treated groups, leaf extract showed moderate reduction (~35 cm), followed by root extract (~33 cm), while stem extract exhibited the greatest reduction (~31 cm). Significant differences were observed among treatments, as indicated by different statistical groups (a, b, bc, and c), with the stem treatment showing the strongest inhibitory effect. Overall, *Ailanthus altissima* demonstrated a pronounced allelopathic effect on leaf length, with increasing inhibition observed from leaf to stem treatments.

Effect of Eucalyptus lanceolatus on leaf length

Leaf length of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Eucalyptus lanceolatus* (Figure 16). The highest leaf width was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in reduced leaf width, with no significant differences observed among these plant parts, as all treatments belonged to the same statistical group. This indicates that all parts of *Eucalyptus lanceolatus* exerted a similar inhibitory effect on leaf width. Overall, *Eucalyptus lanceolatus* showed a strong allelopathic effect by significantly reducing leaf width compared to the control.

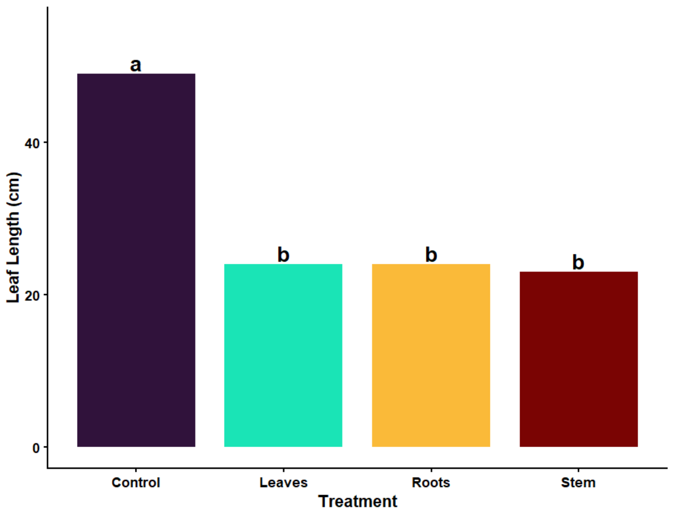

Figure 16: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on leaf width (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of ficus carica on leaf length

Leaf length of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Ficus carica* (Figure 17). The maximum leaf length (approximately 48–50 cm) was recorded in the control treatment, which was significantly higher than all allelopathic treatments. Among the treated groups, root extract showed moderate reduction (~44–45 cm), while leaf and stem extracts exhibited the greatest reduction (~35–38 cm). Significant differences were observed among treatments, as indicated by distinct statistical groups (a, b, and c), with leaf and stem treatments showing the strongest inhibitory effects. Overall, *Ficus carica* demonstrated a strong allelopathic effect on leaf length, with leaf and stem extracts exerting greater inhibition compared to root extracts.

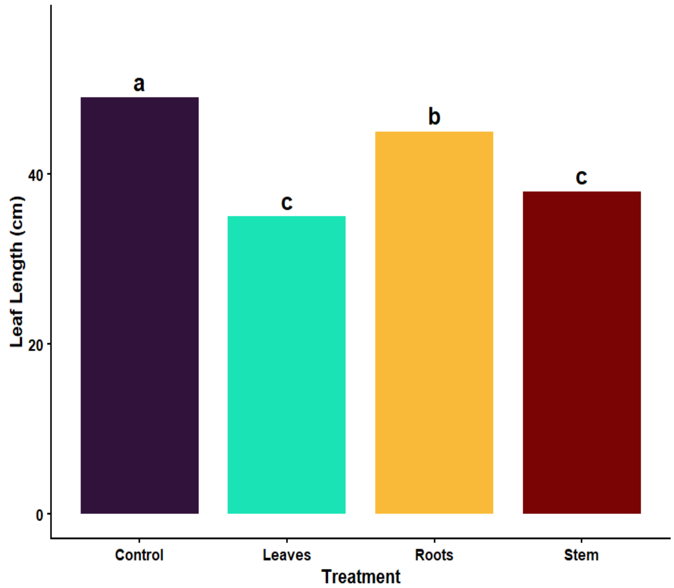

Figure 17: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on leaf length (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Melia azedarach on leaf length

Leaf length of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Melia azedarach* (Figure 18). The maximum leaf length (approximately 48–50 cm) was recorded in the control treatment, which was significantly higher than all allelopathic treatments. Among the treated groups, leaf and stem extracts showed moderate reduction (~38–40 cm), while root extract exhibited the greatest reduction (~25 cm). Significant differences were observed among treatments, as indicated by distinct statistical groups (a, b, and c), with root treatment showing the strongest inhibitory effect. Overall, *Melia azedarach* demonstrated a strong allelopathic effect on leaf length, with root extracts exerting greater inhibition compared to leaf and stem treatments.

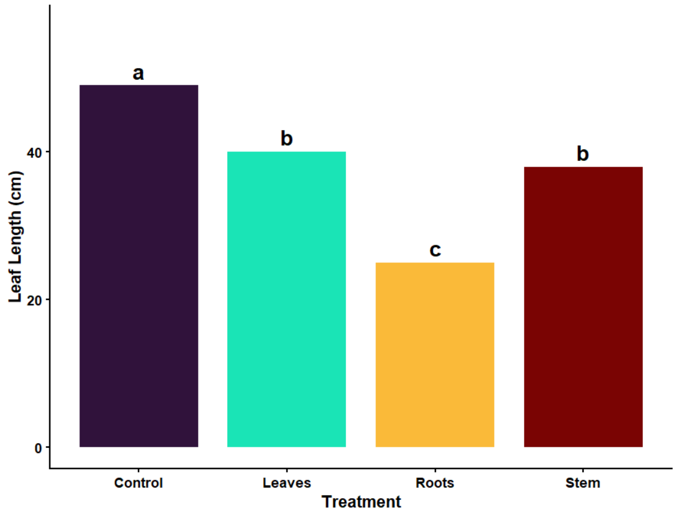

Figure 18: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on leaf length (cm) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of allelopathic plants on the number of grains

The number of grains of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different allelopathic plant species and their respective parts compared to the control treatment.

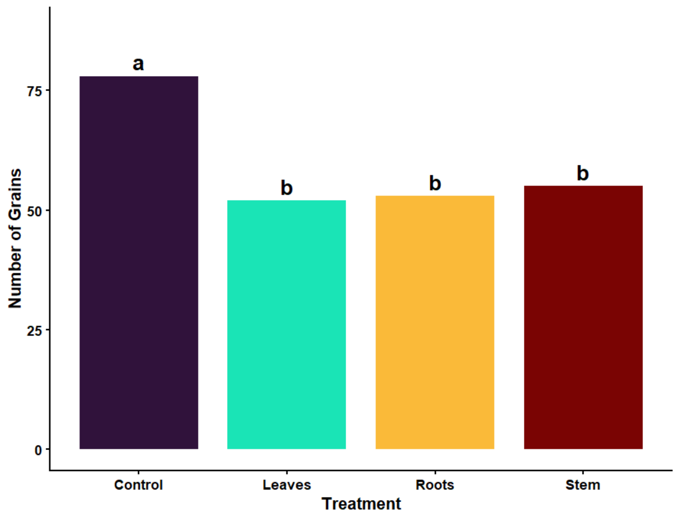

Figure 19: *Effect of different plant parts (leaves, roots, and stems) of Ailanthus altissima on the number of grains of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Ailanthus altissima on the number of grains

The number of grains of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Ailanthus altissima* (Figure 19). The highest number of grains (approximately 78) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a marked reduction in grain number, with values ranging between approximately 52–56 grains per plant. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Ailanthus altissima* exhibited a strong inhibitory effect on grain production, indicating its negative impact on the yield of *Oryza sativa*.

Effect of Eucalyptus lanceolatus on the number of grains

The number of grains of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Eucalyptus lanceolatus* (Figure 20). The highest number of grains (approximately 78) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, root extract showed the greatest reduction (~40 grains), followed by leaf and stem extracts (~47–49 grains). Significant differences were observed among treatments, as indicated by distinct statistical groups (a, b, and c), with root treatment showing the strongest inhibitory effect. Overall, *Eucalyptus lanceolatus* demonstrated a pronounced allelopathic effect on grain production, with root extracts exerting the highest negative impact on yield.

