

# Allelopathic Potential of Selected Invasive Alien Weed Species and Mathematical Modelling of Rhizospheric Soil Impact of *Ageratum conyzoides* on *Phaseolus vulgaris* L.

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## Abstract

Terrestrial invasive alien weed plants are known to infest cultivated land, potentially releasing allelochemicals into the rhizosphere during decomposition, negatively impacting crop growth. This study aimed to evaluate: (1) the allelopathic activity of five invasive weed species (*Ageratum conyzoides*, *Bidens pilosa*, *Cecropia peltata*, *Tithonia diversifolia*, and *Chromolaena odorata*) on *Lactuca sativa* and *Phaseolus vulgaris* growth; and (2) the effects of *A. conyzoides* rhizospheric soil on *P. vulgaris* seed germination. Bioassays of aqueous and leachate extracts were prepared from fresh leaves of the invasive species at concentrations of 0%, 25%, 50%, 75%, and 100% to assess allelopathic effects on *L. sativa* and *P. vulgaris* seed germination. Additionally, rhizospheric soil from *A. conyzoides* stands was collected, processed, and applied at varied weights (0.5 - 7 kg) to *P. vulgaris* seeds, with germination observed over nine days. Polynomial regression analysis was applied to model the data. High-concentration extracts (75% and 100%) significantly inhibited germination, root, and shoot growth in both *L. sativa* and *P. vulgaris* ( $P < 0.05$ ), while lower concentrations (25% and 50%) showed either stimulatory or minimal inhibitory effects. An eighth-degree polynomial model best fits the data, providing predictive insights into allelochemical effects, represented by the equation:  $y = 100.01397 - 28.933788x + 74.985596x^2 - 80.294922x^3 + 41.541115x^4 - 11.747532x^5 + 1.8501702x^6 - 0.1519795x^7 + 0.0050631x^8$ . Allelopathic effects were concentration-dependent, with roots more sensitive than shoots to the invasive extracts. *L. sativa* was the most susceptible, while *P. vulgaris* showed greater tolerance. Modelling the allelopathic impact of *A.*

*conyzoides* rhizospheric soil offers valuable insight into the allelochemical dosage necessary to affect seed germination, informing potential agricultural management strategies for invasive plant control.

## Keywords

Allelopathy, Aqueous Extract, Leachates, Modelling, Rhizospheric Soil

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## 1. Introduction

Plant communities and their diversity are widely influenced and threatened by invasive alien plants [1]. Invasive alien species are now among the top drivers of environmental change globally [2]. Introducing invasive alien species in an environment affects the ecosystem conditions. It leads to competition with native species [3] causing economic losses and habitat degradation making the ecosystem hostile to native species and increasing the rate of biodiversity loss [4]. The estimated damage from invasive alien species worldwide is more than US \$1.4 trillion annually with impacts across a wide range of sectors including agriculture, forestry, aquaculture, transportation, trade, power generation and recreation [5].

Dramatic consequences have been reported from island ecosystems where endemic species have suffered severely from invasive alien species responsible for half to two-thirds of all species extinctions [6]. However, wetlands (marshes, lakes, rivers) and estuary ecosystems worldwide are among the most affected by introduced species [7]. Invasive alien species can be humanly or naturally introduced and upon introduction, their dispersal and establishment on a local scale depend on resource availability and human activities. David *et al.* [8] state that invasive species generally have a large range of tolerance compared to native species, providing a wide range of suitable habitats to the invaders. According to [9], invasive alien species dominate native species when fighting for growth resources (water, temperature, light, soil nutrients) due to their high regeneration capacity and allelochemical potential. They produce several allelochemicals that not only eradicate native flora but also cause serious health hazards in livestock and humans [10].

Allelochemicals have different chemical structures, different concentrations depending on seasonal changes in both biotic and abiotic environmental conditions and different locations in plant tissues between plant species [11]. They can act directly on plants by inhibiting germination, and seedling growth and disrupting the development of a stable population or indirectly by influencing physiological processes in native plants and affecting soil organisms [12]. Some plant species may possess allelopathic potentials and their interactions are an important factor in determining species distribution and abundance within plant communities [13]. The allelochemical interactions and their effects on plants are important aspects to be considered in crop production and biodiversity conservation.

Agroecosystems are greatly affected by weeds which compete with crop plants

for resources, interfere in crop handling, reduce crop yield, deteriorate their quality and thus result in huge financial losses [14]. Therefore, an assessment of the allelopathic potential of selected dominant alien invasive species in the Mount Cameroon Region and their effects on native plant species is of vital importance because of the damage it may cause on crops and native plant. However, *A. conyzoides* one of the invasive species, has been reported to release allelochemicals capable of influencing weed populations, native plant growth, and even soil pathogens, potentially affecting crop productivity and ecosystem stability [15] [16]. The presence of allelochemicals from *A. conyzoides*, once enter the soil are dispatched into plants and could probably influence weeds, growth of native plants and diseases [15] [17]. It is, therefore, also necessary to study the effect of the allelopathic effect of rhizospheric soil of *Ageratum conyzoides* on *Phaseolus vulgaris* seed germination. This study therefore aimed at assessing the allelopathic activity of selected invasive weed species (*Ageratum conyzoides*, *Bidens pilosa*, *Cecropia peltata*, *Tithonia diversifolia* and *Chromoleana odorata*) from the Mount Cameroon Region on the growth of *Lactuca sativa* and *Phaseolus vulgaris*, and to model the concentration-dependent allelopathic effect of *A. conyzoides* rhizospheric soil on *P. vulgaris* seed germination using polynomial regression modelling. We hypothesise that invasive weed species in the Mount Cameroon region exhibit allelopathic effects that inhibit the growth of crop species such as *Lactuca sativa* and *Phaseolus vulgaris*, and that *A. conyzoides* rhizosphere soil exerts a concentration-dependent allelopathic impact on *P. vulgaris* seed germination. Furthermore, we propose that the allelopathic influence of *A. conyzoides* rhizosphere soil can be quantitatively modelled, providing insights into concentration thresholds for potential use in crop and weed management.

