

Allelopathic Responses of Crop Species to *Chromolaena odorata* Root Exudate Extracts: A Comprehensive Study

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How to cite this paper: Akter, P. and Begum, R. (2024). Allelopathic Responses of Crop Species to *Chromolaena odorata* Root Exudate Extracts: A Comprehensive Study. *Grassroots Journal of Natural Resources*, 7(1): 1-20. Doi: <https://doi.org/10.33002/nr2581.6853.070101>

Received: 10 August 2023

Reviewed: 20 February 2024

Provisionally Accepted: 21 February 2024

Revised: 28 February 2024

Finally Accepted: 29 February 2024

Published: 07 March 2024

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Abstract

This study investigates the allelopathic effects of root exudate extracts from *Chromolaena odorata* on the germination and growth of six crop species. The results reveal variable sensitivity among the species, with the control treatment consistently exhibiting superior germination percentages. Initially, some species, including *Abelmoschus esculentus* (okra), *Solanum lycopersicum* (tomato), and *Cicer arietinum* (chickpea), experienced a substantial decline in germination, indicating a potential inhibitory effect of the exudates, although partial recovery was observed in subsequent treatments. *Phaseolus vulgaris* (common bean) displayed a moderate decrease, while *Zea mays* (corn) exhibited the most significant drop in germination rates, albeit with slight recovery at higher concentrations of exudates. Conversely, *Cucumis sativus* (cucumber) appeared least affected by the exudates. Moreover, all species demonstrated reductions in shoot and root lengths with increasing concentrations of exudates. Chlorophyll content analysis revealed a significant reduction across most treatments, highlighting concerns regarding photosynthetic efficiency and overall plant health. The species-specific response to root exudates suggests varying metabolic or adaptive mechanisms among crops. Additionally, malondialdehyde (MDA) levels, indicative of oxidative stress, varied among species, with *A. esculentus* and *P. vulgaris* showing a dose-dependent increase, while *S. lycopersicum* displayed a peak at intermediate treatment levels. *Z. mays* exhibited marginal elevation in MDA content, potentially indicating the presence of protective compounds within the exudates. Conversely, *C. arietinum* and *C. sativus* showed a steady increase in MDA, suggesting limited mitigation of allelopathic effects. These findings feature the complexity of allelopathic interactions and highlight the need for further research into active compounds and their modes of action to develop sustainable weed management strategies while safeguarding crop health. Understanding these dynamics is crucial for maximizing the potential benefits of allelopathy in agriculture.

Keywords

Allelopathy; Root exudates; *Chromolaena odorata*; Crop plants; Seed germination; Chlorophyll content; MDA content

Introduction

Weed management has perennially posed a formidable challenge in agriculture, constituting a significant threat to crop productivity and yield (Storkey *et al.*, 2021). Traditional weed control methods are inefficient, costly, and environmentally harmful (Woyessa, 2022). In response to these challenges, the widespread adoption of herbicides has become a cornerstone of modern agricultural practices (Ofosu *et al.*, 2023). However, concerns regarding herbicide resistance among weed populations, environmental contamination, and potential risks to human health have spurred a critical reevaluation of weed management strategies (Ofosu *et al.*, 2023). The dominance of herbicides in contemporary agriculture reflects their perceived efficacy in selectively targeting and eliminating unwanted plant species while minimizing harm to crops (Kraehmer *et al.*, 2014). Glyphosate, in particular, has emerged as a widely used herbicide due to its broad-spectrum effectiveness and perceived safety (Kanissery *et al.*, 2019). However, the overreliance on herbicides has precipitated several unintended consequences, including the emergence of herbicide-resistant weed biotypes, soil and water contamination, and ecological disruptions (Schütte *et al.*, 2017). Consequently, there is a growing recognition of the need for alternative weed management approaches that prioritize sustainability and environmental stewardship (Chauhan *et al.*, 2017).

Among the emerging paradigms in weed management is the exploration of allelopathy — a natural phenomenon whereby plants release biochemical compounds that inhibits the growth of neighboring plants (Khamare, Chen and Marble, 2022). Allelopathy offers a promising option for sustainable weed management leveraging the allelopathic phenomenon, the synergistic application of allelopathic rhizobacteria (*Pseudomonas fluorescens* and *Bacillus* sp.) combined with *Sorghum* allelopathic extract surpasses conventional weed management practices by efficaciously inhibiting weed proliferation and augmenting wheat productivity, thus emphasizing a viable, sustainable strategy for agricultural weed control (Raza *et al.*, 2021). The allelopathic properties of crops such as rice, wheat, and barley have been extensively studied for their potential to inhibit weed growth and reduce the reliance on herbicides (Khanh *et al.*, 2013).