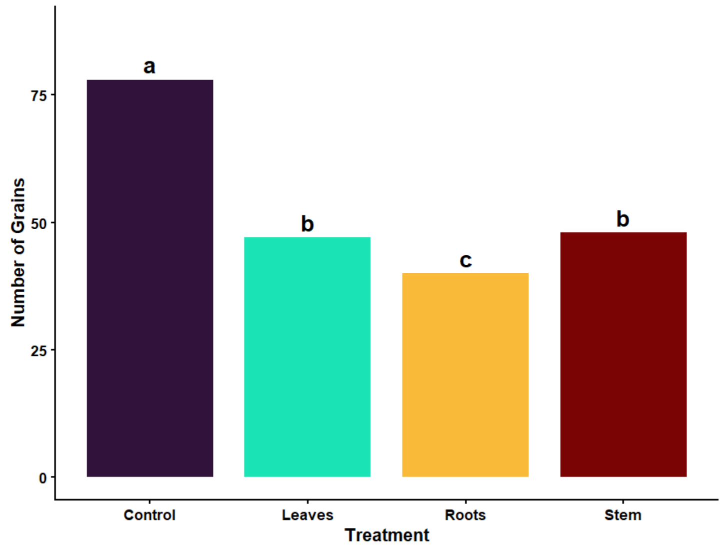

Figure 20: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on the number of grains of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Ficus carica on the number of grains

The number of grains of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Ficus carica* (Figure 21). The highest number of grains (approximately 78) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf extract showed the greatest reduction (~40 grains), followed by stem (~52 grains) and root (~55 grains) treatments. Significant differences were observed among treatments, as indicated by distinct statistical groups (a, b, and c), with leaf treatment showing the strongest inhibitory effect. Overall, *Ficus carica* demonstrated a strong allelopathic effect on grain production, with leaf extracts exerting the highest negative impact on yield.

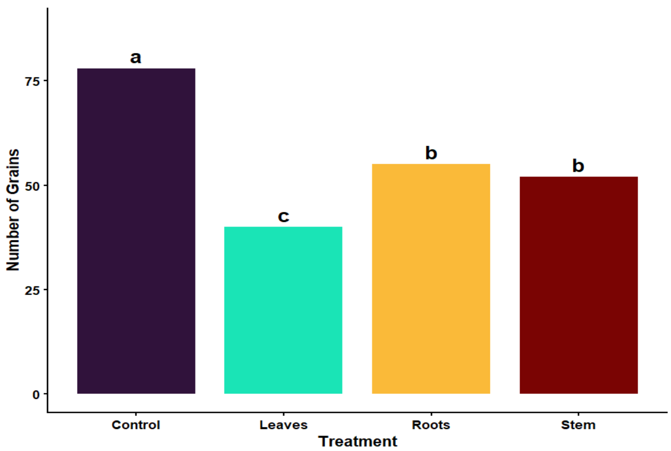

Figure 21: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on the number of grains of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Melia azedarach on the number of grains

The number of grains of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Melia azedarach* (Figure 22). The highest number of grains (approximately 78) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, root extract showed the greatest reduction (~50 grains), followed by leaf extract (~55 grains), while stem extract exhibited comparatively higher grain number (~62 grains) among the treated groups. Significant differences were observed among treatments, as indicated by statistical groups (a, b, bc, and c), with root treatment showing the strongest inhibitory effect. Overall, *Melia azedarach* demonstrated a strong allelopathic effect on grain production, with root extracts exerting the highest negative impact on yield, while stem treatments showed relatively lower inhibition.

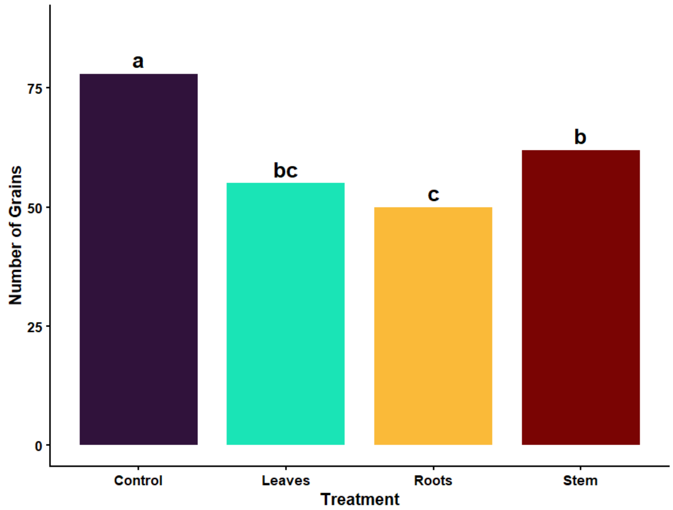

Figure 22: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on the number of grains of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of allelopathic plants on the number of spikelets

Analysis of variance (ANOVA) revealed that different allelopathic plant species and their respective parts had significant effects ($p \leq 0.05$) on the number of spikelets of *Oryza sativa* (Table 3). These results indicate that allelopathic treatments influenced reproductive development and yield-related traits. Overall, the number of spikelets was reduced under allelopathic treatments compared to the control, demonstrating the inhibitory effects of allelochemicals on spikelet formation.

Table 3: *Analysis of variance for effects of allelopathic plants (leaves, stem, root) on yield-related parameters of Oryza sativa*

Effects		**Grain No.**		**Spikelet No.**		**Weight of 100g**	
Species	DF	F	P	F	P	F	P
Ficus carica	3	113.266	<.0001	83.2049	<.0001	31.8958	<.0001
Ailanthus altissmia	3	84.1626	<.0001	56.6116	<.0001	42.2424	<.0001
Eucalyptus lanceolatus	3	157.5609	<.0001	102.397	<.0001	40.428	<.0001

Effect of Ailanthus altissima on the number of spikelets

The number of spikelets of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Ailanthus altissima* (Figure 23). The highest number of spikelets (approximately 21) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a reduction in spikelet number, with values ranging between approximately 11 and 12 spikelets per plant. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Ailanthus altissima* exhibited a strong inhibitory effect on spikelet formation, indicating its negative impact on reproductive development and yield of *Oryza sativa* (Table 3).

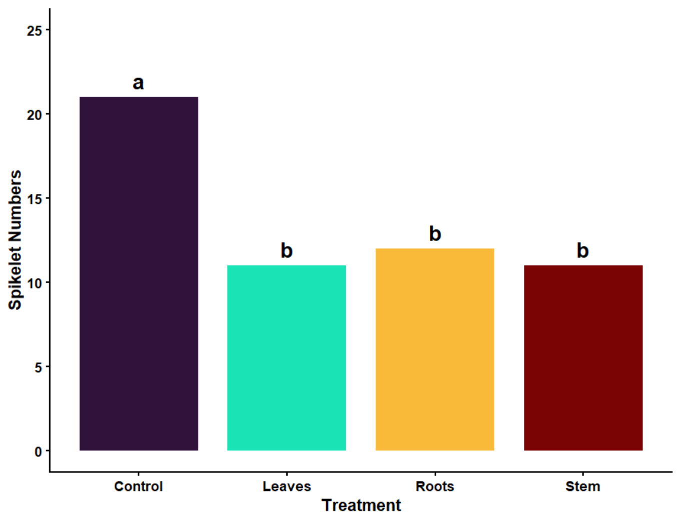

Figure 23: *Effect of different plant parts (leaves, roots, and stems) of Ailanthus altissima on the number of spikelets of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Eucalyptus lanceolatus on the number of spikelets

The number of spikelets of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Eucalyptus lanceolatus* (Figure 24). The highest number of spikelets (approximately 21) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a reduction in spikelet number, with values ranging between approximately 11 and 12 spikelets per plant. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Eucalyptus lanceolatus* exhibited a strong inhibitory effect on spikelet formation, indicating its negative impact on reproductive development and yield of *Oryza sativa*.