## 2. Materials and Methods

### 2.1. Seed Pre-Germination

Seeds of lettuce (*Lactuca sativa*) and beans (*Phaseolus vulgaris*) were purchased from a commercial store in Buea, Cameroon. Seeds were sterilised in 2.0% sodium hypochloride (NaOCl) for two minutes and rinsed with distilled water before being used in each of the experiments [18]. Preliminary germination tests using the blotter method (method similar to control with distilled water) were performed on the seeds to ascertain viability.

### 2.2. Preparation of Extract

Five invasive species were selected from agricultural fields around Mount Cameroon for their significant ecological and agricultural impacts. They serve as a macrocosm of the broader challenges posed by invasive plants in the region, serving as a basis for further research and action to mitigate their effects on both agriculture and the environment.

For preparation of fresh leaves aqueous and leachates extracts, *Chromoleana odorata*, *Ageratum conyzoides*, *Bidens pilosa*, *Tithonia diversifolia* and *Cecropia*

*peltata* were collected from the Mount Cameroon Region latitude 3057'N to 4028'N and longitude 8058'E to 9204'E [19]. The plants were transported to the Life Science Laboratory of the Faculty of Science and the Teaching and Research Farm of the Faculty of Agriculture and Veterinary Medicine of the University of Buea. The leaves of each plant collected were separated for use in the bioassays. The leaves were washed with tap water, then with distilled water, and allowed to dry for 2 hours before extraction.

For fresh aqueous extracts of fresh plant leaves, a litre of distilled water was added to two hundred grams of chopped fresh leaves of each invasive alien species in a blender and homogenized for 5 minutes at room temperature. The mixture was allowed to stand for 30 minutes before filtration through Whatman No. 1 filter paper.

For foliage leachate extracts of fresh plant leaves, 200 g of fresh leaves of each invasive alien species were immersed in 1 litre of distilled water for 5 minutes and then leached water was collected and filtered through a Whatman No.1 filter paper. The filtrates were considered as full-strength concentrations and were stored at 4°C until used. The stock solution of each plant was diluted in distilled water to obtain 100mL of the working solutions (0%, 25%, 50%, 75%, and 100%).

### 2.3. Seed Bioassay

With respect to the seed bioassay, specific concentrations of 25%, 50%, 75%, and 100% were used for the extracts and leachates. These concentrations were chosen to reflect a gradient that allows for the assessment of the varying effects of the extracts on target plants. Ecologically, these concentrations are relevant as they simulate different scenarios in natural settings where allelochemicals may be present in varying amounts due to environmental conditions, plant density, and decomposition rates.

For bioassay with fresh aqueous extract, ten (10) seeds each of *Lactuca sativa* and *Phaseolus vulgaris* were placed separately in each of three sterilised (9 cm diameter) Petri dishes lined with two layers of Whatman No.1 moistened filter paper. 10 mL of solution containing 25%, 50%, 75% and 100% full-strength extract diluted with distilled water was added to the dishes. For the control treatment, 10 mL of distilled water (0%) was added per petri dish. The dishes were incubated in the dark for one week and data on germination, root length and shoot length were recorded.

For bioassay with fresh foliage leachate, ten (10) seeds each of *Lactuca sativa* and *Phaseolus vulgaris* were placed separately in each of three sterilised (9 cm diameter) Petri dishes lined with two layers of Whatman No.1 moistened filter paper. 10 mL of solution containing 25%, 50%, 75% and 100% full-strength extract diluted with distilled water was added to the dishes. For the control treatment, 10 mL of distilled water (0%) was added per petri dish. The dishes were incubated in the dark for one (1) week and a germination test was carried out under the condition of a 12 h light/dark cycle with  $25 \pm 2$  temperature. Data on germination,

root length and shoot length where germination for each seed was recorded once its radicle protruded to  $\geq 1$  mm in length. Lettuce was recorded as (SP1) and beans as (SP2). The percentage of seed germination was calculated as in Eq. (1):

$$\text{Germination percentage (GP)} = \frac{\text{Cumulative number of germinated seed}}{\text{Total number of seeds}} * 100 \quad (1)$$

The root and shoot lengths were obtained by separately measuring the root and shoot lengths of the samples from each treatment by tracing with an inelastic string and reading the length of a meter rule.

#### **2.4. Land Preparation, Treatment of Rhizospheric Soil and Modelling Followed the Method of [10]**

A piece of land measuring 100 m  $\times$  100 m was prepared and divided equitably into 15 mini-plots. Fourteen of the mini-plots were selected for the treatments and the remaining was considered as control and respectively labelled from 1 - 15. Rhizospheric soil samples were collected from natural stands dominated by *Ageratum conyzoides*, crushed into fine powder and weighed into 0.5 Kg, 1 Kg, 1.5 Kg, 2 Kg, 2.5 Kg, 3 Kg, 3.5 Kg, 4 Kg, 4.5 Kg, 5 Kg, 5.5 Kg, 6 Kg, 6.5 Kg and 7 Kg packs. Bean seeds were obtained from a local market in Buea. The control setup involved using soil collected from an area dominated by non-invasive species, specifically not occupied by *Ageratum conyzoides*. This soil was then crushed into a fine powder and weighed, mirroring the preparation method used for the treatment plots.

