

Allelopathic effect of *Amaranthus* sp. on germination and early seedling development of soybean (*Glycine max*) and common bean (*Phaseolus vulgaris* L.)

Efeito alelopático de *Amaranthus* sp. sobre a germinação e o desenvolvimento inicial de plântulas de soja (*Glycine max*) e feijão (*Phaseolus vulgaris* L.)

Efecto alelopático de *Amaranthus* sp. sobre la germinación y el desarrollo inicial de las plántulas de la soja (*Glycine max*) y la alubia común (*Phaseolus vulgaris* L.)

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ABSTRACT

Weed species may impair the initial establishment of agricultural crops through competition for resources and the release of allelopathic compounds. This study aimed to evaluate the allelopathic effect of aqueous extract of *Amaranthus* sp. on the germination and early development of soybean (*Glycine max*) and common bean (*Phaseolus vulgaris* L.) seeds. The experiment was conducted under laboratory conditions in a completely randomized design, with five extract concentrations (0, 1.25, 2.5, 5.0, and 10%) and four replicates. Germination percentage, germination speed index, mean germination time, mean germination speed, shoot and root length, and dry matter accumulation were evaluated. The aqueous extract of *Amaranthus* sp. negatively affected soybean germination and vigor, with predominantly dose-dependent responses, including reductions in germination and delays in germination dynamics, indicating high sensitivity of the crop to secondary metabolites. Seedling growth was also impaired, with decreases in shoot and root development and biomass accumulation. In common bean, germination parameters were not affected by extract concentrations, indicating greater tolerance during this phase. However, early growth and biomass accumulation were reduced at higher concentrations, demonstrating that later developmental stages are more sensitive to allelopathic interference. Overall, the results confirm that *Amaranthus* sp. exhibits significant allelopathic potential capable of impairing crop establishment, particularly in soybean, with more pronounced effects during early developmental stages. These findings highlight the importance of effective management strategies to minimize the impact of this weed on crop performance.

Keywords: weed, secondary metabolites, seed vigor, allelopathic interference

RESUMO

Espécies de plantas daninhas podem comprometer o estabelecimento inicial de culturas agrícolas por meio da competição por recursos e da liberação de compostos alelopáticos. Este estudo teve como objetivo avaliar o efeito alelopático do extrato aquoso de *Amaranthus* sp. sobre a germinação e o desenvolvimento inicial de sementes de soja (*Glycine max*) e feijão comum (*Phaseolus vulgaris* L.). O experimento foi conduzido em condições de laboratório, em delineamento inteiramente casualizado, com cinco concentrações do extrato (0; 1,25; 2,5; 5,0 e 10%) e quatro repetições. Foram avaliados a porcentagem de germinação, o índice de velocidade de germinação, o tempo médio de germinação, a velocidade média de germinação, o comprimento da parte aérea e da raiz, e o acúmulo de matéria seca. O extrato aquoso de *Amaranthus* sp. afetou negativamente a germinação e o vigor da soja, com respostas predominantemente dependentes da dose, incluindo reduções na germinação e atrasos na dinâmica germinativa, indicando alta sensibilidade da cultura aos metabólitos secundários. O crescimento das plântulas também foi prejudicado, com reduções no desenvolvimento da parte aérea e das raízes, além do acúmulo de biomassa. No feijão comum, os parâmetros de germinação não foram afetados pelas concentrações do extrato, indicando maior tolerância nessa fase. No entanto, o crescimento inicial e o acúmulo de biomassa foram reduzidos

nas maiores concentrações, demonstrando que estádios posteriores de desenvolvimento são mais sensíveis à interferência alelopática. De modo geral, os resultados confirmam que *Amaranthus* sp. apresenta significativo potencial alelopático, capaz de comprometer o estabelecimento das culturas, especialmente da soja, com efeitos mais pronunciados nos estádios iniciais de desenvolvimento. Esses achados destacam a importância de estratégias de manejo eficazes para minimizar o impacto dessa planta daninha sobre o desempenho das culturas.

