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Dominance of *Ricinus communis* in the Semi-Arid Region Mediated by Allelopathy

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ABSTRACT

The introduction of invasive alien species can adversely affect the functioning of natural ecosystems. *Ricinus communis* L., widely present in the Brazilian semi-arid region, establishes itself in areas with native species, such as *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, because it does not go dormant and disperses balocorically, which can affect the latter's plant succession. This study aimed to evaluate whether the leaf biomass of *R. communis* exerts a negative allelopathic effect associated with its introduction into natural ecosystems. Leaves of *R. communis*, collected at the end of senescence, were mixed in alternating layers with Caatinga soil and allowed to decompose for 90 days at different concentrations by total soil mass (w/w). The chemical constituents of the decomposed *R. communis* material were identified using GC–MS. The GC–MS chromatographic analysis revealed the presence of 10 compounds, grouped into five main classes: monoglycerides, alkanes, fatty acids, terpenes and monosaccharides. Key compounds identified include Phytol ($C_{20}H_{40}O$) and palmitic acid ($C_{16}H_{32}O_2$). The byproducts of *R. communis* leaf decomposition had negative effects on seedling germination. At the two highest leaf litter concentrations, a 90% reduction in the seed germination rate was observed. For the post-germination period, results showed a correlation between the residence time of allelochemicals in the substrate and the concentration of leaf biomass, with negative effects being most prominent at the highest concentration of *R. communis* leaves. Regarding the morpho-anatomical analysis, significant variations in the tissue thickness of the radicle and hypocotyl were observed, in addition to pronounced qualitative changes. The results of this study confirm *R. communis* exhibits negative allelopathic potential against *H. impetiginosus*. This may lead to the reduction or elimination of the latter species in the medium to long term, directly impacting plant succession within the natural ecosystem.

1 | Introduction

The introduction of invasive alien species into natural ecosystems adversely affects their functioning (Jones and McDermott 2017; Bartz and Kowarik 2019). These species cause significant ecological and socioeconomic impacts, affecting both biodiversity and agricultural production systems (Bellard et al. 2016; Bartz and Kowarik 2019). Key factors driving the introduction and spread of these species include globalisation, the growth of international trade and tourism, climate change and alterations to land and water cycles, particularly those linked to the agribusiness sector (Williams et al. 2020; Dally et al. 2023).

A species is characterised as alien and invasive when, upon introduction to a new environment, it adapts effectively, establishes a self-sustaining population through efficient reproductive

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mechanisms and eventually spreads to areas adjacent to its point of introduction (Richardson et al. 2000). Certain biological mechanisms can facilitate this process; for instance, allelopathy is cited in the literature as a strategy that contributes to successful biological invasion (Santana and Encinas 2008; Chen et al. 2017).

In recent decades, allelopathy has been defined by the International Allelopathy Society (IAS) as a mechanism of interaction mediated by secondary metabolites produced by different organisms (Gniazdowska and Bogatek 2005; Silva et al. 2017). This process can favour or inhibit the development of other plant species through allelochemicals (Duke 2010; Silva 2012). The release of allelochemicals into the environment can occur through different mechanisms, including leaching, volatilization, root exudation and decomposition of plant residues (Zhang and Fu 2009; Cheng and Koskinen 2010). Recent studies have suggested that the decomposition of organic matter is one of the main pathways for the release of allelochemicals into the ecosystem (Huang et al. 2013; Silva et al. 2021).

Ricinus communis L. (Euphorbiaceae), native to Ethiopia, is a widespread invasive alien species (Matthews 2005). It is an oilseed plant, perennial and shrubby in habit, reaching up to 5 m in height (Flora e Funga do Brasil 2026). It is one of the main oilseeds grown in semi-arid and arid regions, such as China, India and Russia, and is a species with high tolerance to dry environments (Babita et al. 2010). Floristic composition studies have documented its presence in various regions across the globe, highlighting its remarkable adaptability to diverse vegetation types (Wagay et al. 2015; Khan and Badshah 2019; Hossain et al. 2022). The species is found in the Americas, Africa and Madagascar (Tropicos 2026) and is commonly reported in floristic composition studies from Brazil, India, Pakistan and Bangladesh—regions characterised by more arid climates (Wagay et al. 2015; Khan and Badshah 2019; Fernando et al. 2022; Hossain et al. 2022).

Recent studies have highlighted the allelopathic potential of *R. communis*, particularly in research employing aqueous extracts or organic solvents such as methanol and ethanol (Anwar et al. 2021; Haque et al. 2020; Silva et al. 2016). However, its allelopathic effects mediated through leaf litter decomposition, considering the ecosystem's own biotic and abiotic factors, remain poorly understood. Among the native semiarid species that may be affected by the introduction and establishment of *R. communis*, *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (Bignoniaceae) is a notable example.

Recent studies have highlighted the need for the conservation of *H. impetiginosus*, particularly in Caatinga regions, given its ecological, economic and medicinal importance (Santos Filho and Messina 2012; Rocha et al. 2019; Lunardi et al. 2019). The hypothesis of this research is that the continuous production of biomass by the exotic species *R. communis* throughout the year, even under extreme environmental conditions, results in the saturation of the environment through the constant release of allelochemicals, negatively impacting the establishment and development of native species in the ecosystem where it was introduced, such as *H. impetiginosus*.

Therefore, this study aimed to evaluate the allelopathic potential of *R. communis* leaf biomass on the germination and post-germination processes of *H. impetiginosus*, as well as to investigate the interactions among different physiological parameters throughout the plant's ontogeny.

Considering the objective of this study, the following research questions were formulated: (i) does the leaf litter decomposition of *R. communis* affect the germination and early seedling development of *H. impetiginosus*? (ii) What chemical compounds remain in the substrate following the decomposition of *R. communis* leaf biomass and how is their persistence related to the decomposition time and the concentration of biomass added to the soil? (iii) Does the allelopathic potential of *R. communis* cause anatomical changes in the various organs of *H. impetiginosus* seedlings? (iv) What are the impacts of introducing this invasive alien species on the ecological succession of the studied native species?