Starting with the mini-plots marked (1), 60 bean seeds were sown on each of the three sections after which 0.5 Kg of rhizospheric soil sample was fully spread, by broadcasting on each plot. The method was repeated using the remaining mini-plots (2)-(14) with respectively 1 Kg, 1.5 Kg, 2 Kg, 2.5 Kg, 3 Kg, 3.5 Kg, 4 Kg, 4.5 Kg, 5 Kg, 5.5 Kg, 6 Kg, 6.5 Kg and 7 Kg of the samples. 60 seeds were also planted on each section of mini-plots, including mini-plots (15), which served as the control.

The setup was watered twice daily with water until the beans fully germinated within 9 days.

#### **2.5. Data Analysis**

Each experimental setup was repeated three times. Data were tested for normality and homogeneity of variance. This was followed by the analysis of variance through the GLM approach, with natural log transformation for data that did not meet the conditions of normality and homoscedasticity. Where significant differences exist, means were separated through the Tukey HSD test at  $\alpha = 0.05$ .

##### **Data collection and analysis of the polynomial regression model**

Data on the total number of germinated seeds per plot was collected and based on the data a mathematical model was formulated using polynomial regression according to [10]. All data in the modelling process was analysed using Scilab 6.1.0 computer software with its Curve Fitting Toolbox.

Polynomial regression is a special case of multiple regressions, with only one

independent variable  $x$ . The  $k$ th order polynomial regression model in one variable can be expressed in Eq. (2):

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + \dots + \beta_k x^k + \epsilon \quad (2)$$

where  $k$  is the degree of the polynomial also known as the order of the model.

The mean squared error  $MSE$  is an unbiased estimator of the variance  $\sigma^2$  of the random error term Eq. (3):

$$MSE = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - (k + 1)} \quad (3)$$

where,  $y_i$  are observed values,  $\hat{y}_i$  are the fitted values of the dependent variable  $Y$  for the  $i$ th case and  $n - (k + 1)$  is the degree of freedom. Since the mean squared error is the average squared error, where averaging is done by dividing by the degrees of freedom,  $MSE$  is a measure of how well the regression fits the data. The root mean squared error,  $RMSE$  is given by the square root of the mean square error.

$$RMSE = \sqrt{MSE}.$$

The  $R$ -squared  $R^2$  (coefficient of determination) of the regression equation (Eq. 3) is defined as

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (3)$$

where,  $\bar{y}$  is the arithmetic mean of the  $y$  variable.  $R^2$ , measures the percentage of variation in the response variable  $y$  explained by the explanatory variable  $x$ . The value of  $R^2$  ranges between zero and one ( $0 \leq R^2 \leq 1$ ). An  $R^2$  value of 0.9 or above is very good, but when the  $R^2$  value is 0.5 or below, the regression explains only 50 % or less of the variation in the data, therefore giving a poor prediction [11].

Adjusted  $R$ -squared  $R^{*2}$  (Eq. 4) is computed as follows

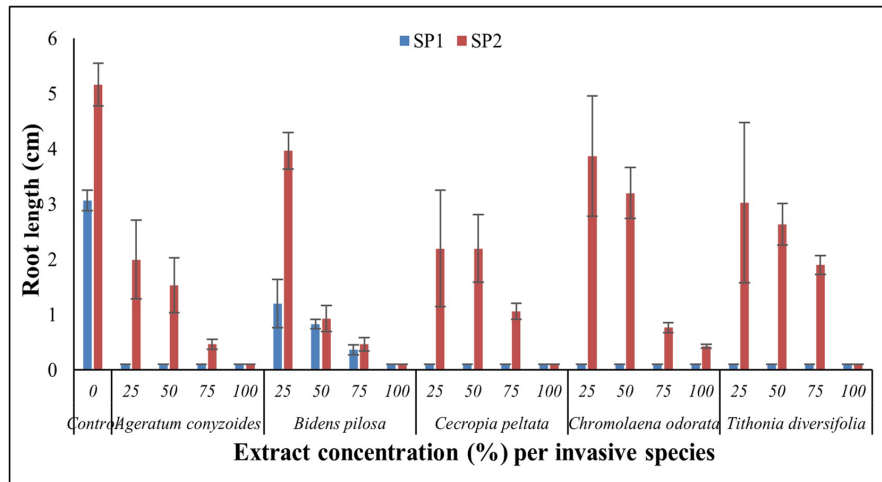
$$R^{*2} = R^2 - \frac{(1 - R^2)k}{n - (k + 1)} \quad (4)$$