Palavras-chave: planta daninha, metabólitos secundários, vigor de sementes, interferência alelopática

RESUMEN

Las especies de malas hierbas pueden comprometer el establecimiento inicial de los cultivos agrícolas mediante la competencia por los recursos y la liberación de compuestos alelopáticos. El objetivo de este estudio fue evaluar el efecto alelopático del extracto acuoso de *Amaranthus* sp. sobre la germinación y el desarrollo inicial de las semillas de soja (*Glycine max*) y de judía común (*Phaseolus vulgaris* L.). El experimento se llevó a cabo en condiciones de laboratorio, con un diseño totalmente aleatorizado, con cinco concentraciones del extracto (0; 1,25; 2,5; 5,0 y 10 %) y cuatro repeticiones. Se evaluaron el porcentaje de germinación, el índice de velocidad de germinación, el tiempo medio de germinación, la velocidad media de germinación, la longitud de la parte aérea y de la raíz, y la acumulación de materia seca. El extracto acuoso de *Amaranthus* sp. afectó negativamente a la germinación y al vigor de la soja, con respuestas predominantemente dependientes de la dosis, incluyendo reducciones en la germinación y retrasos en la dinámica germinativa, lo que indica una alta sensibilidad del cultivo a los metabolitos secundarios. El crecimiento de las plántulas también se vio perjudicado, con reducciones en el desarrollo de la parte aérea y de las raíces, así como en la acumulación de biomasa. En el frijol común, los parámetros de germinación no se vieron afectados por las concentraciones del extracto, lo que indica una mayor tolerancia en esta fase. Sin embargo, el crecimiento inicial y la acumulación de biomasa se vieron reducidos en las concentraciones más elevadas, lo que demuestra que las etapas posteriores del desarrollo son más sensibles a la interferencia alelopática. En general, los resultados confirman que *Amaranthus* sp. presenta un potencial alelopático significativo, capaz de comprometer el establecimiento de los cultivos, especialmente de la soja, con efectos más pronunciados en las etapas iniciales del desarrollo. Estos hallazgos ponen de relieve la importancia de contar con estrategias de gestión eficaces para minimizar el impacto de esta maleza sobre el rendimiento de los cultivos.

Palabras clave: planta adventicia, metabolitos secundarios, vigor de las semillas, interferencia alelopática

1 INTRODUCTION

Weeds are among the main factors limiting agricultural productivity, as they compete with crops for essential resources such as water, light, and nutrients, in addition to exerting allelopathic effects that may impair germination and early plant development. These effects result in increased production costs and reduced crop profitability, representing a recurrent challenge in agricultural systems (Vasconcelos et al., 2012; EMBRAPA, 2024; Nunes et al., 2026).

Among the species of greatest agronomic importance, the genus *Amaranthus*, commonly known as pigweed, stands out due to its wide distribution in Brazilian agricultural areas. Species of

this genus exhibit a high capacity for seed production, high viability, and germination under different environmental conditions, including the presence or absence of light, which favors multiple emergence flushes throughout the crop cycle (Penckowski et al., 2020). This characteristic confers high competitive aggressiveness and makes weed management in production systems more difficult.

In addition to direct competition, *Amaranthus* species may negatively interfere with crop establishment through the release of allelopathic compounds, which affect essential physiological processes such as germination and early seedling growth. The presence of *Amaranthus hybridus*, for example, may cause significant reductions in the yield of crops such as soybean and maize, and may even hinder mechanized harvesting when not properly managed (Penckowski et al., 2020).

Given the increasing occurrence of *Amaranthus* populations resistant to ALS- and EPSPS-inhibiting herbicides, it is essential to understand the effects of this weed on economically important crops, especially during the early stages of development. Therefore, the objective of this study was to evaluate the allelopathic effect of *Amaranthus* sp. on the germination of soybean (*Glycine max*) and common bean (*Phaseolus vulgaris* L.) seeds.