Integrating allelopathic principles into agricultural practices holds the promise of enhancing both weed management and overall crop productivity (Kostina-Bednarz, Płonka and Barchańska, 2023). By incorporating allelopathic cover crops into crop rotations, farmers can effectively suppress weed growth, improve soil health, and mitigate the environmental impacts associated with herbicide use (Kunz *et al.*, 2016). However, realizing the full potential of allelopathy as a sustainable weed management strategy necessitates addressing several challenges. These include identifying allelopathic plant species with potent and consistent effects on target weeds, understanding the ecological impacts of allelochemicals on non-target organisms, and facilitating the adoption of allelopathic cropping systems by farmers (Kunz *et al.*, 2016). The scarcity of research into the influence of *Chromolaena odorata* root exudate on seed germination in Bangladesh is notable. Despite thorough searches in major scientific databases, no dedicated studies have been found concerning this subject. This lack of data highlights a critical gap in our understanding of *C. odorata*'s ecological roles, underlining the originality and significance of our investigation. This study seeks to fill this gap by evaluating the impact of root exudate extracts from *Chromolaena odorata* on the germination and growth of various vegetable crops. By

conducting detailed analyses, it is aimed to explore the effectiveness of allelopathy as an efficient and eco-friendly weed management strategy in agriculture.

Materials and Methods

Sample Collection

In order to assess the allelopathic impact of root exudates from certain weed species on the germination and biochemical measurement of crop seedlings, six seeds from various crop species were gathered from local bazar, university campus, University of Chittagong, Hathazari, Bangladesh. Concurrently, *C. odorata* plants at the flowering stage were gathered as donor plants from the botanical garden of the Department of Botany, University of Chittagong.

Root Exudate Preparation

Approximately 30 weed species were uprooted from the vicinity of the botanical garden at the University of Chittagong. Each specimen was carefully uprooted, ensuring the preservation of the root structure, followed by a thorough cleansing process involving an initial rinse with tap water and a subsequent rinse with distilled water to remove any adherent soil particles. These cleansed roots were then placed in conical flasks containing 1.2 liter of distilled water for duration of 5 hours (exposed to sunlight), a period during which root exudates were allowed to diffuse into the surrounding medium. To collect these exudates, a vacuum filtration method was employed, ensuring a precise and uncontaminated extraction. For experimental analysis, the filtered exudate was equally divided into three aliquots and placed into separate jars for differential treatment: the first aliquot was maintained at its original concentration (T1), the second was concentrated to 50% of the original volume (T2), and the third was further concentrated to 25% of the initial volume (T3). These prepared samples were then stored in a refrigerator to preserve their integrity for subsequent analytical procedures (Akter *et al.*, 2023; Alsherif *et al.* 2013).

Method for Petri Dish Setup and Bioassay

Seeds were picked based on their uniform size, shape, color, and health before being sterilized in 70% ethanol for 1-2 min and then washed five times with sterile distilled water to wash away the chemical (Deepak and Virk, 2022). For the soil experiment, petri dish filled with garden soil collected from botanical garden, University of Chittagong, and 10 seeds were planted and irrigated with 5 mL of aqueous root exudates accordingly. The control receives the same amount of water. The growth chamber was kept at a constant temperature of 25°C, and moisture where the petri dish and other containers were left. When the radicle length reached more than 2 mm, it was determined that the seed had germinated. After 14 days, germination indicators were measured, such as the number of seeds that germinated the length of the roots and shoots, and the weight of the seedlings (Figure 1) (Iman *et al.*, 2006).



Figure 1: Flow diagram of root exudate collection and bioassay

Quantifying Lipid Peroxidation (LPO)

The LPO method, derived from Högborg *et al.* (1974), involved weighing tissue samples (1 g) and homogenizing them in 0.15 mol/L cold KCl. The volume was adjusted to 2 mL with 0.3 M Tris-HCL buffer (pH 7.4) and 0.02 mM sodium pyrophosphate. After 37°C incubation for 30 minutes, 10% trichloroacetic acid (1 mL) was added to halt the reaction, followed by vortexing. Thiobarbituric acid (1.5 mL) was then introduced, and samples were heated for 20 minutes in a boiling water bath, repeated thrice. Post-centrifugation, spectrophotometric measurement at 532 nm quantified malondialdehyde levels, indicative of lipid peroxidation (nmol MDA/mg protein).

Statistical Analysis

Statistical analysis involved three repetitions of data analysis using Microsoft Excel 2010 and GraphPad Prism Data Editor for Windows, Version 8.4.3. Analytical techniques encompassed Dunnett's test, one-way, and two-way ANOVA. Results, depicted as mean $\pm$ Standard Error of Mean (SEM), were considered significant at $p < 0.05$ (Akter *et al.*, 2023).