### 3. Results

#### 3.1. Allelopathic Potential of Invasive Alien Species on Lettuce (SP1) and Bean (SP2) Seeds

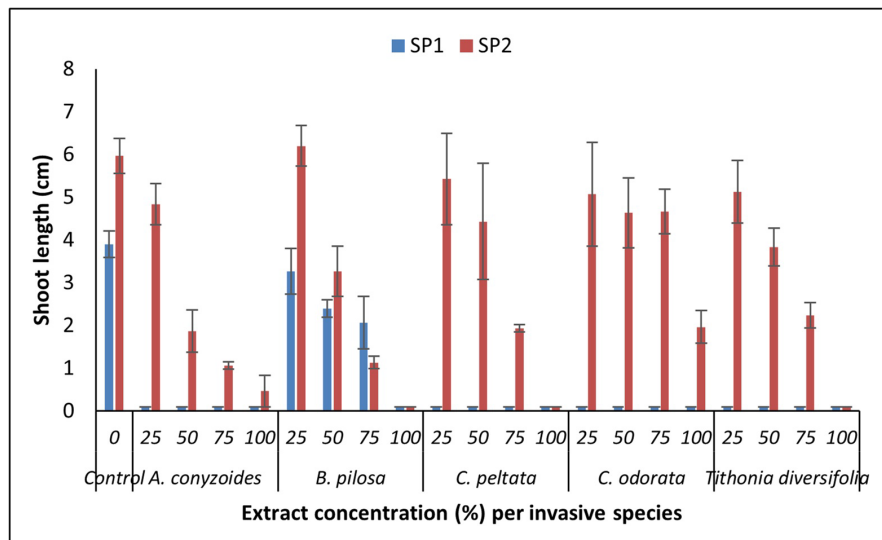
##### 3.1.1. Allelopathic Effects of Fresh Leaf Extracts

The result in **Figure 1** shows that invasive weed species leaf extract at different concentrations significantly ( $P < 0.05$ ) influenced the root length of lettuce (SP1) and beans (SP2). The result revealed a consistent decrease in root length of lettuce (SP1) and beans (SP2) with increasing concentrations of leaf extract across all invasive weed species, with control having the highest root length (5.2 cm) and 100% concentration the lowest root length (0.4 cm) across (**Figure 1**).



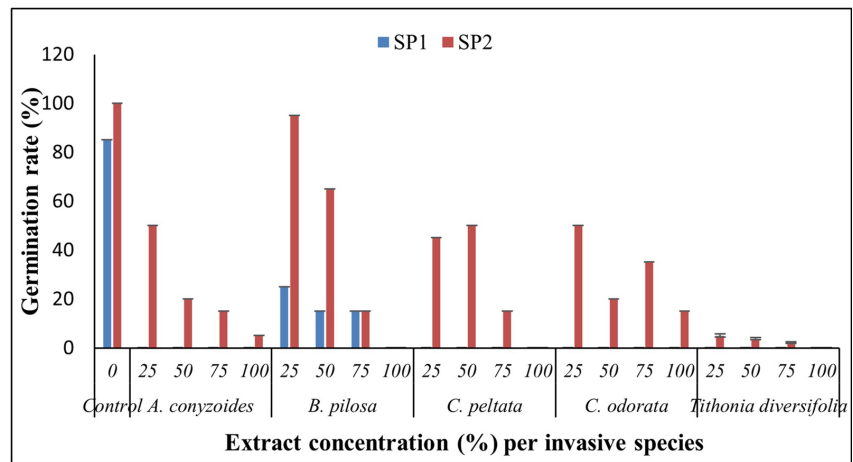
**Figure 1.** Root length of lettuce (SP1) and bean (SP2) for different invasive species leaf extract and concentrations.

A similar result was observed for shoot length where increasing invasive weed species concentrations significantly reduced the shoot length of both lettuce (SP1) and beans (SP2) (Figure 2). The result also showed that lettuce (SP1) shoot length was more significantly reduced by increasing weed species concentration than beans (SP2) shoot length (Figure 2). Shoots of beans (SP2) was longer (6.2 cm) at *Bidens pilosa* 25% concentration while lettuce (SP1) shoot length was highest (3.9 cm) at the control (Figure 2).



**Figure 2.** Shoot length of lettuce (SP1) and bean (SP2) for different invasive species leaf extract and concentrations.

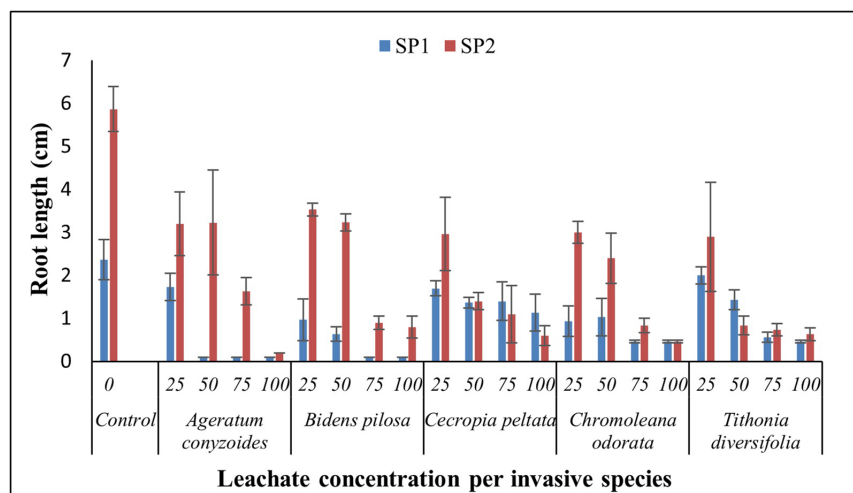
The results in Figure 3 show that the germination rate of SP2 was higher for all treatments with a 100% germination rate in the control. The germination was significantly hindered by *Tithonia diversifolia* treatment at all concentrations.



**Figure 3.** The germination rate of lettuce (SP1) and bean (SP2) as affected by different invasive species leaf extracts and concentrations.