2 MATERIAL AND METHODS

The experiment was conducted at the Plant Physiology Laboratory of the Federal University of Technology – Paraná (UTFPR), Dois Vizinhos campus, Paraná, Brazil. *Amaranthus* sp. plants (shoots and root system) were collected and dried in a greenhouse for seven days and subsequently ground using a blender. The crude extract was prepared at a concentration of 10% (w/v), using 100 g of dry matter in 1,000 mL of distilled water, and allowed to stand for 24 h in a dark environment. From the crude extract, dilutions were prepared to obtain concentrations of 5.0, 2.5, and 1.25%, in addition to a control treatment containing only distilled water (0%). The pH of the solutions was measured using a digital pH meter and remained within the range recommended for germination tests (Brasil, 2009).

The experimental design was completely randomized, with five treatments (0, 1.25, 2.5, 5.0, and 10%) and four replicates. Each experimental unit consisted of 20 soybean (*Glycine max*) seeds, cultivar Brasmax Zeus, and 20 common bean (*Phaseolus vulgaris* L.) seeds, cultivar IPR Urutau. Seeds were placed on germination paper (germitest), moistened with a solution volume equivalent to 2.5 times the dry weight of the paper, using the between-paper method. The rolls were placed in plastic bags and maintained under suitable conditions for germination. The seeds used showed germination above 90% in a preliminary test.

Evaluations were performed at 5 and 8 days after sowing, determining germination percentage, germination speed index, mean germination time, and mean germination speed. At the end of the experimental period, at 8 days, shoot and root length of the seedlings were measured, as well as the dry matter of these structures. Length was measured using a millimeter ruler, and dry matter was obtained after drying the seedlings in a forced-air oven at 65 °C for 72 h, followed by weighing on an analytical balance.

The data were subjected to normality testing and analysis of variance. For quantitative variables, regression analysis was performed, adopting a significance level of 5%. All statistical analyses were carried out using the R software (R Core Team, 2025).

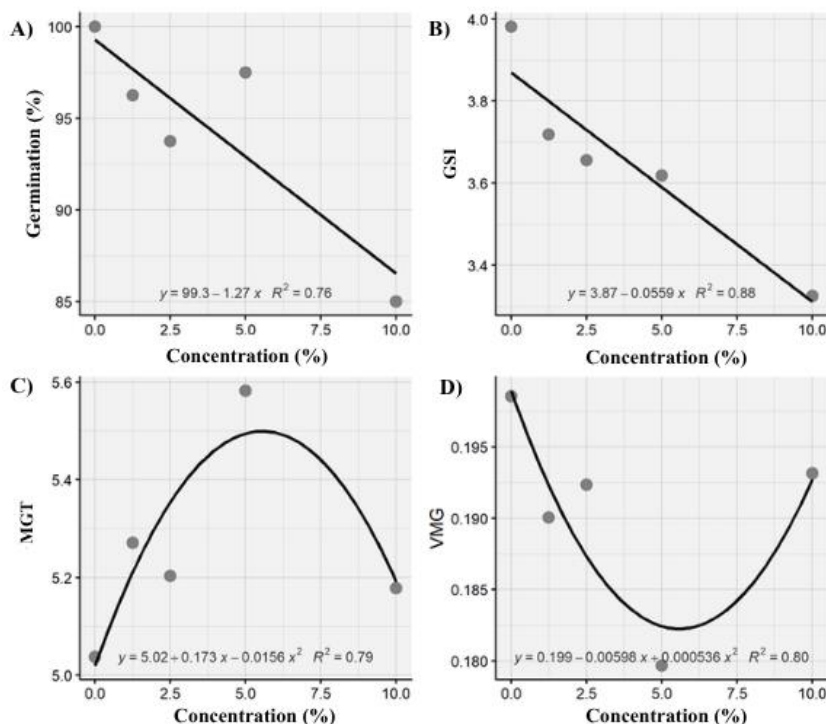
3 RESULTS AND DISCUSSION

Soybean seed germination was negatively affected by the application of aqueous extract of *Amaranthus* sp., showing a decreasing linear response as extract concentration increased (Fig. 1A). The regression equation indicated an approximate reduction of 1.27% in germination for each 1% increase in extract concentration, evidencing a clear dose-dependent effect and suggesting direct interference of the compounds present in the extract on the initial metabolic activation processes of the seeds.

The germination speed index also showed a progressive reduction with increasing extract concentrations (Fig. 1B), indicating not only a lower proportion of germinated seeds but also a delay in the germination process. This behavior reflects a reduction in seed vigor, which may compromise uniform seedling emergence and, consequently, initial crop establishment under field conditions.