Results

Germination Dynamics

The germinative response of six vegetable species to *C. odorata* root exudates was characterized by variable sensitivity, as demonstrated in figure 2. The control treatment (T0) typically exhibited superior germination percentages, suggesting a latent inhibitory potential in the exudates. Initially, *A. esculentus*, *S. lycopersicum*, and *C. arietinum* show a substantial decline in germination at T1 (below 40%), indicating a potential inhibitory effect of the exudates. However, their germination rates partially recover in subsequent treatments, suggesting some level of adaptation or tolerance (Figure 1). *P. vulgaris* displays a moderate decrease throughout the treatments, maintaining almost half of its initial germination rate by T3 (46.70%). *Z. mays* experiences the most significant drop at T1 (30%) and T2 (26.70%) but shows a slight recovery at T3 (36.70%), which may indicate a non-linear response to the exudate concentrations. *C. sativus* appears to be the least affected, with a high germination rate at T1 (80%), only a moderate decline at T2 (60%), and a near return to its initial rate at T3 (70%).

Effect on Shoot and Root Growth

In table 1 and 2 showed the shoot and root length reduction in all species with the introduction of *C. odorata* exudates, as compared to the control. For example, *A. esculentus* showed a pronounced decrease from 20.22 ± 0.08 cm in the control to 7.25 ± 0.08 cm in T3, the highest concentration of exudates. Similarly, *S. lycopersicum* exhibited a reduction from 5.42 ± 0.08 cm to 4.33 ± 0.12 cm. *P. vulgaris* showed a marked decrease from 34.53 ± 0.12 cm to 25.13 ± 0.09 cm. *Z. mays* and *C. arietinum* also followed this trend, with reductions evident from T0 to T3. The least affected was *C. sativus*, showing a minor decrease from 11.15 ± 0.08 cm to 10.13 ± 0.12 cm (Table 1).

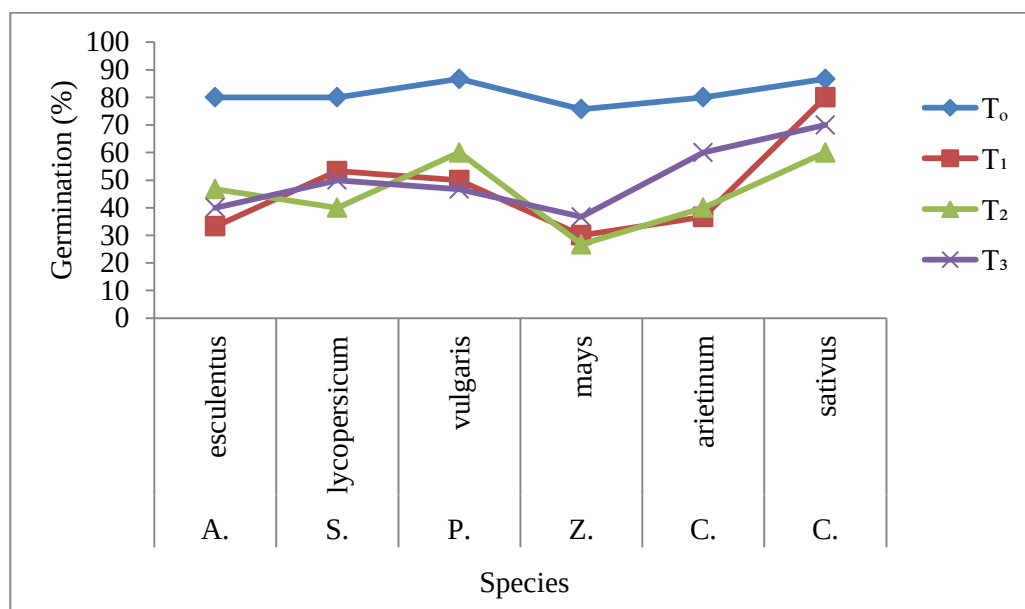


Figure 2: Germination percentage of eight vegetable crops to different concentrations of root exudates of *Chromolaena odorata* at 12 days

Table 1: Shoot Length of eight vegetable crops to different concentrations of root exudates of *Chromolaena odorata* at 12 days (Mean±SEM)