2 | Materials and Methods

2.1 | Plant Material Collection

Fertile branches (bearing flowers and/or fruits) of the donor species, *R. communis* (7°13′13″S, 39°8′34″W) and the target species, *H. impetiginosus* (7°13′14″S, 39°8′40″W), were collected for botanical identification. The collection took place in an area of Caatinga (Northeastern Brazil) within the municipality of Missão Velha, Ceará (CE) (Figure 1). For identification purposes, specimens of both species were prepared for herbarium preservation following standard techniques. They were identified by comparison with previously authenticated material and confirmed using specialised literature. The voucher specimens were deposited in the collection of the Herbarium Caririense Dárdano de Andrade-Lima (HCDAL) at the Regional University of Cariri (URCA) under the accession numbers 15 750 and 15 991, respectively.

The study area is situated near one of the Cariri Metropolitan Regions (RMC) in the southern part of Ceará state. The municipality's average temperature is 25.8°C, with an average annual precipitation of 942 mm. The region's climate is characterised by two well-defined seasons: a rainy season from January to April and a dry season from May to December. August is the driest period in terms of precipitation (averaging 4 mm) and November is the warmest month (averaging 27.2°C).

Senescent leaves of *R. communis*—defined as those naturally shed by the parent plant or fully yellowed leaves that could be detached from the adult plant without exudation—were collected for allelopathy assays in February 2023 during the rainy season (Figure 1). The *H. impetiginosus* seeds used in the germination bioassays were collected from the same area as the *R. communis* leaves (Figure 1), ensuring the natural co-occurrence conditions of both species were maintained. The seeds were collected in August 2022 and subsequently stored in paper bags under refrigeration at 10°C until the assays were performed, a method considered suitable for the storage of forest seeds (Silva et al. 2021).

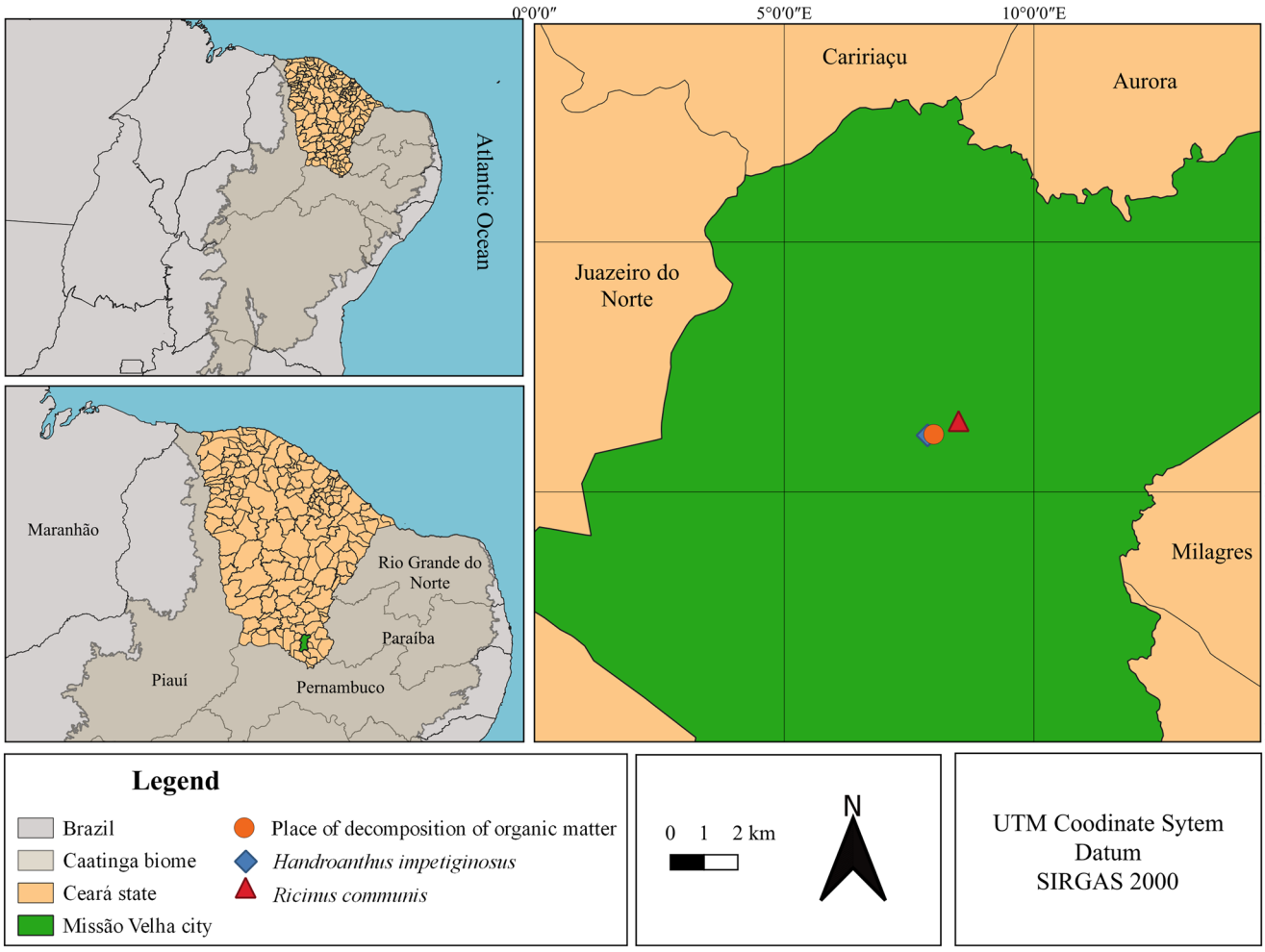

FIGURE 1 | Map showing the collection sites of *Ricinus communis* L. Aiton and *Handroanthus impetiginosus* (Mart. Ex DC) Mattos in the municipality of Missão Velha, Ceará, Brazil.

2.2 | Soil Sampling

The soil used as a substrate for the leaf litter decomposition process was collected from the A horizon (10–20 cm depth). To preserve the natural conditions for germination and the microbiota associated with decomposition, the collection site was the same area where the study's donor and target species occur (Figure 1). Sampling was conducted in February 2023, during the region's rainy season, at the same time and location as the occurrence of *R. communis* (Figure 1).

Soil subsamples were collected randomly at five different locations where the target species (*H. impetiginosus*) and donor species (*R. communis*) occurred within the same study area, comprising the sampling of the study area. This methodology aimed to capture the spatial variability and physicochemical properties of the soil associated with the presence of the exotic species, allowing for the assessment of possible environmental changes and their potential allelopathic effects on the native species.