For mean germination time and mean germination speed (Figs. 1C and 1D), a distinct response was observed at the highest concentration evaluated (10%). Under this condition, there was a reduction in the total number of germinated seeds; however, those that did germinate exhibited shorter mean germination time and higher germination speed. This result suggests a possible selective effect of the extract, in which only seeds more tolerant to allelopathic compounds are able to complete the germination process more rapidly, while more sensitive seeds have their germination inhibited. Such a pattern may indicate physiological variability among seeds, with important implications for interpreting the effects of the extract on vigor and the crop's establishment capacity.

Figure 1. Germination (%), germination speed index (GSI), mean germination time (MGT), and mean germination speed (MGS) of soybean seeds subjected to different concentrations of aqueous extract of *Amaranthus* sp.



Fonte: Elaborado pelos autores (2026).

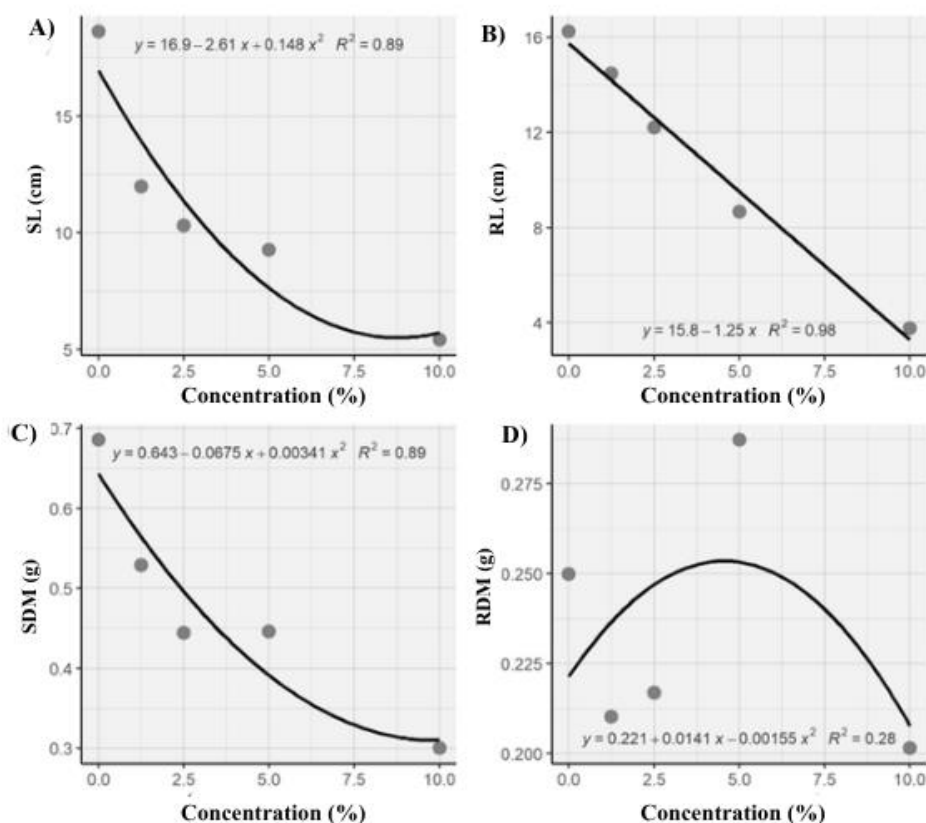
The early growth of soybean seedlings was significantly impaired by the application of aqueous extract of *Amaranthus* sp., as evidenced by consistent reductions in shoot length, root system development, and shoot dry matter accumulation (Fig. 2). These results indicate that the compounds present in the extract exert a direct inhibitory effect on early seedling development, compromising both cell expansion and the establishment of essential structures for water and nutrient uptake.

The limitation in root growth is particularly relevant, as the root system plays a fundamental role in soil exploration and in supporting plant growth. Reductions in this structure may result in lower efficiency in resource uptake and increased vulnerability to abiotic stresses, negatively affecting subsequent crop development.