Treatment	A. <i>esculentus</i>	S. <i>lycopersicum</i>	P. <i>vulgaris</i>	Z. <i>mays</i>	C. <i>arietinum</i>	C. <i>sativus</i>
T ₀	20.22±0.08	5.42±0.08	34.53±0.12	8.52±0.16	12.4±0.18	11.15±0.08
T ₁	10.42±0.08	4.71±0.08	23.13±0.12	4.17±0.12	9.35±0.08	7.13±0.08
T ₂	12.40±0.08	3.43±0.08	17.13±0.12	8.2±0.16	7.67±0.08	8.21±0.08
T ₃	7.25±0.08	4.33±0.12	25.13±0.09	8.23±0.16	4.24±0.08	10.13±0.12

In table 2, the data showed a general trend of declining root length with the increasing concentration of root exudates. The root length of *A. esculentus* exhibited a decrease from 6.56±0.11 cm in the control to 5.11±0.07 cm at the highest exudate concentration (T₃). In *S. lycopersicum*, a similar reduction was observed from 5.44±0.08 cm to 2.45±0.13 cm. The root growth of *P. vulgaris* was also adversely affected, showing a decrement from 13.06±0.09 cm to 6.11±0.07 cm. *Z. mays* and *C. arietinum* demonstrated a decline consistent with the other species. Notably, *C. sativus* presented the least sensitivity to the root exudates, with root lengths mildly reduced from 4.89±0.05 cm to 2.12±0.06 cm.

Table 2: Root Length of eight vegetable crops to different concentrations of root exudates of *Chromolaena odorata* at 12 days (Mean±SEM)

Treatment	A. <i>esculentus</i>	S. <i>lycopersicum</i>	P. <i>vulgaris</i>	Z. <i>mays</i>	C. <i>arietinum</i>	C. <i>sativus</i>
T ₀	6.56±0.11	5.44±0.08	13.06±0.09	14.41±0.09	11.57±0.11	4.89±0.05
T ₁	7.38±0.09	4.17±0.12	11.4±0.08	13.33±0.10	11.17±0.12	2.55±0.04
T ₂	6.15±0.05	3.17±0.12	7.18±0.07	18.35±0.11	9.16±0.08	2.46±0.07
T ₃	5.11±0.07	2.45±0.13	6.11±0.07	5.12±0.08	14.11±0.06	2.12±0.06