2.3 | Leaf Decomposition

The quantity of leaves used for the experiment was determined based on the annual leaf production of the donor species, which is approximately 20 t/ha/year (Cavalcanti et al. 2005). This production rate corresponds to an application rate of 20 g of leaves per kg of soil, which was established as the first experimental treatment (T1). The subsequent treatments were designed to simulate the accumulation of organic matter. The soil amended with *R. communis* leaves was incubated in a 5 m^2 plot within the Caatinga biome in the municipality of Missão Velha, CE and allowed to decompose for a 90-day period (Huang et al. 2013).

To simulate the decomposition process, leaves of *R. communis* were interlayered with soil and allowed to decompose at different concentrations (w/w) (Huang et al. 2013; Silva et al. 2021). The soil and leaf mixtures were contained in fine-mesh bags, which allowed the substrate to interact with the surrounding environment. The treatments consisted of three concentrations: 20 (T1), 40 (T2) and 60 (T3) grams of leaves per kg of Caatinga soil (Silva et al. 2021). The control group (CK) consisted of Caatinga soil alone.

2.4 | Analysis of Soil Physicochemical Properties

Following decomposition, all soil samples (CK, T1, T2 and T3) were quantified for their nutrient content. The analysed

macronutrients were Phosphorus (P), Calcium (Ca), Magnesium (Mg) and Potassium (K) and the micronutrients were Sodium (Na) and Aluminium (Al). Additionally, the soil pH was measured. The pH measurement was performed using a combined electrode immersed in a 1:2.5 soil–liquid suspension (Donagema et al. 2011). All nutrients were analysed according to the methodology presented in Embrapa's Soil Analysis Methods Manual (Embrapa 1997).

2.5 | Phytochemical Analysis

2.5.1 | Extract Preparation

Organic compounds were extracted using organic solvents from soil amended with *R. communis* at a rate of 60 g/kg (T3). The extraction was performed immediately following a 90-day decomposition period. Soil from the control group (CK) was also subjected to the same extraction procedure (Almeida-Bezerra et al. 2022). The physical–chemical analysis was performed only on the highest concentration of leaf litter (60 g of leaves per kg of soil), as it represents the condition of highest organic matter input and, thus, the highest amount of secondary compounds and nutrients released. This concentration allows for more sensitive detection of the compounds released during decomposition.

Initially, the nonpolar compounds present in the soil samples (T3 and CK) were extracted. This was performed through an exhaustive extraction by mixing 4 kg of soil with 8 L of *n*-hexane (a 1:2 w/v ratio). The mixture was kept protected from light for 96 h and was subsequently filtered to separate the solid and liquid phases. The samples were filtered twice using a funnel and cotton disc filters, allowing separation between the solvent and solid substrate. Afterward, the soil residue was air-dried at room temperature and re-extracted with ethanol to obtain the polar compounds. Following filtration, the solvent from the resulting extract was distilled off using a rotary evaporator (Model Q-344B, Quimis, Diadema, Brazil) (Almeida-Bezerra et al. 2022). The extracts were subjected to rotary evaporation at 40°C and 60°C for hexane and ethanol solvents, respectively.

2.5.2 | Identification of Compounds From *R. communis* by Gas Chromatography–Mass Spectrometry (GC–MS)

The crude extracts from both solvents (hexane and ethanol) were weighed on an analytical balance and subsequently diluted in their respective solvent (1:1 w/v). A 50 μL aliquot of each extract was then transferred to a vial insert and dried using a vacuum concentrator. The dried residues were derivatized with 25 μL of pyridine and 25 μL of N,O-bis-(trimethylsilyl)-trifluoroacetamide (BSTFA) for 1 h at 70°C. The samples (1 μL) were injected into a gas chromatograph (Agilent 6850 Network GC System) coupled to a mass spectrometer (Agilent 5975 VL MSD) (GC–MS), equipped with an Agilent HP5-MS capillary column (30 m × 0.25 mm i.d. × 0.25 μm film thickness). The initial column temperature was held at 100°C for 5 min, then increased at a rate of 5°C/min to a final temperature of 320°C, for a total run time of 49 min. Helium was used as the carrier gas at a constant flow rate of 1 mL/min. The injector, ion source and quadrupole temperatures were set to 300°C, 230°C and 150°C, respectively. Ionisation was performed by electron impact (EI) at 70 eV, with the mass spectrometer operating in full scan acquisition mode over a mass range of 50–600 m/z at 2.66 scans/s.

The mass spectrometry data for each extract was processed using deconvolution, peak alignment and Linear Retention Index (LRI) calculation, which was based on a C8 to C40 alkane standard. Compound annotation was performed using matches from the GNPS and NIST libraries, generating a feature table that included peak area, molecular ion, retention time, and a putative identification for each detected compound. A minimum cosine score of 0.30 and an LRI window of 30 were applied for identification. Compounds that exceeded the minimum cosine score but lacked a corresponding LRI match were putatively assigned to the same chemical class as the hit suggested by the GNPS data (Sala-Carvalho et al. 2022).

2.6 | Germination and Growth Assay of *Handroanthus impetiginosus*

Following the decomposition period, the bags containing soil with different concentrations of leaf litter were taken to the Applied Botany Laboratory (LBA) at the Regional University of Cariri (URCA) in Crato, CE, Brazil, to conduct the germination and growth experiments on the *H. impetiginosus* seeds.

2.6.1 | Germination Assay

The target seeds were surface-sterilised in a 5% sodium hypochlorite solution for 5 min, and subsequently rinsed under running and distilled water for the same duration (Pacheco et al. 2008). The germination bioassays were conducted in a greenhouse using polyethylene trays. Soil containing decomposed plant material from *R. communis* was used as the substrate, alongside the control soil (CK).

The experiment was set up in quadruplicate, with each replicate consisting of 30 seeds. A single seed was sown in each cell. The substrate was initially moistened with 7 mL of distilled water to achieve 60% of its field capacity, followed by daily watering to maintain this moisture level (Brasil 2009). Observations were made daily for 15 days, and a seed was considered to have germinated upon hypocotyl emergence.