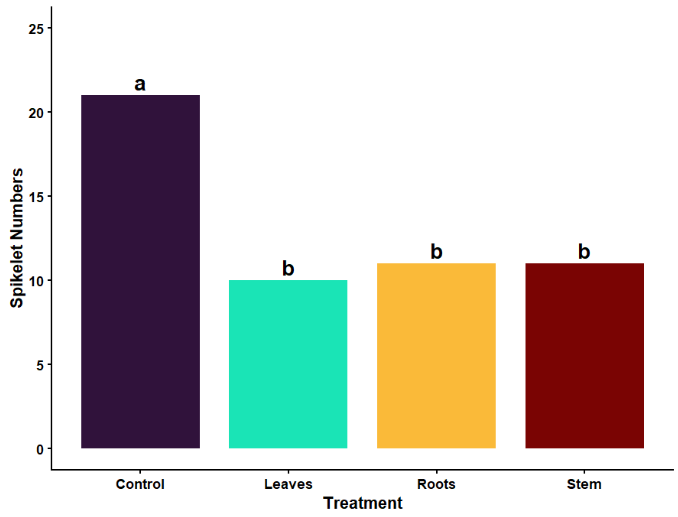

Figure 24: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on the number of spikelets of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

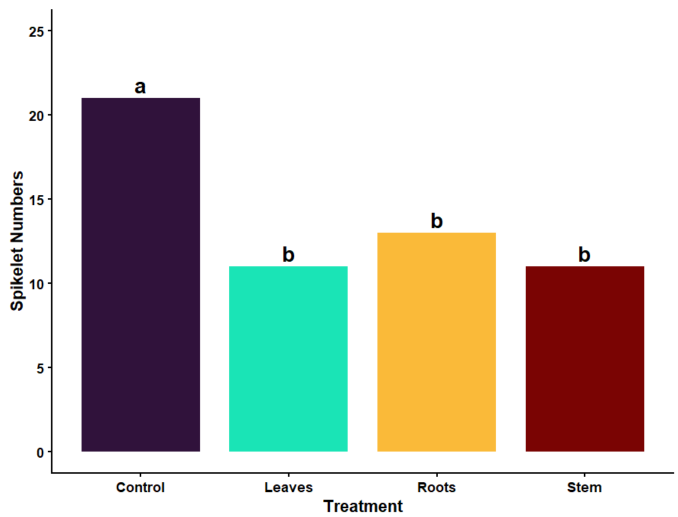

Figure 25: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on the number of spikelets of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Ficus carica on the number of spikelets

The number of spikelets of *Oryza sativa* was significantly affected (p ≤ 0.05) by different parts of *Ficus carica* (Figure 25). The highest number of spikelets (approximately 21) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a reduction in spikelet number, with values ranging between approximately 11 and 13 spikelets per plant. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Ficus carica* exhibited a strong inhibitory effect on spikelet formation, indicating its negative impact on reproductive development and yield of *Oryza sativa*.

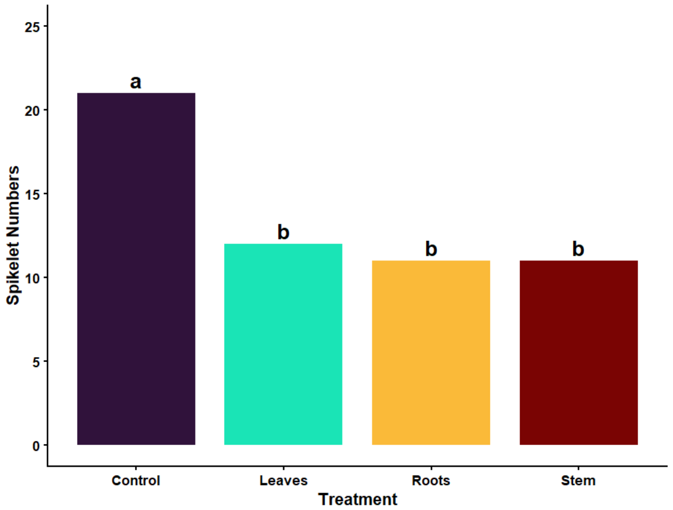

Figure 26: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on the number of spikelets of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Melia azedarach on the number of spikelets

The number of spikelets of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Melia azedarach* (Figure 26). The highest number of spikelets (approximately 21) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a reduction in spikelet number, with values ranging between approximately 11 and 12 spikelets per plant. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Melia azedarach* exhibited a strong inhibitory effect on spikelet formation, indicating its negative impact on reproductive development and yield of *Oryza sativa*.

Effect of allelopathic plants on 100-grain weight

The 100-grain weight of *Oryza sativa* was significantly affected ($p \leq 0.05$) by the selected allelopathic plant species and their respective parts (Table 4). The highest 100-grain weight (6.11 ± 0.26 g) was recorded in the control treatment.

Effect of Ailanthus altissima on 100-grain weight

The 100-grain weight of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Ailanthus altissima* (Figure 27). The highest grain weight (approximately 6.1 g) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a marked reduction in grain weight, with values ranging between approximately 3.0 and 3.3 g. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Ailanthus altissima* exhibited a strong inhibitory effect on grain weight, indicating its negative impact on grain development and overall yield of *Oryza sativa*.

Effect of Eucalyptus lanceolatus on 100-grain weight

The 100-grain weight of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Eucalyptus lanceolatus* (Figure 28). The highest grain weight (approximately 6.1 g) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in a reduction in grain weight, with values ranging betweenapproximately 2.5 and 3.3 g. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Eucalyptus lanceolatus* exhibited a strong inhibitory effect on grain weight, indicating

Table 4: *Analysis of variance for effects of allelopathic plants (leaves, stem, root) on yield-related parameters of Oryza sativa*

Effects		Grain No.		Spikelet No.		Weight of 100g	
Species	DF	F	P	F	P	F	P
Ficus carica	3	113.266	<.0001	83.2049	<.0001	31.8958	<.0001
Ailanthus altissmia	3	84.1626	<.0001	56.6116	<.0001	42.2424	<.0001
Eucalyptus lanceolatus	3	157.5609	<.0001	102.397	<.0001	40.428	<.0001

its negative impact on grain development and overall yield of *Oryza sativa*.

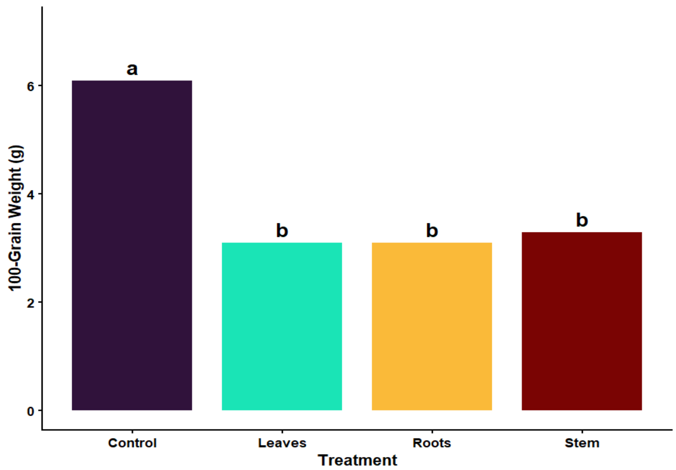

Figure 27: *Effect of different plant parts (leaves, roots, and stems) of Ailanthus altissima on 100-grain weight (g) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

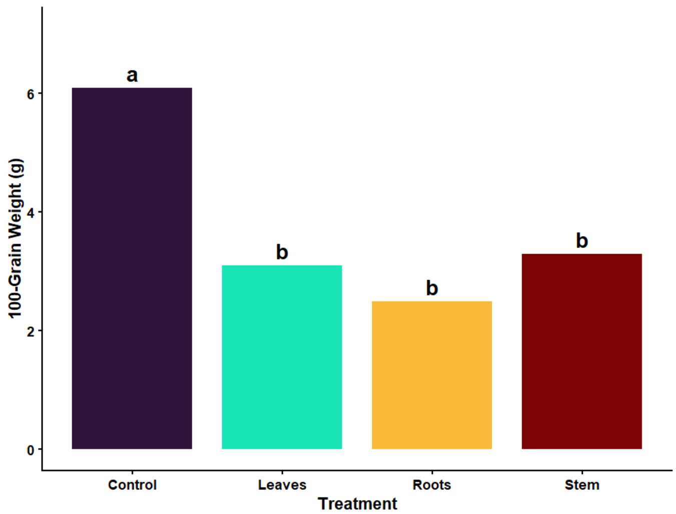

Figure 28: *Effect of different plant parts (leaves, roots, and stems) of Eucalyptus lanceolatus on 100-grain weight (g) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Ficus carica on 100-grain weight

The 100-grain weight of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Ficus carica* (Figure 29). The highest grain weight (approximately 6.1 g) was recorded in the control treatment, which was significantly greater than all allelopathic treatments. Among the treated groups, leaf, root, and stem extracts resulted in reduced grain weight, with values ranging between approximately 3.3 and 3.9 g. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Ficus carica* exhibited a strong inhibitory effect on grain weight, indicating its negative impact on grain development and overall yield of *Oryza sativa*.