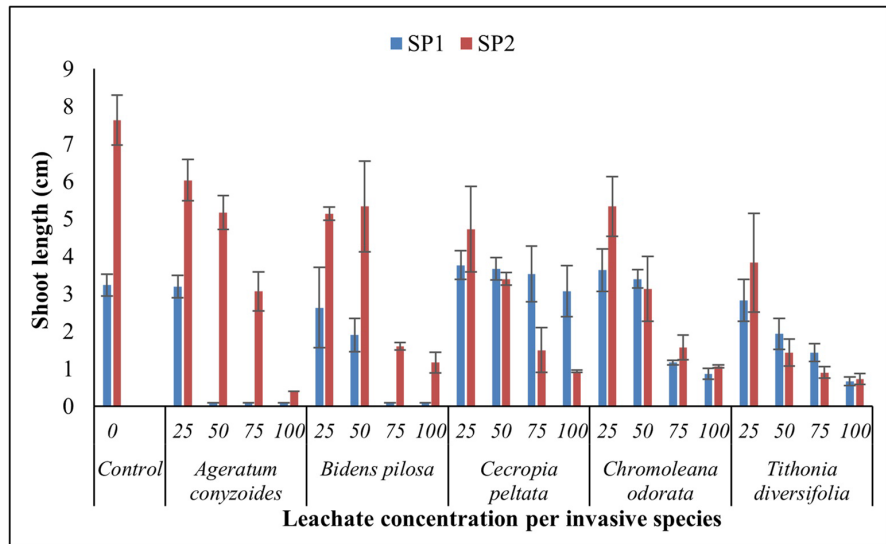
### 3.1.2. Allelopathic Effects of Leaf Leachates

The result shows the allelopathic potential of fresh leaf leachates on the root length of SP1 and SP2 with a significant decrease of root length as leaf leachate concentration (**Figure 4**). Control plants with no allelopathic potential invasive weed species had the longest root lengths for SP1 and SP2 (2.37 cm and 5.87 cm respectively) with the shortest root lengths in plants treated with leaf leachate of *Ageratum conyzoides* at 100% concentrations for SP1 (0.1cm) and SP2 (0.2 cm).



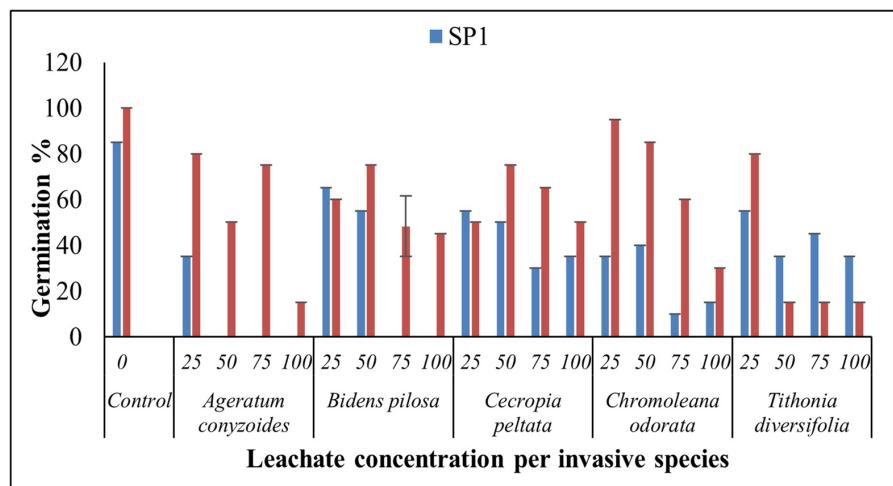
**Figure 4.** Root length of lettuce (SP1) and bean (SP2) for different invasive species leachate and concentrations.

The pattern of variation of the shoot length in SP1 and SP2 is observed in **Figure 5**. Plants with the longest shoots for SP1 were those in the *Cecropia peltata* treatment at 25% concentration (3.8 cm) while SP2 plants with the longest shoots were those under the control treatment (7.63 cm). SP1 plants with the shortest shoots were those that received leachate from *Ageratum conyzoides* at 100 concentrations (0.1 cm) and at 100% concentration for SP2 (0.4 cm) (**Figure 5**).



**Figure 5.** Shoot length of lettuce (SP1) and bean (SP2) for different invasive species leachate and concentrations.

The pattern of variation of germination percentages in SP1 and SP2 is shown in **Figure 6**. Plants with the highest germination percentage for both SP1 and SP2 were those in the control treatment (85.1% and 100% respectively). Plants treated with leachate extracts at various concentrations experience a significant reduction in the germination rate with 100% concentration of *Tithonia diversifolia* leachate exerting the most effect (15.1%).



**Figure 6.** Germination percentage of lettuce (SP1) and bean (SP2) for different invasive species leachate concentrations

### 3.2. Contribution of Allelopathy to Interference by the Rhizospheric Soil of *Ageratum conyzoides* on a Model Plant Using Mathematical Modelling

The results show that as the quantity of rhizospheric soil increased, the percentage of germination of the bean seeds decreased (**Table 1**).

**Table 1.** *Ageratum conyzoides* rhizospheric soil modulated number of bean seeds germinated.

Treatments (soil in Kg)	Number of germinated seeds	Germination percentage
0.0	60	100
0.5	58	96.67
1.0	58	96.67
1.5	57	95.00
2.0	53	88.33
2.5	50	83.33
3.0	48	80.00
3.5	46	76.67
4.0	42	70.00
4.5	38	63.33
5.0	35	58.33
5.5	34	56.67
6.0	30	50.00
6.5	27	45.00
7.0	16	26.67

The statistical outputs of the polynomial regression model are given in **Table 2**.