At the end of each evaluation, the following parameters were calculated: germination percentage (%), the Emergence Speed Index (ESI), synchrony (E), and the time to 50% germination (T_{50}). The germination percentage for the target species' seeds was calculated using the formula: $G = (N/A) \times 100$, where G is the germination percentage, N is the number of germinated seeds, and A is the total number of seeds sown (Laboriau 1983).

Emergence Speed Index (ESI) was calculated according to Maguire (1962) using the formula: ESI = E1/N1 + E2/N2 +...+ En/Nn. Where E1, E2,...En is the number of normal seedlings

that emerged, recorded at the first, second, and final count, respectively; and N1, N2, ...Nn is the number of days from sowing to the first, second, and final count.

The time required to reach 50% germination (T_{50}) was determined using the formula proposed by Coolbear et al. (1984): $T_{50} = ti + (N/2 - ni) \times (tj - ti)/(nj - ni)$, where N is the final number of germinated seeds, and ni and nj are the cumulative numbers of germinated seeds at times ti and tj, respectively, such that $ni < N/2 < nj$. The synchronisation index was calculated according to the formula proposed by Labouriau and Pacheco (1978).

2.6.2 | Growth Assay

Seeds of the target species were set to germinate in previously disinfected germination boxes. The substrate consisted of two sheets of germination paper moistened with 5 mL of distilled water. The bioassays were maintained in a BOD (Biochemical Oxygen Demand) incubator at a constant temperature of 30°C and a 12-h light/dark photoperiod (Pacheco et al. 2008).

Following germination, seedlings exhibiting 10 mm of radicle protrusion were transplanted into 30-cell (200 mL) polyethylene trays. The trays contained the soil for the different leaf litter concentration treatments (T1, T2 and T3) and the control group (CK). Prior to planting, the substrate in the containers was moistened with distilled water to 60% of its field capacity (Brasil 2009).

The experimental design consisted of 30 replicates for each treatment, with each replicate comprising a single *H. impetiginosus* seedling. Following sowing, the containers were moved to a greenhouse where they remained for a 2-month (60-day) period. Throughout the experiment, the seedlings were watered every 2–3 days as needed to maintain adequate soil moisture. At the end of the 60-day growth period, the seedlings were transported to the laboratory, removed from their containers, and carefully washed with running water. They were then processed for the subsequent measurement of growth parameters, dry weight, chlorophyll and carotenoid content, and leaf area.

The lengths of the root, hypocotyl, and epicotyl of *H. impetiginosus* seedlings were measured using a ruler graduated in millimetres. Hypocotyl length was measured from the root collar to the cotyledon, and epicotyl length was measured from the cotyledon to the shoot apex. Root length was measured from the root collar to the root tip. All results were expressed in millimetres (mm).

To determine the dry weight, the seedlings were separated into shoots and roots. These parts were placed in previously labelled paper bags and then put into a forced-air oven set at 105°C for 30 min. Following this period, the temperature was lowered to 80°C, where the samples remained for 24 h. Subsequently, the dry weight of the shoots and roots was measured using an analytical balance (Huang et al. 2013).

To determine the leaf area, 10 seedlings were selected from each treatment. The petioles were removed from the leaves, which were then photographed. The leaf blade area was subsequently calculated using ImageJ software (version 1.54 h).

2.7 | Morphoanatomical Analysis

The morphoanatomical analysis was conducted on the radicle and hypocotyl of H. impetiginosus. Seedlings were collected 15 days after the germination test was initiated. All collected plant materials were fixed in FAA 50 (formaldehyde, glacial acetic acid, and 50% ethanol, v/v) for 48 h and subsequently stored in 70% ethanol, according to the method proposed by Johansen (1940).

Anatomical sections were prepared by freehand sectioning. The standard starting point for sectioning was defined as 4 mm below the root collar for the radicle and 4 mm below the cotyledons for the hypocotyl. For the anatomical analysis, sections from five radicles and five hypocotyls were used per replicate.

The samples were stained with fuchsin and astra blue (Roeser 1962) and mounted in glycerinated gelatin between a microscope slide and a coverslip. The specimens were then analysed using a light microscope (at 10× and 40× objective magnifications) connected to a computer running Motic software (version 3.0). To better understand how allelopathic compounds influence the target species' morphology, several variables were measured, including the thickness of the epidermis, cortex, and vascular cylinder. A qualitative and quantitative analysis of the changes and thickness of the plant tissues was performed to generate data for subsequent statistical analysis.

2.8 | Statistical Analysis

Data were analysed by one-way analysis of variance (ANOVA), with means compared using Tukey's multiple comparisons test. A significance level of $p < 0.05$ was used. Before analysis, data were assessed for normality using the D'Agostino & Pearson, Shapiro–Wilk, and Kolmogorov–Smirnov tests, while homoscedasticity was verified using Levene's test. Data that were not normally distributed were analysed using the non-parametric Kruskal-Wallis test. All statistical analyses were performed using GraphPad Prism software (version 6.0). The correlation of metadata from the main classes of metabolites detected in the experiment was analysed using the MetaboAnalyst online platform. The results were visualised in a heat map generated in the tool itself, using relative abundance data (%).

3 | Results and Discussion

3.1 | Analysis of Physicochemical Parameters

The analysis of the Caatinga soil's physicochemical parameters revealed an increase in most essential nutrients with the addition of *R. communis* leaf litter, with the exception of aluminium (Al), which decreased (Table 1). Aluminium (Al) levels were reduced to 0 Cmolc/dm^3 in all treatments (T1, T2 and T3) compared to the control group, which had a value of 0.80 Cmolc/dm^3 (Table 1).

TABLE 1 | Physicochemical analysis of Caatinga soil treated with different concentrations of *Ricinus communis* litter.

Treatments	P mg/dm³	pH (H_2O)	Ca	Mg	Na	K	Al
			Cmolc/dm³				
CK	1	4.40	0.05	0.30	0.01	0.04	0.80
T1	12	8.00	2.85	0.60	0.01	0.28	0.00
T2	25	8.10	3.90	0.60	0.01	0.20	0.00
T3	26	7.60	3.50	0.80	0.02	0.30	0.00

Note: CK: Control; T1: 20 g/kg; T2: 40 g/kg; T3: 60 g/kg; pH; P: phosphorus; K: potassium; Na: sodium; Al: aluminium; Ca: calcium; Mg: magnesium.