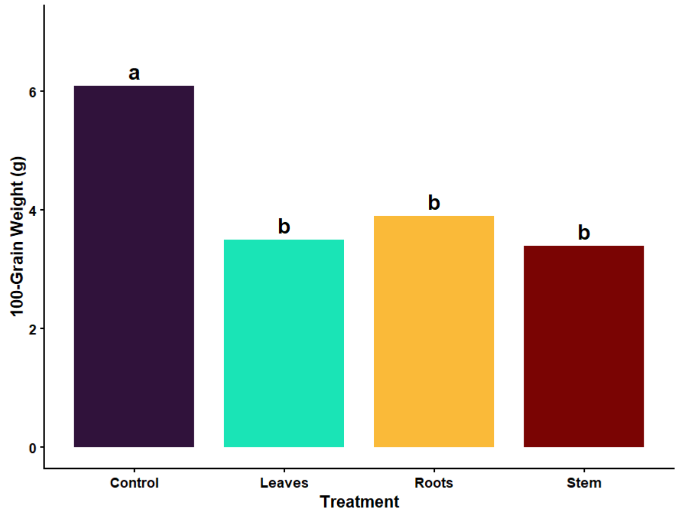

Figure 29: *Effect of different plant parts (leaves, roots, and stems) of Ficus carica on 100-grain weight (g) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

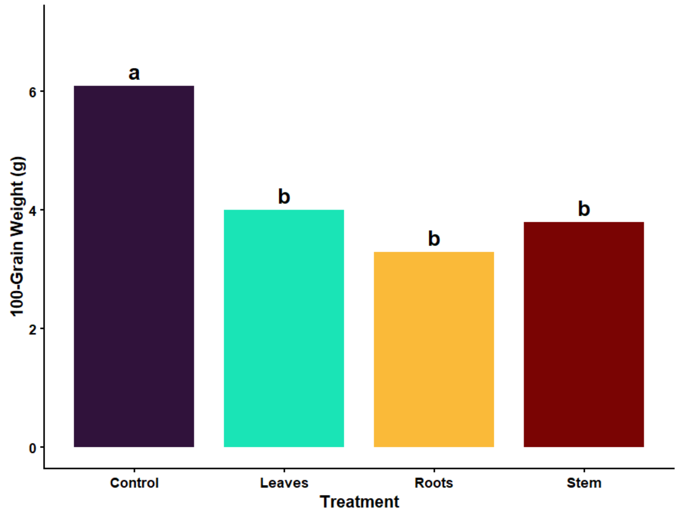

Figure 30: *Effect of different plant parts (leaves, roots, and stems) of Melia azedarach on 100-grain weight (g) of Oryza sativa. Bars represent mean values ± standard error. Different letters above bars indicate significant differences at p ≤ 0.05 based on the LSD test.*

Effect of Melia azedarach on 100-grain weight

The 100-grain weight of *Oryza sativa* was significantly affected ($p \leq 0.05$) by different parts of *Melia azedarach* (Figure 30). The highest grain weight (approximately 6.1 g) was recorded in the control treatment, which was significantly greater than all allelopathic treatments.

Links Researchers

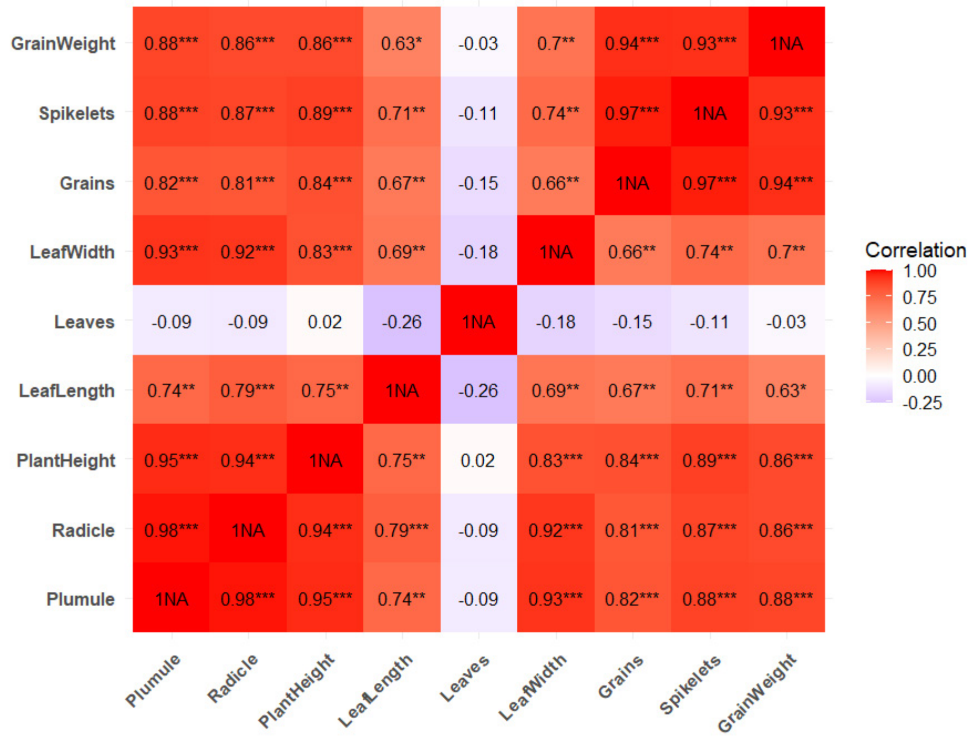

Figure 31: *Correlation matrix showing relationships among germination (radicle, plumule), growth (plant height, leaf length, leaf width, number of leaves), and yield traits (grain number, spikelet number, and 100-grain weight) of Oryza sativa. Values represent Pearson correlation coefficients, with significance levels indicated as *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.*

Among the treated groups, leaf, root, and stem extracts resulted in reduced grain weight, with values ranging between approximately 3.2 and 4.0 g. However, no significant differences were observed among these plant parts, as all treatments belonged to the same statistical group (b). Overall, *Melia azedarach* exhibited a strong inhibitory effect on grain weight, indicating its negative impact on grain development and overall yield of *Oryza sativa*.

Correlation between laboratory and greenhouse traits

Correlation analysis revealed strong and significant relationships among germination, growth, and yield traits of *Oryza sativa* under allelopathic treatments (Figure 31). Radicle length showed very strong positive correlations with plumule length (r = 0.98***), plant height (r = 0.94***), leaf width (r = 0.92***), grain number (r = 0.81***), spikelet number (r = 0.87***), and grain weight (r = 0.86***), indicating that early root development plays a crucial role in determining subsequent plant growth and yield. Similarly, plumule length was strongly correlated with plant height (r = 0.95***), leaf width (r = 0.93***), grain number (r = 0.82***), spikelet number (r = 0.88***), and grain weight (r = 0.88***), demonstrating that early shoot development is also a strong predictor of later performance. Plant height exhibited significant positive correlations with leaf length (r = 0.75***), leaf width (r = 0.83***), grain number (r = 0.84***), spikelet number (r = 0.89***), and grain weight (r = 0.86***), highlighting its importance as an integrative growth parameter. Leaf length and leaf width were also positively correlated with yield traits, including grain number, spikelet number, and grain weight, suggesting that improved vegetative growth contributes to enhanced reproductive output. In contrast, the number of leaves showed weak or negative correlations with most traits, indicating its limited contribution to overall plant performance under allelopathic stress. Overall, these results demonstrate a strong linkage between laboratory and greenhouse experiments, confirming that early germination traits (radicle and plumule growth) are reliable indicators of subsequent growth and yield performance of *Oryza sativa* under allelopathic conditions.