**Table 2.** Polynomial regression model of allelopathic interference by *Ageratum conyzoides* rhizospheric soil.

	Polynomial model							
	Degree 2	Degree 3	Degree 4	Degree 5	Degree 6	Degree 7	Degree 8	Degree 9
RMSE	2.9159736	2.9824812	2.3274466	1.8067551	1.6994071	1.4671623	1.2961592	1.3528221
R <sup>2</sup>	0.9849439	0.9855618	0.9920067	0.9956648	0.9956648	0.9977766	0.9985126	0.9986497
R <sup>2</sup>	0.9824345	0.9816241	0.9888094	0.9932564	0.9924134	0.9955532	0.9965294	0.9962193

The best fit polynomial regression model occurred at polynomial of degree 8 and its parameter estimates are seen in Equation (5).

$$y = 100.01397 - 28.933788x + 74.985596x^2 - 80.294922x^3 + 41.541115x^4 - 11.747532x^5 + 1.8501702x^6 - 0.1519795x^7 + 0.0050631x^8 \quad (5)$$

where x = concentrations of rhizospheric soil and y = number of germinated seeds.

**Figures 7 and 8** show the comparisons of the polynomial models with the measured data. A curvilinear relationship was observed and polynomials of degrees 2, 3, 4, 5, 6, 7, 8 and 9 (1 to 9) were fitted as shown in **Figure 7 and 8** respectively. The best fit polynomial regression model occurred at a polynomial of degree 8 (8) (**Figure 8**).

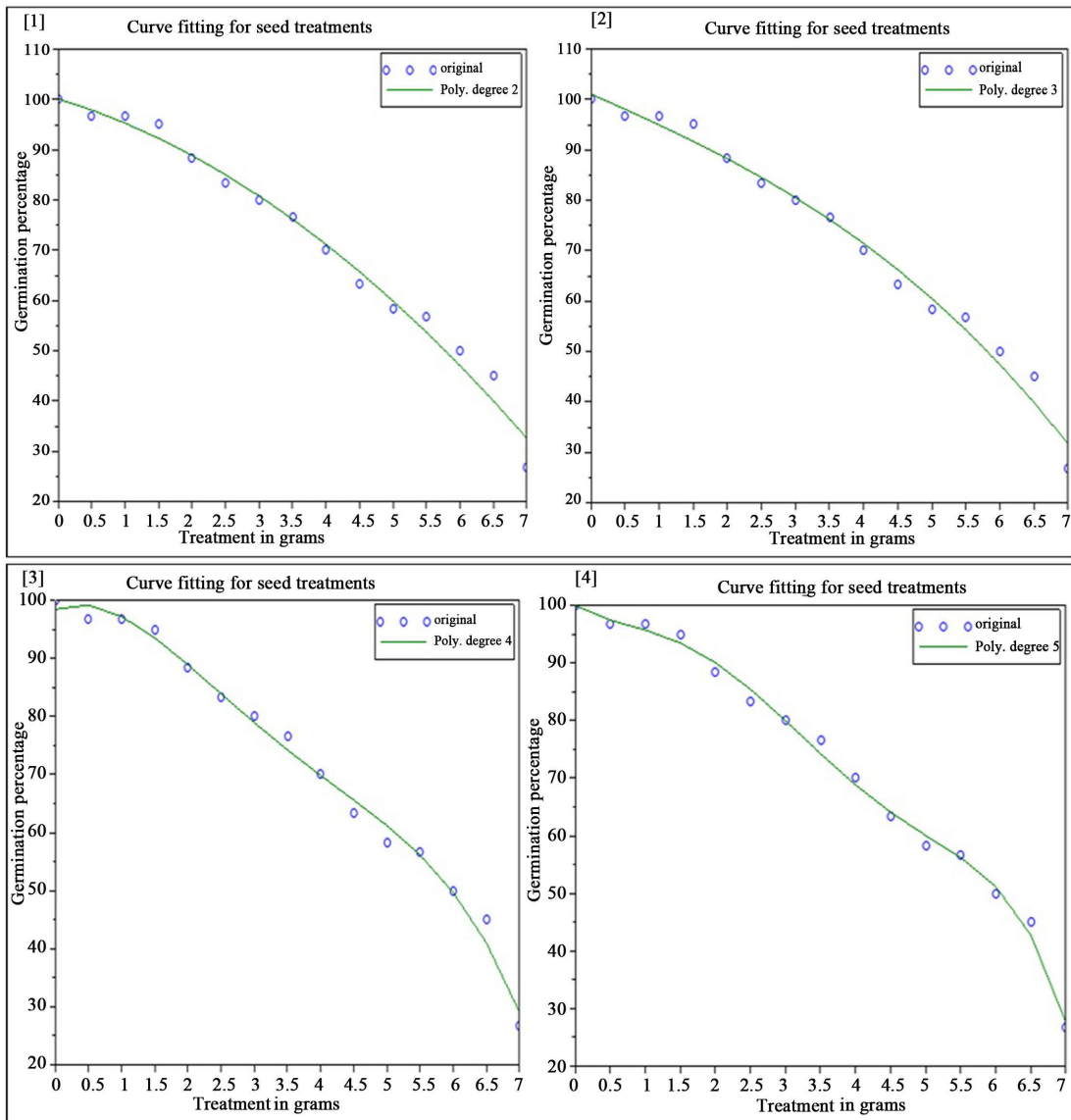
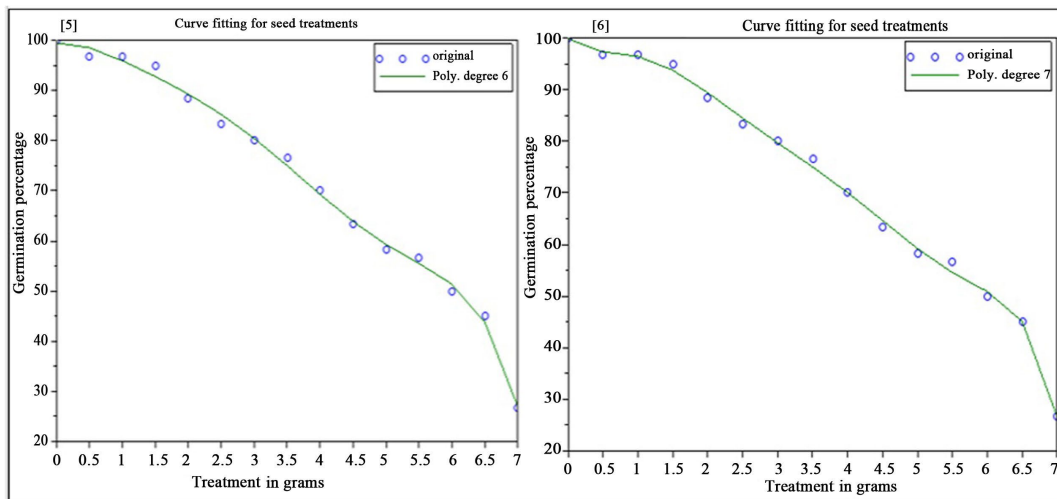
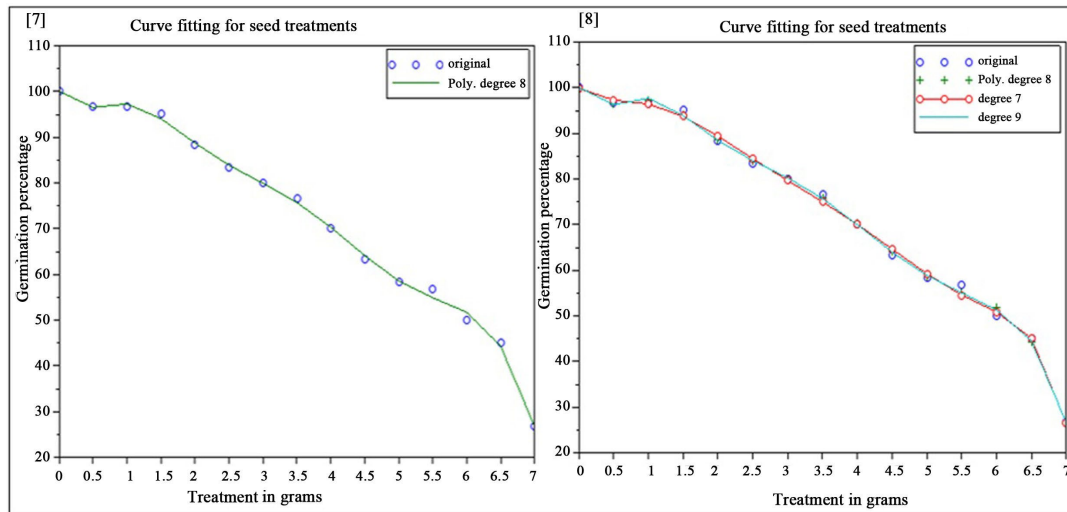