Recent studies have demonstrated that the addition of foliar biomass from various invasive alien species to Caatinga soil results in a significant increase in nutrients (macronutrients and micronutrients) (Silva et al. 2021; Almeida-Bezerra et al. 2022). In a natural environment, the incorporation of nutrients into the soil occurs through the decomposition of litter produced by the species within that ecosystem (Cronan 2018). This could explain the increase in certain nutrients observed in the different treatments containing *R. communis* litter in the substrate (Table 1).

The study by Silva et al. (2021) observed an increase in the macronutrients Calcium (Ca), Magnesium (Mg), and Potassium (K) in response to the addition of leaf biomass from *Azadirachta indica* A. Juss. (Meliaceae) to Caatinga soil. Similarly, an increase in magnesium (Mg) and calcium (Ca) was also reported by Almeida-Bezerra et al. (2022) following the addition of litter from *Mesosphaerum suaveolens* (L.) Kuntze, a finding consistent with the results of the present study (Table 1). This nutrient availability, driven by the mineralization of decomposing organic matter, serves to meet the energy demands of both decomposer organisms and plants (Chapin et al. 2011).

Regarding the substrate's pH, the treatments (T1, T2 and T3) exhibited higher values, ranging from 7.70 to 8.10, in comparison to the control group (CK), which had a pH of approximately 4.40 (Table 1). The release of bicarbonate ions resulting from the addition of organic matter to the soil neutralises acidity, thereby reducing the solubility and environmental availability of aluminium (Yan et al. 1996). This is supported by the data in Table 1, which shows a decrease in aluminium (Al) values alongside an increase in the values of Phosphorus (P), Potassium (K), Calcium (Ca), and Magnesium (Mg), confirming the effect of the substrate's pH adjustment.

3.2 | GC/MS Analysis

The GC–MS analysis identified 10 compounds exclusively associated with *R. communis*; compounds also found in the control group (CK) for both solvents were disregarded (Tables 2 and 3). These compounds shared between the T3 treatment (60 g/kg) and the control group (CK) were attributed to naturally occurring secondary metabolites released by other species within the ecosystem. The identified compounds belong to five main classes: monoglycerides, alkanes, fatty acids, terpenes, and monosaccharides. Regarding the extraction solvent used, six compounds were detected in both the hexane and ethanolic extracts, while four were found exclusively in the ethanolic extract (Table 2).

Soils in natural ecosystems harbour a high diversity of microorganisms (fungi, bacteria, and protozoa), found both on the surface and within the substrate (Coleman 2008). It is therefore essential to distinguish between the secondary metabolites that are naturally present in the ecosystem and those introduced by the invasive alien species *R. communis* through leaf litter decomposition. The interaction of these microorganisms with the substrate and its organic matter plays a key role in the soil's structure and chemical composition (Wall et al. 2001; Riesenfeld et al. 2004).

According to Scavo et al. (2019), the concentration and activity of allelochemicals can be affected by multiple factors, including climatic conditions (solar radiation, precipitation, and temperature), soil factors (texture, ion exchange capacity, organic matter content, moisture, and soil microbiota), and plant characteristics (species, stage of development, and plant part). Thus, allelopathic effects may vary depending on the time of year and the conditions of the ecosystem in which the exotic and invasive species are found.

In treatment T3 (60g/kg), four fatty acids, two alkanes, two terpenes, one monosaccharide, and one monoglyceride were identified. For the ethanolic extract, terpenes (2.02%), alkanes (1.54%), and fatty acids (0.78%) were the major classes of compounds detected in the soil containing *R. communis* leaf litter (Table 2). In the hexanic extract, only terpenes (1.39%) and fatty acids (1%) were identified (Table 3).

Terpenes (C_5H_8), the predominant class of compounds observed at the final stages of the decomposition of *R. communis* leaf litter (Table 2), are known to be volatile compounds. They are released naturally as organic matter breaks down, becoming stored in the soil and subsequently affecting neighbouring species (Souza Filho and Alves 2002). This group of bioactive compounds has recognized allelopathic potential, influencing the germination and growth of other plant species (Oliveira Junior et al. 2011).

A comparative analysis of the major compound classes identified in the control (CK) and T3 (60 g/kg) treatment groups shows that the extraction solvent used (ethanol or hexane) influenced the abundance of compounds within each treatment (Figure 2). In the control group (CK), the ethanolic and hexane extracts showed the highest abundance of alkanes (45.50% and

TABLE 2 | Substances identified by GC–MS in Caatinga soil after 90 days of *Ricinus communis* leaf litter decomposition.

Compound name/class	Retention time (min)	(%)	Molecular formula	Molecular weight (g/mol)
Fatty acids				
Pentadecanoic acid, ethyl ester	26.121	0.15	$C_{15}H_{30}O_2$	270.5
Palmitic acid	27.891	0.13	$C_{16}H_{32}O_2$	256.4
Behenic acid	30.183	0.36	$C_{22}H_{44}O_2$	340.6
Pentacosanoic acid	42.343	0.14	$C_{25}H_{50}O_2$	382.7
Alkene				
n-Tetradecane	17.518	0.1	$C_{14}H_{30}$	198.39
n-Heptatriacontano	51.405	1.44	$C_{37}H_{76}$	521.0
Monossacarídeo				
Glucopiranose	26.369	0.12	$C_6H_{12}O_6$	180.16
Monoglicerídeo				
1-Monooleoylglycerol	40.094	0.3	$C_{27}H_{56}O_4Si_2$	500.9
Diterpenos				
Phytol	30.852	0.4	$C_{20}H_{40}O$	296.5
Triterpenoids				
Ursolic acid	50.746	1.62	$C_{30}H_{48}O_3$	456.7

Note: Ethanolic extract.

TABLE 3 | Substances identified by GC–MS in Caatinga soil after 90 days of *Ricinus communis* leaf litter decomposition.

Compound name/class	Retention time (min)	(%)	Molecular formula	Molecular weight (g/mol)
Fatty acids				
Pentadecanoic acid, ethyl ester	26.118	0.36	$C_{15}H_{30}O_2$	270.5
Palmitic acid	27.893	0.25	$C_{16}H_{32}O_2$	256.4
Behenic acid	38.176	0.49	$C_{22}H_{44}O_2$	340.6
Pentacosanoic acid	42.344	0.26	$C_{25}H_{50}O_2$	382.7
Diterpenos				
Phytol	30.853	0.72	$C_{20}H_{40}O$	296.5
Triterpenoids				
Ursolic acid	50.735	0.67	$C_{30}H_{48}O_3$	456.7

Note: Hexane extract.