Principal component analysis (PCA)

Principal Component Analysis (PCA) revealed clear patterns of variation among germination, growth, and yield traits of *Oryza sativa* under allelopathic treatments (Figure 32). The first two principal components explained a substantial proportion of

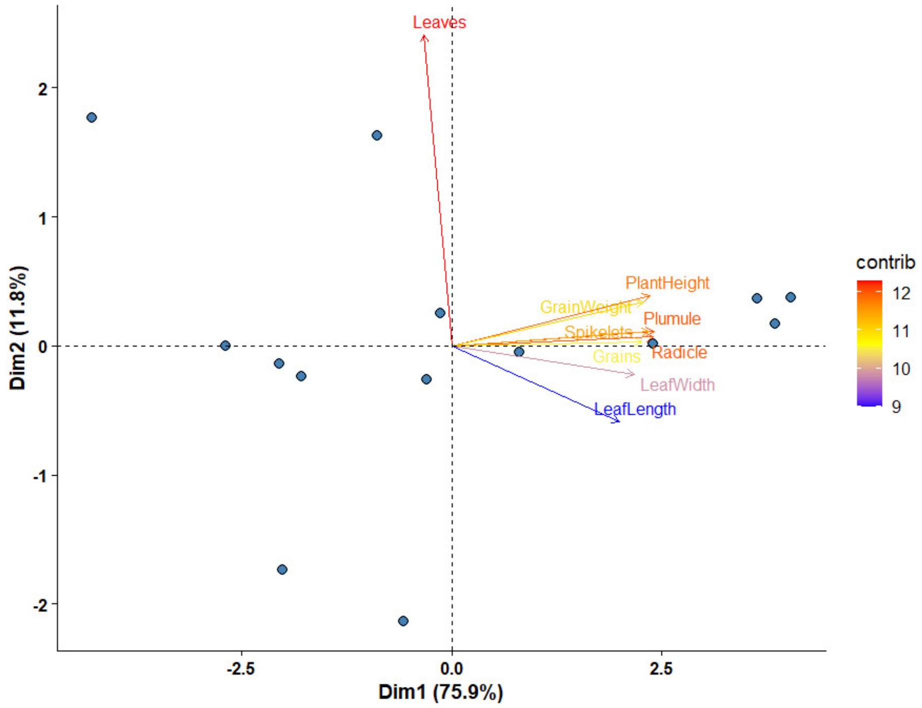

Figure 32: *Principal Component Analysis (PCA) biplot showing relationships among germination (radicle, plumule), growth (plant height, leaf length, leaf width, number of leaves), and yield traits (grain number, spikelet number, and 100-grain weight) of Oryza sativa. PC1 and PC2 explain 75.9% and 11.8% of the total variance, respectively. Arrows indicate trait loadings and their contributions to overall variation.*

total variation, with PC1 accounting for 75.9% and PC2 for 11.8%, cumulatively explaining 87.7% of the total variance. PC1 was strongly associated with most growth and yield-related traits, including plant height, radicle length, plumule length, grain number, spikelet number, grain weight, and leaf width, all of which were positively loaded along this axis. This indicates that these traits are closely interrelated and collectively represent overall plant performance and productivity.

In contrast, PC2 was primarily influenced by the number of leaves, which showed a distinct loading pattern compared to other traits, suggesting its limited contribution to overall variation and weaker association with yield parameters. The PCA biplot further demonstrated that yield traits (grain number, spikelet number, and grain weight) clustered closely with early germination traits (radicle and plumule) and plant height, confirming strong positive relationships among these variables. Conversely, leaf number was positioned separately, indicating weak or negligible correlation with other traits. Overall, the PCA results highlight that early germination traits and plant height are the most influential factors governing growth and yield of *Oryza sativa* under allelopathic stress, reinforcing the findings of the correlation analysis.

Discussion

The root, stem, and leaves of *Ficus carica*, *Ailanthus altissima*, and *Eucalyptus lanceolatus* at different concentrations (5 g, 10 g, and 15 g) showed significant allelopathic effects on radicle and plumule growth of *Oryza sativa*. Among the tested species, *Melia azedarach* exhibited the strongest allelopathic effect, whereas comparatively lower inhibitory effects were observed in *Ficus carica* and *Ailanthus altissima* (Wan *et al*., 2010). The inhibitory effects increased with increasing concentration of plant extracts, indicating a clear dose-dependent response (Wan *et al*., 2010). The strong inhibitory effect of *Melia azedarach* may be attributed to the presence of potent allelochemicals such as limonoids, phenolics, and terpenoids, which are known to suppress seed germination and seedling growth by interfering with physiological and biochemical processes, including enzyme activity, nutrient uptake, and cell division (Jhariya *et al*., 2022). In contrast, the comparatively lower effects observed in *Ficus carica* and *Ailanthus altissima* may reflect lower concentrations or different compositions of allelochemicals in their tissues (Saifullah *et al*., 2025). The present results are in line with the findings of (Saifullah *et al*., 2025), who reported that *Silene villosa* exhibited significant allelopathic effects against wheat, with increased concentrations reducing germination percentage, radicle and plumule length, and biomass accumulation. Similarly, (Shakir *et al*., 2023b) demonstrated that aqueous extracts of different parts of *Cardaria draba* significantly inhibited seed germination and seedling growth of wheat compared to the control (Asif *et al*., 2025). These studies support the present findings that allelopathic effects are concentration-dependent and vary among plant species and plant parts (Saifullah *et al*., 2025). The variation in allelopathic effects among different plant parts (root, stem, and leaves) observed in this study may be due to differences in the type and concentration of allelochemicals present in each tissue (Khan *et al*., 2025). Leaves generally contain higher concentrations of water-soluble phenolic compounds, while roots may release allelochemicals directly into the soil environment, influencing neighboring plants. This differential distribution of bioactive compounds explains the variation in inhibitory effects among plant parts, with some parts showing stronger suppression than others (Khan *et al*., 2024). The present study revealed that plant height, number of leaves, leaf length and width, grain number, spikelet number, and 100-grain weight were reduced when *Oryza sativa* was exposed to powders of allelopathic plant parts (Ullah *et al*., 2025c). Among the tested species, leaf powder of *Ficus carica*, *Ailanthus altissima*, and *Eucalyptus lanceolatus* generally exhibited strong inhibitory effects on plant height, although the effect of *Eucalyptus lanceolatus* leaves on plant height was comparatively less pronounced and, in some cases, non-significant (Subhan *et al*., 2025). The stem powder of *Ficus carica* and *Ailanthus altissima* also reduced plant height, whereas *Eucalyptus lanceolatus* stem powder showed a reduction that was not always statistically significant (Erida *et al*., 2023). In contrast, the root powder of *Melia azedarach* caused a significant decrease in plant height, indicating its strong allelopathic potential, while roots of other species showed relatively weaker effects (Khatri *et al*., 2020).

These variations in allelopathic responses among plant parts and species may be attributed to differences in the concentration and composition of allelochemicals, such as phenolics, flavonoids, and terpenoids, which are known to inhibit plant growth by interfering with physiological processes such as cell division, nutrient uptake, and hormonal regulation (Khan *et al*., 2024). The present findings are supported by (Poudel *et al*., 2019), who reported that aqueous extracts of *Cassia tora* (seed, root, and leaves) significantly inhibited growth parameters of *Brassica campestris*, with leaf extracts showing stronger inhibitory effects compared to other plant parts. Similarly, leaf powder of *Eucalyptus lanceolatus* exhibited a strong allelopathic effect on leaf length and leaf width of *Oryza sativa*, whereas *Ficus carica* and *Ailanthus altissima* leaves showed comparatively weaker effects (Wang *et al*., 2011). The stem powder of *Ailanthus altissima* and *Eucalyptus lanceolatus* significantly reduced leaf length and width, while *Ficus carica* stem powder showed relatively less inhibition. Root powder of *Eucalyptus lanceolatus* also decreased leaf length and width, whereas roots of *Ficus carica* and *Ailanthus altissima* had comparatively minor effects (Niu *et al*., 2007). These differences further support the idea that allelochemical concentration and mobility vary among plant tissues (Javaid *et al*., 2006). These results are in agreement with previous studies. According to Xuan *et al*. (2005), extracts of *Ficus carica* leaves and bark significantly inhibited germination and growth of *Triticum aestivum*, *Zea mays*, *Lactuca sativa*, and *Trifolium repens*. Similarly, Aleem et al. (2014) reported comparable inhibitory effects on germination and growth of cowpea, confirming that allelopathic effects are widespread across plant species and can significantly affect crop performance (Khan *et al*., 2024). Overall, the findings demonstrate that allelopathic plant parts, particularly leaves and roots, can significantly suppress vegetative growth and yield-related traits of *Oryza sativa*, with effects varying among species and plant parts (Xuan *et al*., 2004). The leaves of *Ficus carica* strongly reduced the number of grains compared to other allelopathic tree species, indicating its higher inhibitory potential on yield formation. In contrast, the stems of *Ficus carica* and *Ailanthus altissima* showed comparatively weaker effects on grain number (Quayyum *et al*., 2000). The roots of *Eucalyptus lanceolatus* significantly reduced grain number, highlighting the strong allelopathic influence of below-ground plant parts (Batish et al., 2002b; Ullah *et al*., 2025c).