Regarding root dry matter, the quadratic response observed, with maximum accumulation at the 5% concentration and a reduction at higher concentrations (Fig. 2D), suggests the occurrence of a possible hormetic effect. This pattern indicates that low to moderate concentrations of the compounds present in the extract may stimulate certain physiological processes, whereas higher concentrations exert a toxic effect, inhibiting growth. However, the reduction observed at higher concentrations reinforces the phytotoxic potential of the extract, indicating that the predominant effect at elevated levels is inhibition of root development.

Overall, the results demonstrate that, in addition to affecting germination, the extract of *Amaranthus* sp. significantly compromises the early growth of soybean seedlings, which may have direct implications for crop establishment and, consequently, for final productivity under field conditions.

Figure 2. Shoot length, root length, shoot dry matter, and root dry matter of soybean seedlings subjected to different concentrations of aqueous extract of *Amaranthus* sp.



Fonte: Elaborado pelos autores (2026).

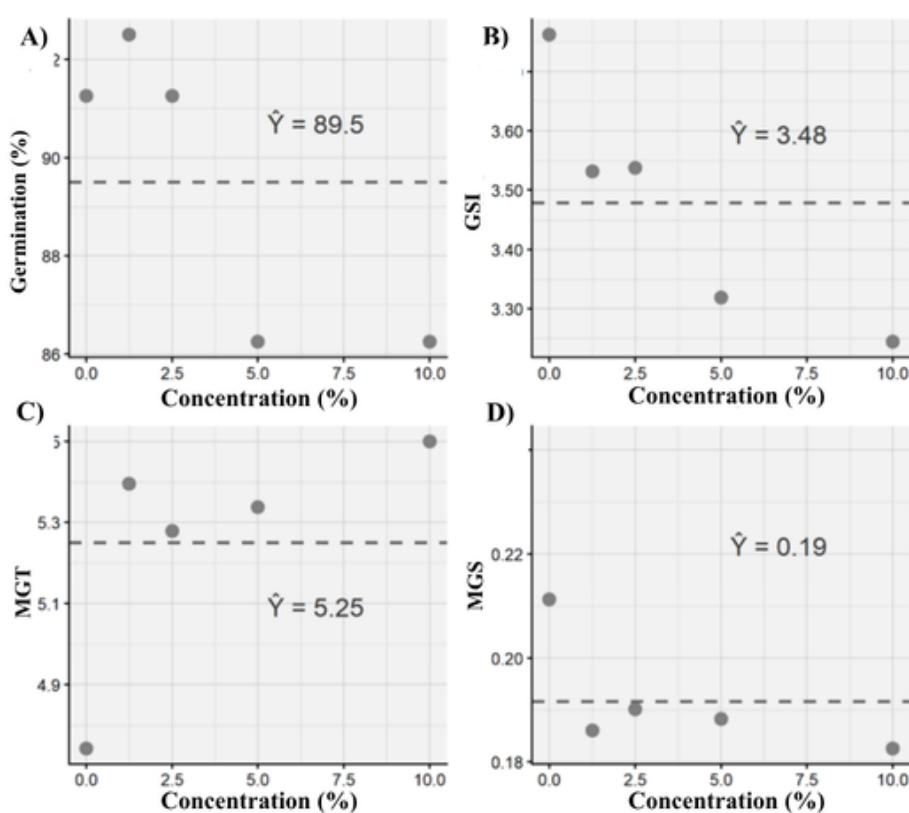
In common bean, germination-related parameters were not influenced by the different concentrations of the aqueous extract (Fig. 3), indicating the absence of a significant allelopathic effect during this initial stage of development. Germination percentage, germination speed index, mean germination time, and mean germination speed remained stable across treatments, demonstrating that the germination process occurred consistently regardless of the presence of compounds in the extract.

This behavior suggests greater physiological tolerance of common bean seeds to the secondary metabolites released by *Amaranthus* sp. during the germination phase, possibly due to mechanisms that limit the uptake or effects of these compounds during the early stages of seed

metabolism. The stability of these indices also indicates that processes such as imbibition, enzymatic activation, and reserve mobilization were not significantly affected.