37.61%, respectively) and fatty acids (23.07% and 21.8%, respectively). For the T3 treatment (60 g/kg), the hexane and ethanolic extracts showed the highest concentration of alkanes (19.45% and 42.54%, respectively) and terpenes (18.04% and 17.04%, respectively).

A comparison of compound concentrations between the two extraction solvents (ethanol and hexane) within the same treatment group revealed distinct profiles. In the control group (CK), the hexane extract yielded higher concentrations of disaccharides, tocopherols, and alkanes, whereas the ethanol extract was richer in monosaccharides and steroids (Figure 2). A similar trend was observed in the T3 treatment (60 g/kg), where the hexane extract also showed higher concentrations of tocopherols, disaccharides, and fatty acids, consistent with the control group. Conversely, for this same treatment with *R. communis* leaf litter, the ethanol extract primarily yielded steroids, alkanes, and monosaccharides when compared to its corresponding hexane extract.

Among the major compounds observed in the Caatinga soil containing decomposing *R. communis* leaf biomass were ursolic acid ($C_{30}H_{50}O_2$), phytol ($C_{20}H_{40}O$), and n-heptatriacontane ($C_{37}H_{76}$). The identification of phytol ($C_{20}H_{40}O$), one of the major metabolites listed in Table 2, is consistent with the work of Linima et al. (2023), who also reported this compound in their GC–MS analysis of bioactive compounds in *R. communis* leaves.

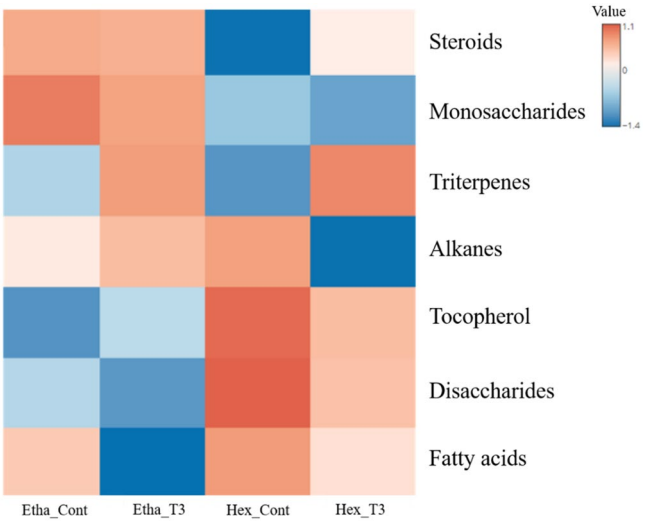

FIGURE 2 | Metadata correlation of the major metabolite classes detected in the experiment. The heatmap illustrates similarities and patterns for hexane and ethanol extracts from the control group (CK) and from Caatinga soil after 90 days of decomposition of *Ricinus communis* leaf litter at a concentration of 60 g/kg (T3). Higher and lower abundance values are coloured red and blue, respectively.

In a study by Warra (2015), a GC–MS analysis of the essential oil from *R. communis* seeds identified two compounds also found in the present work: palmitic acid ($C_{16}H_{32}O_2$) and behenic acid ($C_{22}H_{44}O_2$), both of which are classified as fatty acids. Similarly, Jan et al. (2022) reported the presence of palmitic acid ($C_{16}H_{32}O_2$) in their GC–MS analysis of *R. communis* oil.

A species' chemical composition is influenced by various factors, such as genetic and environmental characteristics, which can result in variations among individuals within the same taxonomic group (Li et al. 2015). Recent studies have demonstrated that in plant species, chemical composition varies depending on the plant organ and the geographical location of the individuals (Yahia et al. 2020). This variability may explain the different findings on the chemical composition of *R. communis* reported across various studies (Warra 2015; Jan et al. 2022; Linima et al. 2023).

3.3 | Germination Assay

The germination of *H. impetiginosus* was adversely affected by all concentrations of *R. communis* leaf litter (T1, T2 and T3). The most significant reduction in germination percentage was observed in the treatments with the highest concentrations of leaf litter, T2 (5.83% ± 5.0%) and T3 (5% ± 4.3%). Similar findings were reported by Saadaoui et al. (2015), who evaluated the effect of *R. communis* leaf extract on crop species and observed reductions of over 90% in the germination rate for *Medicago sativa* L. and *Lens culinaris* Medik. Saadaoui et al. (2015) attributed their findings to the presence of compounds within the terpene class (monoterpenoids and sesquiterpenoids), which were also identified in the phytochemical analysis of the present study.

In their study, Islam and Kato-Noguchi (2013) evaluated the effect of a methanolic leaf extract from *R. communis* on three monocot and eudicot species, observing a reduction in the germination processes of *Lepidium sativum* L. (Brassicaceae) and *Echinochloa crus-galli* (L.) P. Beauv. (Poaceae). Similarly, Parreno et al. (2020) assessed the effect of *R. communis* leaf extract on crop species, noting significant reductions in the germination of *Zea mays* L. (Poaceae), *Vigna radiata* L. (Fabaceae), and *Solanum lycopersicum* L. (Solanaceae). The inhibitory effects observed in the study by Parreno et al. (2020) were attributed to terpenes, a finding consistent with other research (Islam and Kato-Noguchi 2013; Saadaoui et al. 2015).

Regarding the Emergence Speed Index (ESI), the results were similar to those of the germination process, where treatments with higher concentrations of *R. communis* leaf litter yielded the most significant outcomes (T2 and T3) (Figure 3B). The effects were most pronounced at concentrations of 60 g/kg (0.15 ± 0.12) and 40 g/kg (0.16 ± 0.14), followed by 20 g/kg (1.15 ± 0.14) when compared to the control group (2.28 ± 0.06). The action of allelochemicals is not entirely specific, as their effects can vary depending on concentration and translocation within the plant (Almeida 1993). In this case, the parameters related to the germinability of the target species (germination and ESI) demonstrated a more significant, concentration-dependent response to the compounds present in the substrate.