Figure 7. Comparison of polynomial model with measured data.





**Figure 8.** Comparison of polynomial model with measured data.

## 4. Discussion

### 4.1. Allelopathic Potential of Invasive Alien Plant Species on Lettuce (SP1) and Bean (SP2) Seeds

The results of this study showed that different strengths of leaf extracts and leaf leachates of the selected plants significantly inhibited seed germination and seedling growth of lettuce and beans. The observed inhibition of the germination of lettuce and bean seeds could be attributed to a contribution of allelochemicals present in the leaf extracts of *Ageratum conyzoides*, *Bidens pilosa*, *Cecropia peltata*, *Tithonia diversifolia* and *Chromoleana odorata*. These allelochemicals have various chemical structures and phytotoxic effects responsible for inhibiting seed germination and plant growth via interferences with core biochemical and physiological processes such as cell division, energy transfer, water and nutrient uptake [20]. Different studies have shown that allelochemicals are water-soluble and can accumulate upon release within seeds in direct contact with bioactive concentrations [21]. Therefore, the inhibitory effect may be due to the entry of water-soluble allelochemicals into the seed supporting this study [22]. Similar results were obtained by [23] who investigated the allelopathic activity of fresh leaf extracts and leachates of *Diplotaxis erucoides* on four crops. These results also corroborate the findings of [24] [25] who reported the allelopathic effects of extracts of different weeds on seedling growth and germination of test plants.

The inhibition was observed as concentration-dependent. The germination percentage of seeds treated with 100% and 75% weed extracts was significantly lower than those treated with 50% and 25% extracts, respectively. Pronounced increases in allelopathic inhibition due to the effect of dosage have been reported [26]. Fresh leaf extract and leaf leachates exerted some stimulatory effects at the lowest applied concentrations (25%) in some germination parameters. The observed stimulation could be due to growth-promoting substances in tissues [27]. This phenomenon is called hormesis [28] and has been recorded in several studies

in allelopathy. Germination was observed to be higher in the control than in the applied extract treatments. This may be due to the absence of leaf extract concentration facilitating water uptake which is an important component in stimulating some metabolic and physiological processes occurring in seed germination [29].

The changes in the root and shoot length reflect the allelopathic influences on each organ. The results of this study indicated that the extracts of the selected weeds inhibited root and shoot growth of lettuce and bean seeds and it was observed that the roots were more sensitive to the extracts than the shoots. This shows an organ-based sensitivity of the species to phytotoxic compounds. Possible reasons are that roots are the first to emerge and are in direct contact with extracts and thus are exposed to peak periods and concentrations of phytotoxins. According to [30], the highest level of allelopathic suppression occurs when maximum levels of phytotoxins coincide with the early stages of plant growth. Similar findings were reported by [31] who investigated the allelopathic potentiality of *Euphorbia hypericifolia* L. on germination and seedling development of sympatric crops and weeds.