Similarly, leaf powders of *Ficus carica*, *Ailanthus altissima*, and *Eucalyptus lanceolatus* significantly affected the number of spikelets, while stem powders of these species also reduced spikelet formation (Batish et al., 2002a). Notably, the root powder of *Eucalyptus* *lanceolatus* exhibited the strongest inhibitory effect on spikelet number (Batish *et al*., 2002a; Ullah *et al*., 2025b). These results indicate that allelopathic effects extend beyond early growth stages and significantly influence reproductive traits, ultimately affecting crop yield (Ullah *et al*., 2025a). These findings are consistent with (Kohli *et al*., 1997), who reported that the accumulation and release of phytotoxins from *Parthenium hysterophorus* significantly reduced crop productivity. All parts of *Parthenium hysterophorus* were found to be toxic to crop plants, supporting the present observation that allelopathic effects are widespread across plant tissues and can severely impact yield components (Khatri *et al*., 2020; Shakir *et al*., 2023a). In terms of grain weight, leaf powders of *Ailanthus altissima*, *Eucalyptus lanceolatus*, and *Morus alba* significantly reduced 100-grain weight, whereas *Melia azedarach* and *Ficus carica* leaves showed comparatively lower effects (Subhan *et al*., 2025). This variation further suggests that the type and concentration of allelochemicals differ among plant species and plant parts, influencing their inhibitory strength (Erida *et al*., 2023; Shakir *et al*., 2023b).

Correlation analysis revealed strong positive relationships among germination, growth, and yield traits. Radicle length was strongly correlated with plumule length, plant height, leaf length, number of leaves, and leaf width, indicating that early root development plays a crucial role in determining subsequent plant growth (Batish *et al*., 2002a). Radicle length also showed strong correlations with grain number, spikelet number, and 100-grain weight, highlighting its importance as a predictor of final yield (Khan *et al*., 2018a; Khan *et al*., 2025). Similarly, plumule length was strongly correlated with plant height and leaf width, while showing non-significant relationships with leaf length and number of leaves (Sajid *et al*., 2023). Plumule length also exhibited positive correlations with grain number, spikelet number, and grain weight, suggesting that early shoot development contributes to improved reproductive performance (Subhan *et al*., 2025). Plant height was significantly correlated with grain number, spikelet number, leaf length, and leaf width, further confirming its role as an integrative indicator of plant performance under allelopathic stress (Niu *et al*., 2007; Ullah *et al*., 2025b). Additionally, grain number was positively correlated with leaf width, spikelet number, and 100-grain weight, demonstrating the interconnected nature of yield components. The observed reduction in morphological traits, radicle length, and plumule length indicates that allelopathic plants release harmful allelochemicals that inhibit growth and development of *Oryza sativa* (Javaid *et al*., 2006; Erida *et al*., 2023). These allelochemicals likely interfere with physiological processes such as cell division, nutrient uptake, and hormonal balance, ultimately leading to reduced plant performance and yield (Xuan *et al*., 2005). These findings are supported by Xuan *et al*. (2004), who reported significant positive correlations between seed germination, radicle length, and plumule length, reinforcing the importance of early growth traits in determining overall plant performance. These findings have practical implications for agricultural management, as the presence of allelopathic tree species near rice fields should be carefully controlled (Quayyum *et al*., 2000; Khatri *et al*., 2020). Removal or proper management of leaf litter and plant residues of highly allelopathic species such as *Melia azedarach* and *Eucalyptus lanceolatus* may help to reduce their negative effects on crop growth and improve rice productivity (Wang *et al*., 2011; Poudel *et al*., 2019)

Conclusions

The present study demonstrated that allelopathic tree species significantly influence the germination, growth, and yield-related traits of *Oryza sativa*. The application of leaf, stem, and root powders of *Ficus carica*, *Ailanthus altissima*, *Eucalyptus lanceolatus*, and *Melia azedarach* resulted in a reduction of radicle and plumule growth, plant height, leaf length and width, grain number, spikelet number, and 100-grain weight. Among the tested species, *Melia azedarach* exhibited the strongest allelopathic effects, while *Ficus carica* and *Ailanthus altissima* showed comparatively moderate effects. The inhibitory effects were concentration-dependent and varied among plant parts, indicating differences in the type and concentration of allelochemicals present in each species. Correlation and PCA analyses further confirmed that early germination traits are strongly associated with subsequent plant growth and yield performance, highlighting the importance of early-stage development in determining crop productivity under allelopathic stress. These findings emphasize the ecological and agricultural significance of allelopathy in rice-based systems. From a practical perspective, the presence of allelopathic tree species near rice fields should be carefully managed. The removal or controlled management of plant residues, particularly from highly allelopathic species such as *Melia azedarach* and *Eucalyptus lanceolatus*, may help to minimize their negative effects and improve crop yield. Overall, this study provides valuable insights into plant–plant interactions and highlights the importance of considering allelopathic effects in sustainable crop management. Future research should focus on the identification of specific allelochemicals and their mechanisms of action under different environmental conditions to further enhance understanding and practical application.

Recommendations

Farmers should avoid planting highly allelopathic tree species such as *Melia azedarach* and *Eucalyptus lanceolatus* near rice fields, as they can significantly reduce crop growth and yield.

Leaf litter, root residues, and other plant materials of allelopathic species should be regularly removed or properly managed to minimize their inhibitory effects on *Oryza sativa*.

Since allelopathic effects are concentration-dependent, careful management of plant biomass and residues is necessary to prevent the accumulation of harmful allelochemicals in agricultural soils.

Future research should focus on the identification and characterization of specific allelochemicals responsible for inhibitory effects, which may help in developing eco-friendly weed management strategies.

Additional long-term field experiments under different environmental conditions and soil types are recommended to better understand the practical implications of allelopathy in rice-based cropping systems.

Novelty Statement

This study provides a comprehensive evaluation of the allelopathic effects of multiple tree species (*Ficus carica*, *Ailanthus altissima*, *Eucalyptus lanceolatus*, and *Melia azedarach*) on both early germination traits and later growth and yield parameters of *Oryza sativa*. Unlike previous studies that focus primarily on germination or single-species effects, this research integrates laboratory and field experiments to establish a clear linkage between early seedling responses and final crop productivity. Furthermore, the combined use of correlation analysis and Principal Component Analysis (PCA) offers new insights into the relationships among germination, growth, and yield traits under allelopathic stress. The identification of species-specific and plant part–specific inhibitory effects, particularly the strong impact of *Melia azedarach*, provides novel contributions to understanding plant–plant interactions and offers practical implications for sustainable rice cultivation.

Practical Applications

The results indicate that highly allelopathic species such as *Melia azedarach* and *Eucalyptus lanceolatus* can negatively affect rice growth and yield. Therefore, their presence near rice fields should be managed, and plant residues should be removed or controlled to reduce allelochemical accumulation. These findings may also support the development of eco-friendly weed management strategies.

Limitations

This study did not identify specific allelochemicals responsible for the observed effects, and experiments were conducted under controlled conditions. Further studies under natural field conditions are needed to better understand allelopathic interactions and their practical implications.