The study by Silva, Zoca, et al. (2022) evaluated the effect of decomposing leaf biomass from *A. indica* on the germination of *Myracrodruon urundeuva* Allemão. A negative, dose-dependent effect was observed on the Emergence Index. Silva, Almeida-Bezerra, et al. (2022) attributed their findings to the presence of terpene compounds, which is consistent with the data from our study. Considering the negative effects on the germination rate of various plant species, it is possible to link these outcomes to specific groups of compounds, regardless of the donor species used.

Regarding the time required for 50% emergence (T_{50}) of the target species' seedlings, an inhibitory effect was observed only at the 60 g/kg concentration (T3) (Table 4). Almeida-Bezerra et al. (2022) also reported negative effects on the T50 parameter, which were more pronounced at higher concentrations of *Mesosphaerum suaveolens* (L.) Kuntze leaf litter on the growth of Cactaceae species from a Seasonally Dry Tropical Forest. Of the nine constituents identified in *M. suaveolens* by Almeida-Bezerra et al. (2022), three are C_{30} terpenoids. One of these, ursolic acid ($C_{30}H_{40}O_3$), was also detected in the present study and may have contributed to the observed allelopathic effect.

The germination synchrony of *H. impetiginosus* seedlings was adversely affected by the two highest-concentration treatments (T2 and T3) when compared to the control group (CK). Overall, the allelochemicals had a similar effect in both treatments, which showed no statistical difference in their mean values (Table 4). When assessing the effects of the *R. communis* allelochemicals on the various germination parameters, the T3 treatment (60 g/kg) was notably the only concentration that had a negative impact across all measured parameters.

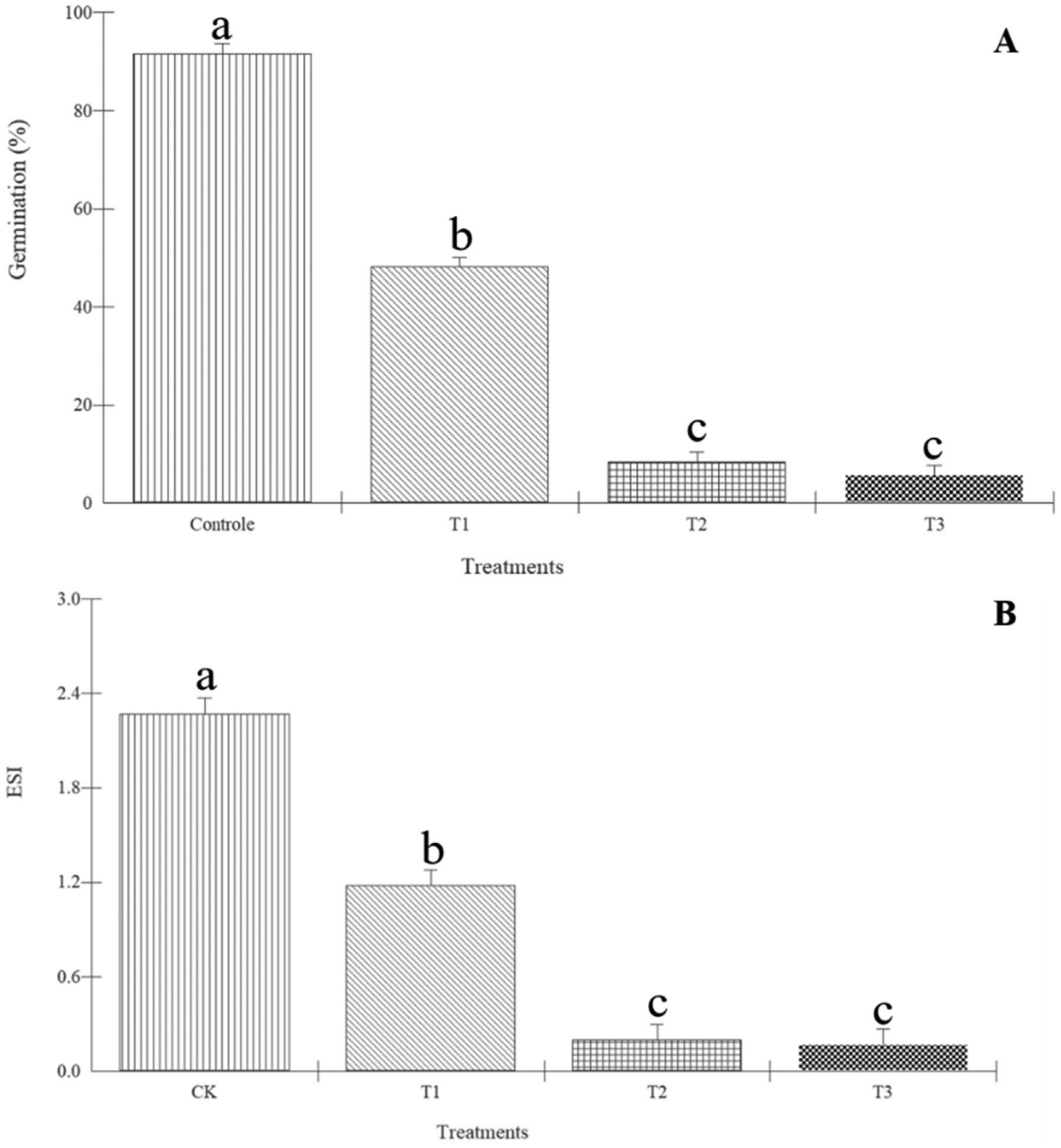

FIGURE 3 | Germination percentage (A) and Emergence Speed Index (ESI) (B) of *Handroanthus impetiginosus* seedlings subjected to different concentrations of *Ricinus communis* leaf litter extracts. Values represent the mean ± standard error (SE) for 20 replicates. Bars topped with different letters indicate a significant difference according to a one-way ANOVA followed by Tukey's test ($p \leq 0.05$).

TABLE 4 | Allelopathic effect of *Ricinus communis* leaf litter extracts on the germination synchrony and time to 50% germination (t50) of *Handroanthus impetiginosus* seeds.