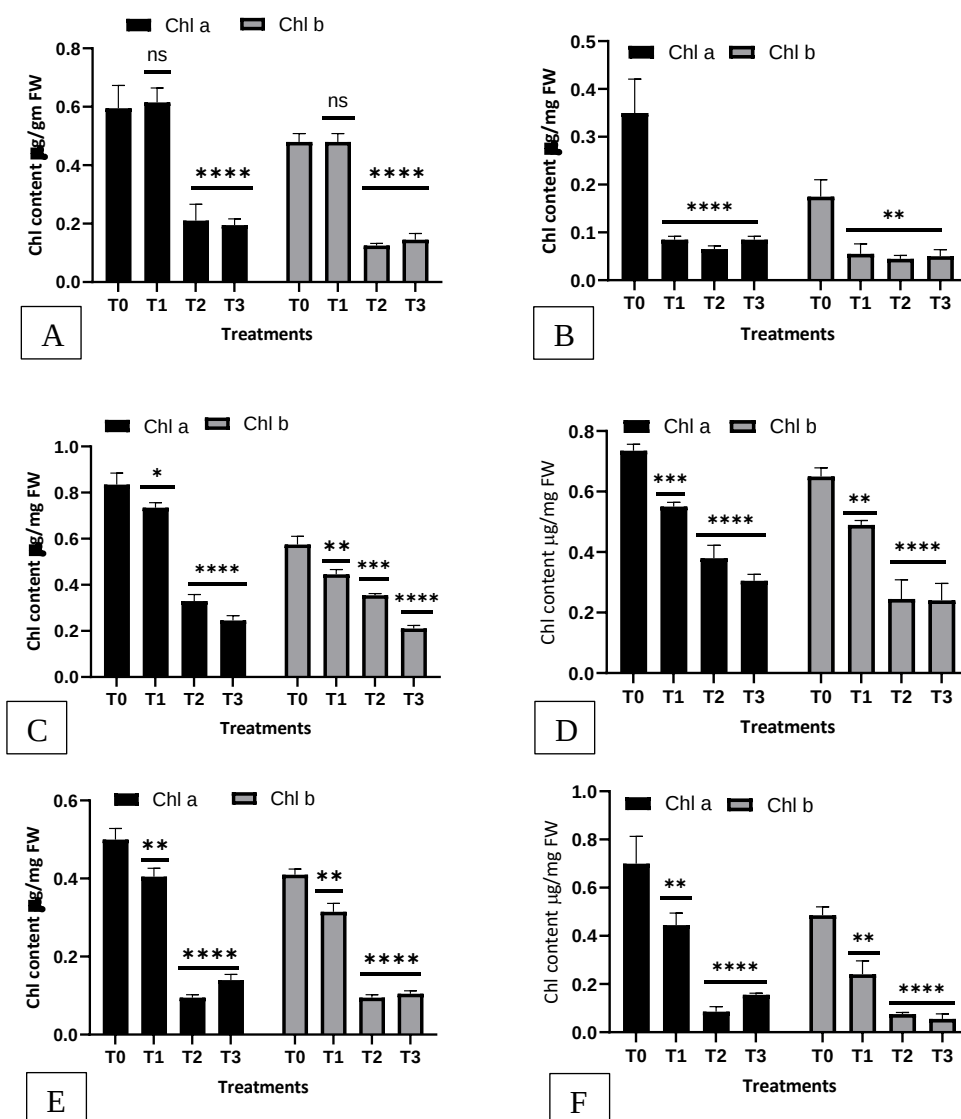


Figure 3: Treatment of aqueous (T1-T3) root exudate extracts of *C. odorata* on the germination of crop plants (A-F) at 12 days. Where * = $p < 0.05$, ** $p < 0.01$, *** = $p < 0.001$, and **** = $p < 0.0001$ indicates significance levels between the treatments and control (T0). ns = not significant. A (*Abelmoschus esculentus*), B (*Solanum lycopersicum*), C (*Phaseolus vulgaris*), D (*Zea mays*), E (*Cicer arietinum*), F (*Cucumis sativus*)

Chlorophyll Content in Response to Root Exudates

The experimental analysis presented in figure 3 investigates the impact of extracts from *C. odorata* root exudates (T1-T3) on chlorophyll levels in six different crop species over a 10-day period. The findings reveal a generally suppressive effect on chlorophyll production across the species, with variations in response. *Abelmoschus esculentus* showed a significant reduction in chlorophyll levels in response to all treatments, with the effect being statistically significant ($p < 0.0001$) particularly for T3. *Solanum lycopersicum* experienced a notable decline in chlorophyll a levels under all three

treatments (T1-T3) ($p < 0.0001$), whereas chlorophyll b levels were also reduced significantly ($p < 0.01$), though to a lesser extent; T1 showed no significant impact (ns, $p > 0.05$). *Phaseolus vulgaris* displayed a significant inhibition in germination with T2 and T3 treatments ($p < 0.0001$), while *Zea mays* was distinctly sensitive, with all treatments markedly decreasing chlorophyll contents, exhibiting similar effects for T2 and T3 ($p < 0.0001$). A similar pattern was observed for chlorophyll content in *Cicer arietinum* with T2 and T3. *Cucumis sativus* experienced a significant decrease in chlorophyll with T2 and T3 ($p < 0.0001$), whereas T1 led to a less pronounced reduction ($p < 0.01$). The overarching and dose-dependent inhibitory effect of T3 across all tested species suggested a potent response to the exudates from *C. odorata*.

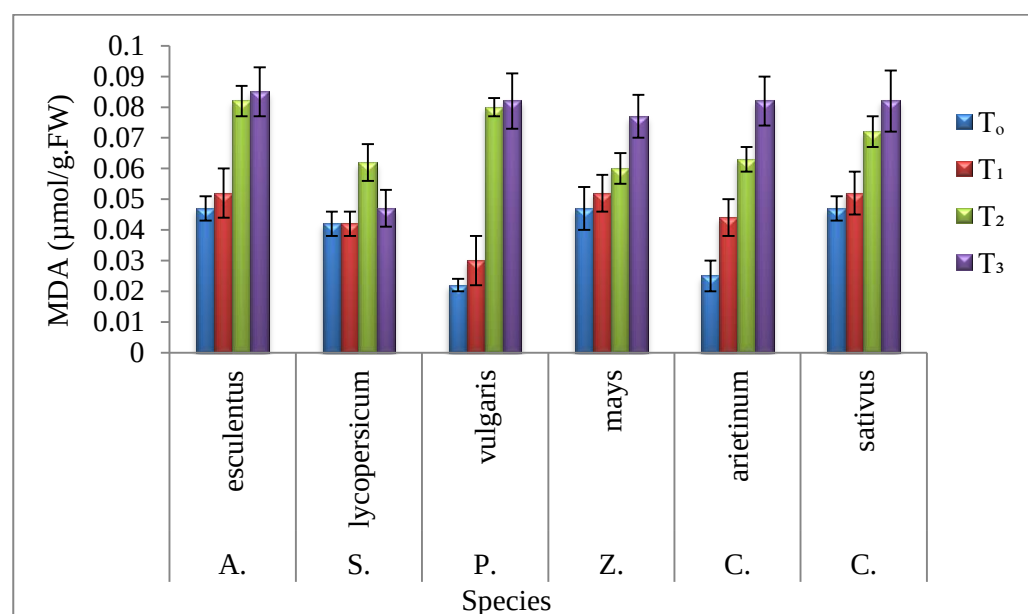


Figure 4: Treatment of aqueous (T1-T3) root exudate extracts of *C. odorata* on the MDA contents of crop plants at 12 days (Mean±SEM)