Fresh leaf extracts showed more inhibition than the leachates and this may be because the chemicals were released slowly in the leachates. The most effective allelopathic weed was *Ageratum conyzoides* followed by *Tithonia diversifolia* while *Bidens pilosa* had the least inhibitory effect on lettuce and bean growth. *Ageratum conyzoides* exhibits stronger allelopathic effects due to its potent secondary metabolites, especially volatile oils and water-soluble phytochemicals, which inhibit the growth of various crops. Its adaptability to diverse environments and invasive nature further enhance its competitive edge. Research comparing its chemical compositions with other species can help to identify specific allelochemicals responsible for these effects, highlighting the importance of chemical type and concentration in allelopathy. However, the chemical composition was not compared between species in this study.

#### **4.2. Mathematical Modelling of Allelopathic Interference by the Rhizospheric Soil of *Ageratum conyzoides* on a Model Plant Using the Polynomial Regression Model**

Rhizospheric soil samples of *Ageratum conyzoides* were used to explore the effects of the extracts on the germination and growth of bean seeds. The addition of the samples of the rhizospheric soil affected the germination rate of bean seeds implying that the germination rate was dependent on the quantity of rhizospheric soil used for the treatments. Similar results were reported by [7] who tested the effects of rhizospheric soil of *Tectona grandis* L plantation on the germination of *Lycopersicon esculentum*. Environmental variables like soil composition and climate significantly influence the allelopathic effects of plants in natural settings compared to controlled conditions. Soil nutrients, pH, and microbial communities can affect the availability and effectiveness of allelochemicals, while climate factors such as temperature and humidity impact their production and release. In controlled environments, these variables are standardized, which may not reflect

the complex interactions present in natural ecosystems, leading to different allelopathic outcomes.

The purpose of our study was to model the allelochemical effect of the rhizospheric soil sample of *Ageratum conyzoides* on the seed germination of *Phaseolus vulgaris* (bean seeds). From our results obtained from the field experiment, a scattered plot showed a curvilinear relationship between the rhizospheric soil treatments and the mean number of germinated seeds and polynomials of degrees 2, 3, 4, 5, 6, 7, 8 and 9 were fitted to see which of the models will provide a good approximation of the relationship that exist between plotted data points. The best fit was observed at polynomial of degree 8 with the lowest error statistic (RMSE = 1.2961592) and high deterministic coefficient ( $R^2 = 0.9985126$ ) (**Table 2**). The value of  $R^2$  at best fit polynomial degree 8 denotes that the allelopathic concentration of rhizospheric soil of *Ageratum conyzoides* is responsible for 99.85 % variability of germination percentage in *Phaseolus vulgaris* and 0.15% (100% - 99.85%) of the variation is caused by other factors. Though R-squared ( $R^2$ ) indicates how well a regression model fits a set of data, the “Adjusted R Square” ( $R^{*2}$ ) is preferred in the interpretation of results to avoid false relationships and should always be less than or equal to R Square with small differences between them for the best fit of a model [9]. [10] states that,  $R^2$  shows how well data points fit a regression line assuming every single variable explains the variation in the dependent variable which is not true. Whereas, adjusted R Square tells how well the data points fit a regression line showing the percentage of variation explained only by the independent variables that affect the dependent variable. From the results, the value of the adjusted R square ( $R^{*2} = 0.9965294$ ) for our best fit polynomial model of degree 8 indicates that truly, 99.65% of the variation in the germination percentage in *Phaseolus vulgaris* is caused by rhizospheric soil of *Ageratum conyzoides* and the remaining 0.35% of the variation is caused by other factors.

The standard error is a measure of the precision of the model and indicates how wrong the estimated coefficient could be if used to make predictions. It should be as small as possible relative to the estimated coefficient. The error statistic (RMSE) of the best fit of the model (polynomial of degree 8) in this study is 1.2961592 indicating that on average, our estimates of germination percentage with this model will be wrong at 1.29. The cubic spline method was used to smoothen the model and reduce error due to the Runge’s phenomenon (problem of oscillations at the edges of an interval that occurs when using the polynomial of a high degree over a set of equally spaced interpolation points).

## 5. Conclusion

All the selected invasive species inhibited seed germination and seedling growth of lettuce and bean seeds; allelopathic effects of alien plant extracts are species-specific and concentration-dependent. *Ageratum conyzoides* demonstrated a greater inhibitory effect on germination, shoot and root growth of lettuce and bean seeds compared to *Bidens pilosa*, *Cecropia peltata*, *Tithonia diversifolia* and

*Chromoleana odorata*. However, 8-degree polynomial model was developed ( $y = 100.01397 - 28.933788x + 74.985596x^2 - 80.294922x^3 + 41.541115x^4 - 11.747532x^5 + 1.8501702x^6 - 0.1519795x^7 + 0.0050631x^8$ ) for allelopathic effects of rhizospheric soil samples of *Ageratum conyzoides* on germination of *Phaseolus vulgaris*. The model demonstrates that it could be used to predict the allelopathic impact on plant growth for any concentration of rhizospheric soil. It could also be exploited in allelopathic studies to determine a plant's concentration of allelochemical released as a potential bioherbicide. It is crucial to investigate the long-term effects of allelochemicals on soil health and successive crops. By understanding these long-term interactions, we can better harness the potential of allelopathy in sustainable farming while safeguarding the health of our soils.

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### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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