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Author's Contributions

Basit Ali: Conceived and designed the study and performed the experiments.
Tariq Aziz: Contributed to data analysis and interpretation.
Nazli Rahid: assisted in experimental work and literature review.
Rahid Khan was involved in data collection and fieldwork.
Abdul Basit: Performed statistical analysis and

prepared the figures.
Shakir Ullah: Supervised the study, provided critical revisions, and approved the final manuscript.
All authors read and approved the final version of the manuscript.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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References

Arnon, D.I. 1949. Copper enzymes in isolated chloroplasts: polyphenoloxidase in *Beta vulgaris*. Plant Physiol., 24(1): 1–15. https://doi.org/10.1104/pp.24.1.1

Aleem, A., A. Malik, M. Zubair, and S. Khan. 2014. Allelopathic effects of plant extracts on germination and seedling growth of wheat (*Triticum aestivum* L.). Pak. J. Bot., 46(6): 2113–2118.

Asif, S., M. Nisar, S. Ullah, and M. Naeem. 2025. Impact of seed-borne mycoflora on mycotoxin accumulation: a threat to lentil genetic resources. Toxicon., Article 108290. https://doi.org/10.1016/j.toxicon.2025.108290

Batish, D.R., H.P. Singh, R.K. Kohli, S. Kaur, D.B. Saxena, and S. Yadav. 2007. Assessment of phytotoxicity of parthenin. Z. Naturforsch. C., 62(5–6): 367–372. https://doi.org/10.1515/znc-2007-5-609

Batish, D.R., H.P. Singh, J.K. Pandher, V. Arora, and R.K. Kohli. 2002a. Phytotoxic effect of *Parthenium* residues on the growth of radish and chickpea and selected soil properties. Weed Biol. Manag., 2(2): 73–78. https://doi.org/10.1046/j.1445-6664.2002.00050.x

Batish, D.R., P. Tung, H.P. Singh, and H.P. Kohli. 2002b. Phytotoxicity of sunflower residues against some summer season crops. J. Agron. Crop Sci., 188(1): 19–24. https://doi.org/10.1046/j.1439-037x.2002.00526.x

Erida, G., C.N. Ichsan, Syamsuddin, T. Kurniawan, I.H. Khan, and A. Javaid. 2023. Potential of secondary metabolites of *Ageratum conyzoides* L. in weed management: a review. Allelopathy J., 58(1): 23–40. https://doi.org/10.26651/allelo.j/2023-58-1-1417

Fabbro, C.D., S. Gusewell, and D. Prati. 2014. Allelopathic effects of three plant invaders on germination of native species: a field study. Biol. Invas., 16(5): 1035–1042. https://doi.org/10.1007/s10530-013-0555-3

Gulzar, A. and M.B. Siddiqui. 2013. Evaluation of allelopathic impact of *Terminalia arjuna* (Roxb.) Wight & Arn bark against *Cassia sophera*. Afr. J. Agric. Res., 8(39): 4937–4940.

Hiscox, J.D. and G.F. Israelstam. 1979. A method for the extraction of chlorophyll from leaf tissue without maceration. Can. J. Bot., 57(12): 1332–1334. https://doi.org/10.1139/b79-163

Hussain, M.I. and M.J. Reigosa. 2011. Allelochemical stress inhibits growth, leaf water relations, PSII photochemistry, non-photochemical fluorescence quenching, and heat energy dissipation in three C3 perennial species. J. Exp. Bot., 62(13): 4533–4545. https://doi.org/10.1093/jxb/err161

Ismail, B.S. and A. Kumar. 1996. Effects of aqueous extracts and residue decomposition of *Mikania micrantha* HBK on selected crops. Allelopathy J., 3(2): 195–206.

Javaid, A., S. Shafique, and S. Shafique. 2006. *Parthenium* weed—an emerging threat to plant biodiversity in Pakistan. Int. J. Biol. Biotechnol., 3(3): 619–622.

Jhariya, M.K. and D.K. Yadav. 2017. Invasive alien varieties: challenges, threats and management. In: Rawat, S.K. and Narain, S. (eds.), Agriculture technology for sustaining rural growth. Biotech Books, New Delhi, pp. 263–285.

Jhariya, M.K., A. Banerjee, A. Raj, R.S. Meena, N. Khan, S. Kumar, and S.S. Bargali. 2022. Variety invasion and ecological risk. In: Natural resources conservation and advances for sustainability. Elsevier, pp. 503–531. https://doi.org/10.1016/978-0-12-822976-7.00014-4

Khan, M., M. Haris, M.R. Khan, I. Ali, N. Nasreen, M. Sohail, and S. Ullah. 2024. Acaricidal efficacy of *Melia azedarach*, *Olea ferruginea*, and *Zanthoxylum armatum* against *Rhipicephalus microplus* from Khyber Pakhtunkhwa, Pakistan. Adv. J. Sci. Eng. Technol., 3(1): 99–114. https://doi.org/10.47264/idea.ajset/3.1.7

Khan, N., M.K. Jhariya, and D.K. Yadav. 2019. Invasion and impact of non-native varieties on indigenous flora in an urban ecosystem of India: a case study. Int. J. Ecol. Dev., 34: 103–118.

Khan, R., N. Rahid, W. Khan, N. Shah, L. Shakir, H.A. Ghafoor, and S. Ullah. 2025. Mitigation of salinity stress in maize (*Zea mays* L.) using the endophytic fungus GR7. Pak. J. Weed Sci. Res., 31(2): 151–166.

Khan, S., G. Jan, H. Bibi, J. Sher, S. Ullah, and S. Abidullah. 2018a. Phytochemical screening and antimicrobial activity of *Cichorium intybus* (Asteraceae) and *Medicago sativa* (Fabaceae), Peshawar, Pakistan. J. Pharmacogn. Phytochem., 7(3): 603–616.

Khan, S., G. Jan, H. Bibi, K. Ullah, and S. Ullah. 2018b. Plants traditional medication in the arid and semi-arid zone of Tehsil Domal, District Bannu, Khyber Pakhtunkhwa, Pakistan. J. Appl. Environ. Biol. Sci., 8(8): 14–21.

Khan, S., G. Jan, H. Bibi, K. Ullah, and S. Ullah. 2018c. Antimicrobial, phytochemical, and traditional studies of selected medicinal plants in Bajaur Agency, Pakistan. Int. J. Res. Pharm. Sci., 8(2): 4–21.

Khan, M.A., R.A. Afridi, S. Hashim, A.M. Khattak, Z. Ahmad, F. Wahid, and B.S. Chauhan. 2016. Integrated effect of allelochemicals and herbicides on weed suppression and soil microbial activity in wheat (*Triticum aestivum* L.). Crop Prot., 90: 34–39.

Khatri, K., K. Bargali, B. Negi, and S.S. Bargali. 2020. Germination and early seedling growth of two rice varieties as affected by invasive *Ageratina adenophora*. Curr. Agric. Res. J., 8: 108–117. https://doi.org/10.12944/CARJ.8.2.06

Kohli, R.K. and D. Rani. 1994. *Parthenium hysterophorus*—a review. Res. Bull. Panjab Univ. Sci., 44(1–4): 105–119.

Kohli, R.K., D.R. Batish, and H.P. Singh. 1997. Allelopathy and its implications in agroecosystems. J. Crop Prod., 1(1): 169–202. https://doi.org/10.1300/J144v01n01_08

Malik, R.N. and S.Z. Husain. 2007. *Broussonetia papyrifera* (L.) L'Hér. ex Vent.: an environmental constraint on the Himalayan foothills vegetation. Pak. J. Bot., 39(4): 1045–1053.

Manan, F., I. Ahmad, F. Asad, L. Shakir, and S. Ullah. 2025. Pharmacognosy, phytochemistry, and antimicrobial potential of Pteris cretica L. collected from Dir (Lower), Khyber Pakhtunkhwa. Pak. J. Weed Sci. Res., 31(2).

Mann, J. 1987. *Secondary metabolism*. 2nd ed. Clarendon Press, Oxford.

Mizutani, J. 1999. Selected allelochemicals. *Crit. Rev. Plant Sci.*, 18(5): 653–671. https://doi.org/10.1080/07352689991309432

Morghan, E.C. and Overholt. 2004. Wildland weeds: paper mulberry, *Broussonetia papyrifera*. ENY-702. Entomology and Nematology, Florida Cooperative Extension Service, University of Florida IFAS.