MDA Content as a Marker of Oxidative Stress

Research examining oxidative stress across different crop species uncovered distinct responses, as evidenced by malondialdehyde (MDA) measurements (Figure 4). *Abelmoschus esculentus* exhibited a sequential increment in MDA levels from 0.045 $\mu\text{mol/g.FW}$ in the baseline control (T₀) to 0.05, 0.082, and 0.085 $\mu\text{mol/g.FW}$ across treatments T₁ to T₃, respectively. Conversely, *Solanum lycopersicum* showed a rise in MDA to 0.065 $\mu\text{mol/g.FW}$ in T₂, then a decline to 0.05 $\mu\text{mol/g.FW}$ in T₃, indicating an adaptive response to stress. *Phaseolus vulgaris*'s MDA levels escalated from 0.025 $\mu\text{mol/g.FW}$ at T₀ to 0.080 $\mu\text{mol/g.FW}$ by T₃. Additionally, *Z. mays*, *Cicer arietinum*, and *Cucumis sativus* all experienced a consistent increase in MDA levels, peaking at 0.085 $\mu\text{mol/g.FW}$ in T₃, pointing to their heightened sensitivity to *C. odorata*-induced stress reflecting diverse antioxidative defense capabilities among the studied species (Figure 4).

Discussion

Root secretions play a pivotal role in how plants interact with their environment, with a variety of allelo-chemicals extracted using methods like water or organic solvent techniques (Bertin, Yang and Weston, 2003; Lou, Davis and Yannarell, 2015; Singh *et al.*, 2021). Weeds stand out for their ability to quickly generate large amounts of biomass and withstand environmental pressures, negatively influencing surrounding plants through both allelopathic effects and direct competition for nutrients and space (Khamare, Chen and Marble, 2022; Kubiak, 2022). The outcomes of this study indicate that the root exudates of *C. odorata* have substantial allelopathic impacts, significantly influencing the germination processes of six different crop species. Variability in the effects of these exudates was observed, contingent upon the specific plant species under consideration and the concentration levels of the exudates applied (Figure 2). The initial germination inhibition observed in *Abelmoschus esculentus*, *Solanum lycopersicum*, and *Cicer arietinum* underlines the potent allelopathic influence of *C. odorata*. These findings are in concordance with previous studies that have documented the inhibitory effects of allelo-chemicals on seed germination and plant growth (Krumisri, Kato-Noguchi and Poonpaiboonpipat, 2020; Poonpaiboonpipat, Krumisri and Kato-Noguchi, 2021; Sisodia and Siddiqui, 2010; Xuan *et al.*, 2004). Notably, the partial recovery in germination rates in subsequent treatments may indicate an adaptive mechanism (Raza *et al.*, 2022) or reduced sensitivity to lower concentrations of exudates, suggesting a distinction interaction between plant species and allelo-chemicals (Liu *et al.*, 2021; Sahid and Yusoff, 2014; Se, Se and Se, 2023; Shaolin, Wen and Qin-Feng, 2004).

P. vulgaris displayed a moderate but consistent decline in germination, which aligns with the theory that certain species possess inherent tolerance levels to allelo-chemicals (Hickman *et al.*, 2020; Reigosa, Pedrol and González, 2006). This tolerance can be attributed to the activation of detoxification pathways or the alteration of membrane permeability to mitigate the effects of allelo-chemicals (Bakhshayeshan-Agdam and Salehi-Lisar, 2020; Shabala, 2010). *Zea mays* exhibited a non-linear response, with a significant drop in germination followed by a slight recovery. This pattern may reflect a threshold effect where germination inhibition occurs up to a certain concentration of allelo-chemicals, beyond which the effect plateaus or diminishes (Em, 2017). *C. sativus* emerged as the least affected species, maintaining high germination rates throughout the treatments. This resilience could be advantageous for intercropping systems, where *C. sativus* could be paired with crops susceptible to *C. odorata*'s allelopathic effects to mitigate overall yield losses (Zhang, Yan and Wu, 2022). Inhibition of *C. sativus* when co-cultivated with neighboring plant species, such as *Eruca sativa* suggested a species-specific manner (Sahid and Yusoff, 2014).