Moreover, the maintenance of germination speed and timing across treatments shows that there was no delay in the germination process, which is an important indicator of preserved initial vigor at this stage. However, the absence of effects on germination does not necessarily imply tolerance throughout the entire developmental cycle, making it essential to evaluate subsequent growth stages to fully understand the impact of allelopathic compounds on the crop.

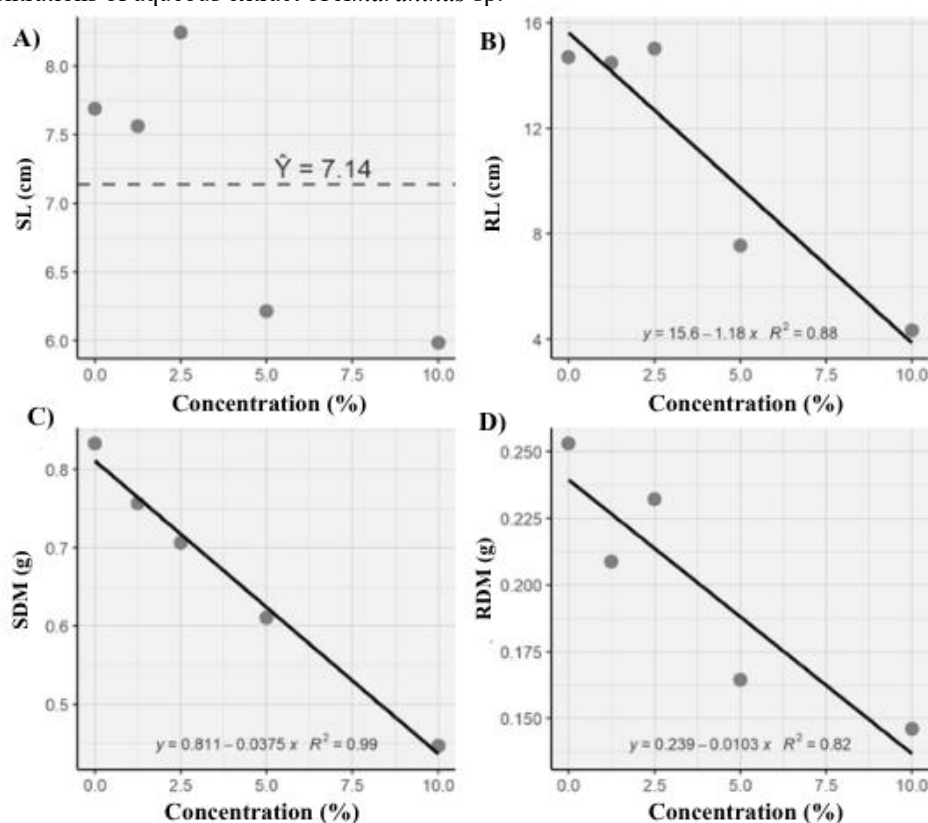
Figure 3. Germination (%), germination speed index (GSI), mean germination time (MGT), and mean germination speed (MGS) of common bean seeds subjected to different concentrations of aqueous extract of *Amaranthus* sp.



Fonte: Elaborado pelos autores (2026).

Early growth of common bean was negatively affected, especially at higher concentrations (Fig. 4). Root length, root dry matter, and shoot dry matter showed reductions with increasing extract dose.

Figure 4. Shoot length, root length, shoot dry matter, and root dry matter of common bean seedlings subjected to different concentrations of aqueous extract of *Amaranthus* sp.



Fonte: Elaborado pelos autores (2026).

The negative effects observed on soybean germination and vigor consistently indicate a dose-dependent allelopathic action of secondary metabolites released by *Amaranthus* sp., which may directly interfere with fundamental physiological processes such as water uptake, enzymatic activity, and reserve mobilization (Ferreira & Aquila, 2000; Rice, 2012). The progressive reduction in germination and germination speed index suggests that these compounds act from the earliest stages of the germination process, impairing seed metabolic reactivation and, consequently, uniform seedling emergence. This type of interference may result in stand irregularity, reducing crop competitiveness during the initial stages of development.