Nie, X., S. Lv, Y. Zhang, X. Du, L. Wang, S.S. Biradar, X. Tan, F. Wan, and S. Weining, 2012. Complete chloroplast genome sequence of a major invasive plant, crofton weed (*Ageratina adenophora*). PLoS ONE, 7: e36869. https://doi.org/10.1371/journal.pone.0036869

Niu, H., W. Liu, F. Wan, and B. Liu. 2007. An invasive aster (*Ageratina adenophora*) invades and dominates forest understories in China: altered soil microbial communities facilitate the invader and inhibit natives. Plant Soil, 294: 73–85. https://doi.org/10.1007/s11104-007-9230-8

Poudel, A.S., P.K. Jha, B.B. Shrestha, and R. Muniappan. 2019. Biology and management of the invasive weed *Ageratina adenophora* (Asteraceae): current state of knowledge and future research needs. Weed Res., 59: 79–92. https://doi.org/10.1111/wre.12351

Quayyum, H.A., A.U. Mallik, D.M. Leach, and C. Gottardo. 2000. Growth inhibitory effects of nutgrass (*Cyperus rotundus*) on rice (*Oryza sativa*) seedlings. J. Chem. Ecol., 26(9): 2221–2231. https://doi.org/10.1023/A:1005532802836

Rani, D. and R.K. Kohli. 1991. Fresh matter is not an appropriate relation unit for chlorophyll content: experience from experiments on effects of herbicide and allelopathic substances. Photosynthet., 25(4): 655–658.

Rice, E.L. 1984. *Allelopathy*. Academic Press, Orlando, FL, USA.

Saifullah, M., N. Dilawar, A. Rahman, A. Ahmad, M. Usman, S. Ullah, and M. Nawaz. 2025. Role of rhizofungus (*Aspergillus terreus*) in improving biochemical and physiological parameters affected by lead stress in *Allium*. SSRN, Article 5737248. https://doi.org/10.2139/ssrn.5737248

Sajid, M., F. Rahim, S. Ullah, R. Ullah, R. Bilqees, and L. Shakir. 2023. Qualitative and quantitative ethnobotanical study of Arrang Valley, District Bajaur, Khyber Pakhtunkhwa, Pakistan. J. Agric. For. Res., 2(3).

Shakir, L., S. Asif, A. Haq, S. Haq, K. Zada, M. Said, M. Sajid, S. Ullah, and R. Ullah. 2023a. Phytochemical detection and medicinal studies of selected plants from war-affected areas of Khyber Pakhtunkhwa, Pakistan. J. Agric. For. Res., 2(5).

Shakir, L., S. Ullah, M. Suhail, and R. Ullah. 2023b. Phytochemical analysis, antipyretic and antifungal activities of *Solanum nigrum* L. Nat. J. Pharm. Sci., 3(2): 6–12.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: A biometrical approach, 2nd ed. McGraw-Hill Book Co., New York.

Singh, B., K.R. Reddy, E.D. Redona, and T. Walker. 2017. Developing a screening tool for osmotic stress tolerance classification of rice cultivars based on in vitro seed germination. Crop Sci., 57: 387–394. https://doi.org/10.2135/cropsci2016.03.0196

Stachon, W.J. and R.L. Zimdahl. 1980. Allelopathic activity of Canada thistle (*Cirsium arvense*) in Colorado. Weed Sci., 28(1): 83–86. https://doi.org/10.1017/S004317450002782X

Subhan, G., L. Shakir, S. Habib, U. Hassan, A. Begum, S. Rahman, M. Sohail, Falaknaz, W. Hayat Khan, R. Khan, N. Dilawar, and S. Ullah. 2025. Influence of extracts from *Euphorbia helioscopia* L. and *Oxalis corniculata* L. on the germination and seedling development of *Triticum aestivum* L. Asian J. Agric. Allied Sci., 8(1): 343–364. https://doi.org/10.56557/ajaas/2025/v8i177

Swain, D., S. Paroha, M. Singh, and H.N. Subudhi. 2012. Evaluation of allelopathic effect of *Echinochloa colona* on rice (*Oryza sativa* L. 'Vandana'). J. Environ. Biol., 33: 881–889.

Swain, T. and W.E. Hillis. 1959. The phenolic constituents of *Prunus domestica*. I. The quantitative analysis of phenolic constituents. J. Sci. Food Agric., 10(1): 63–68. https://doi.org/10.1002/jsfa.2740100110

Ullah, S., L. Shakir, M. Sajid, and R. Ullah. 2023b. Pathogenicity and survey of root rot disease of cotton in different villages of Dir Upper and Dir Lower, Khyber Pakhtunkhwa, Pakistan. J. Agric. For. Res., 2(5): 74–81.

Ullah, S., L. Shakir, M. Sohail, F. Falaknaz, S. Ali, G. Subhan, and N. Dilawar. 2025a. *Anagallis arvensis* as a natural allelopathic agent: effects on growth of *Zea mays*, *Triticum aestivum*, and *Pennisetum glaucum*. Int. J. Food Agric. Nat. Resour., 6(4): 102–112. https://doi.org/10.46676/ij-fanres.v6i4.558

Ullah, S., L. Shakir, M. Sohail, I. Hussain, and G. Subhan. 2025c. Integrated use of biofertilizers and zinc sulphate for enhanced growth and productivity of wheat (*Triticum aestivum* L.). SSRN, Article 5737282. https://doi.org/10.2139/ssrn.5737282

Ullah, S., L. Shakir, M. Sohail, I. Hussain, F. Naz, A. Noreen, and N. Dilawar. 2025b. Performance evaluation of different varieties of *Mirabilis jalapa* L. under agro-climatic conditions at Ghazi Umara Khan Degree College, Samarbagh. J. Plant Health Ecol. Evol., 1(1): 28–38.

Ullah, S., L. Shakir, M. Sohail, A. Noreen, and L. Aziz. 2025a. Controlling of cotton leaf worm in *Solanum nigrum* L. at District Swat (Switzerland of Pakistan) under semi-field conditions. Pak. J. Weed Sci. Res., 31(1).

Ullah, S., L. Shakir, G. Subhan, and M. Sohail. 2023a. Different soybean varieties are affected by irrigation in Mardan, Khyber Pakhtunkhwa, Pakistan. Pak. J. Weed Sci. Res., 29(4): 229.

Vitousek, P.M. and L.R. Walker. 1989. Biological invasion by *Myrica faya* in Hawai'i: plant demography, nitrogen fixation, and ecosystem effects. Ecol. Monogr., 59: 247–265. https://doi.org/10.2307/1942601

Wan, F., W. Liu, J. Guo, S. Qiang, B. Li, J. Wang, G. Yang, H. Niu, F. Gui, W. Huang, Z. Jiang, and W. Wang. 2010. Invasive mechanism and control strategy of *Ageratina adenophora* (Sprengel). Sci. China Life Sci., 53: 1291–1298 https://doi.org/10.1007/s11427-010-4080-7.

Wang, R. and Y.Z. Wang. 2006. Invasion dynamics and potential spread of the invasive alien plant *Ageratina adenophora* (Asteraceae) in China. Divers. Distrib., 12: 397–408. https://doi.org/10.1111/j.1366-9516.2006.00250.x

Wang, R., J.F. Wang, Z.J. Qiu, B. Meng, F.H. Wan, and Y.Z. Wang. 2011. Multiple mechanisms underlie rapid expansion of an invasive alien plant. New Phytol., 191: 828–839. https://doi.org/10.1111/j.1469-8137.2011.03720.x

Xuan, T.D., T. Shinkichi, N.H. Hong, T.D. Khanh, and C.L. Min. 2004. Assessment of phytotoxic action of *Ageratum conyzoides* L. on weeds. Crop Prot., 23(10): 915–922. https://doi.org/10.1016/j.cropro.2004.02.005

Xuan, T.D., S. Tawata, T.D. Khanh, and I.M. Chung. 2005. Decomposition of allelopathic plants in soil. J. Agron. Crop Sci., 191(3): 162–171. https://doi.org/10.1111/j.1439-037X.2005.00170.x

Yang, G.Q. 2006. Physiological effects of allelochemicals from leachates of *Ageratina adenophora* (Spreng.) on rice seedlings. Allelopathy J., 18: 237–246.