Assessing plant shoot and root lengths is crucial for understanding weed-crop competition. Typically, increased weed competition leads to reduced shoot and root lengths in crops. However, it's not just competition that poses a threat; the allelopathic effects of weeds are particularly concerning for crop growth. This study focused on how root exudates from different weeds affect the shoot lengths of crop species (Table 1 and 2). This supports previous research indicating that root exudates hinder both shoot and root growth due to the presence of harmful substances (El-Halmouch, Benharrat and Thalouarn, 2006; Sun *et al.*, 2022). The findings of this study echo

earlier studies, suggesting that the detrimental effects on crop seedlings result from weed allelopathic residues, rather than nutrient scarcity. Specifically, water-soluble phenolic acids released by weeds are identified as key inhibitors. Channappagoudar and Agasimani (2003) emphasized the role of phenolic compounds as significant phytotoxins, crucially hindering the early growth stages of seedlings (El-Halmouch, Benharrat and Thalouarn, 2006; Guangdong, Zhang and Cheng, 2009). However, *C. sativus* demonstrated resilience with marginal reduction in shoot and root lengths. These findings align with previous studies illustrating plant-specific responses to allelopathic substances (Bais *et al.*, 2003; Saleh and Madany, 2004; Tokarz *et al.*, 2020). The inhibition of seedling growth in the target species echoes earlier studies on the growth of some ornamental plants (Zhang, 2008) and vegetable crops (Cheng and Peng, 2013). Results of this study are consistent with existing literature indicating that the inhibitory effect is influenced by the concentration of the extract (Guo *et al.*, 2010; Yasumoto *et al.*, 2011). Zhang *et al.* (2012) found *F. bidentis* residues to adversely affect the early growth of cotton and impact soil fertility by releasing water-soluble allelo-chemicals. Root secretion is its main allelo-chemical release pathway (Fen, Tao and Pang, 2009), which mainly includes flavonoids, thiophenes, phenolics, esters and steroids (Li, Hou and He, 2014; Sun *et al.*, 2022). Moreover, Lei *et al.* (2010) reported that the allelopathic effects of ginseng root exudates on the seed germination of four medicinal plants were concentration and receptor dependent.

The experimental analysis demonstrates a consistent suppressive impact of *C. odorata* root exudates on chlorophyll levels across various crop species in response to treatments T1-T3 over a 10-day period (Figure 3). Notably, *A. esculentus* and *S. lycopersicum* experienced significant reductions in chlorophyll levels across all treatments, with some variations in the extent of suppression among the species. This broad-spectrum inhibitory effect, especially pronounced with treatment T3, suggests a potent response to *C. odorata* root exudates (Figure 3) aligning with previous studies conducted by Taïbi *et al.* (2016) on *P. vulgaris* L. This decrease in chlorophyll content is indicative of oxidative stress, a common response observed in various crops (Aazami, Rasouli and Ebrahimzadeh, 2021). The decline in chlorophyll levels can be attributed to the inhibition of chlorophyll synthesis and the activation of chlorophyll degradation facilitated by chlorophyllase enzymes (Kuai, Chen and Hörtensteiner, 2017). Whether through impeding synthesis or accelerating breakdown, the reduction in chlorophyll content suggests a photo-protection mechanism aimed at diminishing light absorbance (Harpaz-Saad, 2007; Zhao *et al.*, 2020). The research conducted by Scavo and Mauromicale (2021) brings attention to the potential resilience of crops in the face of allelopathic stress, as indicated by the lack of malondialdehyde (MDA) accumulation despite the reductions in chlorophyll levels. This finding suggests that certain crop genotypes possess inherent mechanisms for mitigating the physiological impacts of allelochemical exposure (Álvarez *et al.*, 2023).

The increase in MDA content across different treatments and species suggests oxidative stress as a result of the root exudate exposure (Figure 4). Previous research has identified MDA as a biomarker for lipid peroxidation, which is a consequence of oxidative damage (Xu *et al.*, 2022). The escalating MDA levels from T0 to T3 align with findings of Jaballah, Zribi and Haouala (2017) who revealed that chickpea aqueous extracts induce a significant increase in MDA levels in the Nsir lentil variety, indicating enhanced oxidative stress. Huang *et al.* (2017) observed a similar response