The response observed at the highest concentration, characterized by faster germination among a reduced number of seeds, may be associated with the selection of physiologically more tolerant individuals. This behavior suggests intraspecific variability in resistance to the compounds released by *Amaranthus* sp., which may have important implications for crop adaptation under chemical stress conditions. Under field conditions, a shorter mean germination time for tolerant individuals may represent an adaptive advantage, favoring initial crop establishment, especially in competitive environments (Martins et al., 2016). However, the reduction in the total number of emerged seedlings tends to offset this potential benefit, resulting in losses in final plant stand.

The slight acidification of the medium was not considered a determining factor for the observed effects, since pH values remained within the suitable range for soybean development. This finding reinforces that the observed impacts are predominantly due to the action of allelochemicals rather than physicochemical changes in the medium (Fageria & Baligar, 1999). Thus, it is evident that the secondary metabolites present in the extract have sufficient biological activity to interfere with physiological processes independently of pH variations.

The reduction in seedling growth, evidenced by decreases in shoot length, root length, and dry matter accumulation, confirms the phytotoxic effect of compounds such as phenolics, flavonoids, and terpenes, which act by inhibiting cell elongation and possibly affecting processes related to cell division and membrane integrity (Ain et al., 2023). These effects directly compromise the formation of essential structures for water and nutrient uptake, such as roots, limiting early plant development and its capacity to explore the soil.

The quadratic response observed for root dry matter, with an increase at intermediate doses and a reduction at higher concentrations, suggests the occurrence of a hormetic effect, in which low concentrations of potentially toxic compounds may stimulate certain physiological processes, while higher doses promote inhibition (Zhao & Wang, 2012; Butov et al., 2001). However, data variability indicates that this effect should be interpreted with caution, considering the possibility of differential responses depending on individual seedling sensitivity.

The reduction in biomass accumulation observed in both shoot and root systems has direct implications for crop productivity, since biomass is closely related to physiological efficiency and yield potential, reflecting the plant's ability to convert resources into growth and, subsequently, grain production (Liu et al., 2024; Somerville, 2001; Gai & Zhang, 2017; Bao & Yao, 2024). Therefore, allelopathic interference during early stages may have persistent effects throughout the crop cycle, resulting in significant yield losses.

In common bean, the absence of effects on germination parameters indicates greater tolerance during this initial phase, corroborating studies that report lower sensitivity of germination to allelochemicals compared to other developmental stages (Ferreira & Aquila, 2000). However, the observed reduction in early growth and biomass production demonstrates that subsequent developmental stages are more susceptible to the action of compounds released by *Amaranthus* sp. This response pattern highlights the importance of evaluating not only germination but also vigor and early growth when investigating allelopathic effects.

Overall, the results confirm the high allelopathic potential of *Amaranthus* sp., with more pronounced effects on soybean compared to common bean. This interference may impair initial crop establishment, reducing competitiveness in agricultural systems, especially under field conditions

where competition for resources occurs simultaneously (Pitelli & Pitelli, 2004). Thus, these findings reinforce the need for efficient and early management strategies for *Amaranthus* species, particularly due to their high aggressiveness and potential negative impact on crop productivity.

4 CONCLUSION

The results of this study consistently demonstrate that species of the genus *Amaranthus* exhibit significant allelopathic potential, capable of negatively interfering with the initial establishment of agricultural crops. Soybean (*Glycine max*) proved to be highly sensitive to the secondary metabolites released, showing reductions in germination, vigor, and early seedling growth, with predominantly dose-dependent responses. These effects indicate that the presence of this weed can compromise essential physiological processes during the early stages of crop development.

On the other hand, common bean (*Phaseolus vulgaris*) showed greater tolerance during the germination phase, although its early growth and biomass production were negatively affected at higher extract concentrations. This behavior indicates that even when germination is not directly impacted, subsequent development may be significantly impaired, compromising crop performance throughout the cycle.

Thus, it can be concluded that the allelopathic interference of *Amaranthus* sp. represents a relevant factor in weed management, especially in soybean production systems, where the impacts are more severe. These findings reinforce the importance of efficient and early management strategies for these species in order to minimize their effects on crop establishment and, consequently, on agricultural productivity.

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