in *Z. matrella* exposed to *A. philoxeroides* subjected to allelopathic stress. In this study, *Z. mays* and *C. arietinum* suggest a common oxidative stress, which is corroborated with Motmainna *et al.* (2021) who found the same in *Ageratum conyzoides* L., *Oryza sativa* f. spontanea (weedy rice) and *Cyperus iria* L. in glasshouse condition when treated with *Parthenium hysterophorus* extract. The variance in the sensitivity among different species, as observed in *C. sativus* showing elevated MDA (malondialdehyde) levels, may be ascribed to distinctive antioxidant defense mechanisms unique to each species. It has been supported by the work of Hasanuzzaman, Nahar and Fujita (2013). Moreover, the unique response of *Solanum lycopersicum*, which exhibited an initial increase followed by a decrease in MDA levels in T3, might be indication of an adaptive antioxidative strategy. This pattern mirrors the observations made by Yang *et al.* (2024), who reported a similar adaptive response in *Camellia oleifera* under drought stress. The variance in stress responses among the species studied could also reflect genetic differences in antioxidative defense pathways. As noted by Sarkar and Oba (2020), genetic variability plays a significant role in determining the efficiency of enzymatic and non-enzymatic antioxidative defenses, which could explain the differential responses observed in this study. Furthermore, the heightened sensitivity of certain species to stress from *C. odorata* gives emphasis to the understanding inter-species interactions and their impact on antioxidative defenses. Studies such as those by Silva *et al.* (2018) highlight the ecological and biochemical complexities of plant-plant interactions under stress conditions, which could offer insights into the varied responses observed in this research.

The extraction method employed to isolate specific compounds plays a crucial role in understanding the mechanisms behind allelopathy. It facilitates the identification of the compounds that contribute to the chemical interactions of *C. odorata* with its environment, highlighting its competitive edge over other flora (Poonpaiboonpipat, Krumsri and Kato-Noguchi, 2021). In this study, a water extraction method is used, which is a common approach in this field. For instance, Mason-Sedun, Jessop and Lovett (1986) noted a pronounced inhibitory effect of water extracts from *Brassica nigra* on wheat growth, while Oleszek (1987) found that volatiles from *B. nigra* suppressed germination in lettuce, barnyard grass, and wheat. Brown and Morra (1996) proposed that such inhibition might stem from the enzymatic breakdown of certain compounds, which release substances that block germination. In a similar vein, Alsherif *et al.* (2013) observed that water extracts and root exudates from black mustard significantly hindered the germination and growth of *Trifolium alexandrinum*, *Triticum aestivum*, *Phalaris paradoxa*, and *Sisymbrium irio*, noting a concentration-dependent effect where higher concentrations of aqueous extracts completely halted germination in all studied species. This finding corroborates the results of investigation under this study. Current findings align with theories proposing that the allelopathic influence of *C. odorata* results from the collective action of multiple compounds, rather than a solitary substance (Poonpaiboonpipat, Krumsri and Kato-Noguchi, 2021). This collaborative effect might generate new inhibitory agents or intensify the phytotoxic properties of existing molecules. Understanding these dynamics aids in elucidating plant-plant interactions and optimizing crop management strategies (Beck, Kleiner and Garrell, 2022).

Conclusion

In conclusion, the study elucidates the substantial allelopathic impacts of *Chromolaena odorata* root exudates on the germination and growth of six crop species unveiling the intricate and varied responses among different crops, underlying the complexity of allelopathic interactions in agricultural settings. The differential sensitivity observed among the species concentrates the potentiality for utilizing allelopathy as a strategic tool in sustainable weed management, though it also highlights the necessity for a distinct understanding of these interactions to avoid detrimental effects on crop health. The findings reveal a spectrum of responses from substantial inhibition to slight or partial recovery in germination rates across species, indicating the presence of specific metabolic or adaptive mechanisms to counteract allelopathic stress. The pronounced reductions in shoot and root lengths, alongside the significant decrease in chlorophyll content and increase in malondialdehyde levels, further emphasize the potential stress and damage induced by the allelo-chemicals present in *C. odorata* exudates. This research contributes to the growing body of knowledge on the ecological roles and impacts of allelopathy in agriculture, suggesting the necessity for further detailed studies to isolate and identify the active compounds within *C. odorata* exudates. Understanding these allelo-chemicals and their modes of action could lead to the development of novel, eco-friendly weed management strategies that leverage the natural inhibitory effects of certain plant species while safeguarding crop health and productivity. The possibility of using allelopathy as a sustainable substitute for conventional herbicide approaches in weed management is evident. However, its effective implementation demands a careful balance to harness its benefits without inadvertently harming desired crop species.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2
Conceived and designed the research or analysis	Yes	Yes
Collected the data	No	Yes
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	Yes
Editing of the article/paper	Yes	No
Supervision	Yes	Yes
Project Administration	Yes	Yes
Funding Acquisition	No	No
Overall Contribution Proportion (%)	55	45

Funding

No financial support was received for the research and writing of this article.

Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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