	Treatments			
Parameter	**CK**	**T1**	**T2**	**T3**
T_{50} (%)	11.66 ± 0.53^{a}	10.50 ± 0.65^{ab}	10.56 ± 0.96^{ab}	8.83 ± 0.96^{b}
Synchrony	0.27 ± 0.03^{c}	0.98 ± 0.02^{bc}	0.03 ± 0.06^{ab}	0.03 ± 0.06^{a}

Note: CK: Control; T1: 20 g/kg; T2: 40 g/kg; 60 g/kg. Values represent the mean ± standard error (SE) from 20 replicates per treatment. Bars indicate the standard error. Means followed by different letters are significantly different according to a one-way ANOVA followed by Tukey's post hoc test ($p \leq 0.05$).

3.4 | Growth Assay

The leaf litter of *R. communis* produced a concentration-dependent effect; that is, the significance and nature of the effect (whether positive or negative) varied according to the biomass quantity of the donor species and the parameter being evaluated. The mean radicle length of *H. impetiginosus* showed a stimulatory effect in treatment T1 (137.80 ± 15.41 mm) and an inhibitory

effect in treatment T3 (66.00 ± 6.46 mm) when compared to the control group (87.20 ± 17.21 mm) (Table 4).

Regarding the shoot development of the seedlings, only the T3 treatment showed a significant effect on both the epicotyl and hypocotyl when compared to the control group. Overall, the treatment with the highest concentration of *R. communis* leaf litter negatively influenced the seedlings' mean growth. This finding is consistent with the results for the germination processes, where the greater amount of leaf biomass also adversely affected various parameters.

One possible explanation for the positive effect on mean radicle length observed in the T1 treatment (20 g/kg) is that as the leaf decomposition process progresses, the quantity of biomass and allelochemicals in the substrate is gradually degraded and reduced by the action of soil microorganisms. Consequently, these compounds are transformed into nutrients available to the plant community (Li et al. 2015). Higher concentrations of biomass tend to require more time to break down, demonstrating that the persistence of allelochemicals in the soil is time-dependent. In the T3 treatment (60 g/kg), the negative effects persist, suggesting that secondary metabolites are still present in the substrate.

In their study, Haque et al. (2020) evaluated the effect of an aqueous extract of *R. communis* on several economically important species. They observed a negative effect on the average growth of *Brassica juncea* (L.) Czern. and *Corchorus capsularis* L., with the effect being more significant on the root system of both species studied, similar to the findings of our study. Likewise, Saadaoui et al. (2015) also observed a negative growth response in *M. sativa*, *L. culinaris*, *Corchorus olitorius* L., *Hordeum vulgare* L., and *Cicer arietinum* L. when subjected to a leaf extract of *R. communis*.

Almeida-Bezerra et al. (2022) assessed the effect of *M. suaveolens* biomass on the mean growth of *Pilosocereus gounellei* (F.A.C.Weber) Byles & Rowley, observing a negative effect on the target species' roots at the highest leaf litter concentration tested, similar to the results of the present study (Table 5). Among the compounds associated with *M. suaveolens* and *R. communis* that may have caused the observed allelopathic effect is phytol ($C_{20}H_{40}O$). Huang et al. (2013) also identified this compound as responsible for the reduced mean growth of *Eucalyptus grandis* W.Hill, which was attributed to the leaf decomposition of *Cinnamomum septentrionale* Hand. Mazz.

The leaf litter of *R. communis* affected the dry biomass of the *H. impetiginosus* hypocotyl only at the highest litter concentration (0.005 ± 0.002 g), when compared to the control group (0.01 ± 0.002 g) (Table 6).

Regarding the leaf area of young *H. impetiginosus* plants, the decomposing leaf litter of *R. communis* had a negative effect at concentrations of 40 g/kg (T2) and 60 g/kg (T3), resulting in a decrease in leaf area compared to the control group (CK) (Figure 4). The T2 (7.52 ± 1.10 cm^2) and T3 (7.23 ± 0.92 cm^2) treatments showed no statistically significant difference from each other. In contrast, the T1 (20 g/kg) treatment had a positive effect, increasing leaf area, which is consistent with results previously observed for other parameters at this same concentration.

Therefore, the concentration of allelochemicals in the substrate is one of the main factors determining the phytotoxic activity

TABLE 5 | Allelopathic effect of *Ricinus communis* leaf litter on the root, epicotyl, and hypocotyl length of *Handroanthus impetiginosus* seedlings.

	Root	Epicotyl	Hypocotyl
Treatments		**Length (mm)**	
Control (CK)	87.20 ± 17.21 ^{b}	71.10 ± 16.28 ^{a}	25.50 ± 4.64 ^{a}
T1	137.80 ± 15.41 ^{a}	64.40 ± 12.85 ^{ab}	23.70 ± 5.67 ^{a}
T2	74.70 ± 4.49 ^{bc}	63.40 ± 15.14 ^{ab}	25.70 ± 5.87 ^{a}
T3	66.00 ± 6.46 ^{c}	56.80 ± 8.48 ^{b}	17.80 ± 4.34 ^{b}

Note: CK: Control; T1: 20 g/kg; T2: 40 g/kg; T3: 60 g/kg. Values represent the mean ± standard error (SE) from 20 replicates. Error bars indicate the standard error. Values followed by different letters are significantly different according to a one-way analysis of variance (ANOVA) followed by Tukey's test ($p \leq 0.05$). Unit of measurement: mm (millimetres).

TABLE 6 | Allelopathic effect of *Ricinus communis* leaf litter on the root, epicotyl, and hypocotyl dry mass of *Handroanthus impetiginosus*.

	Root	Epicotyl	Hypocotyl
Treatments		**Peso seco (g)**	
Control (CK)	0.02 ± 0.007 ^{ab}	0.07 ± 0.01 ^{a}	0.01 ± 0.002 ^{a}
T1	0.04 ± 0.01 ^{a}	0.10 ± 0.01 ^{b}	0.01 ± 0.004 ^{a}
T2	0.02 ± 0.006 ^{ab}	0.06 ± 0.01 ^{a}	0.01 ± 0.003 ^{a}
T3	0.01 ± 0.006 ^{b}	0.06 ± 0.009 ^{a}	0.005 ± 0.002 ^{b}

Note: CK: Control; T1: 20 g/kg; T2: 40 g/kg; T3: 60 g/kg. Values represent the mean ± standard error (SE) of 20 replicates. Means followed by different letters are significantly different according to a one-way analysis of variance (ANOVA) followed by Tukey's test ($p \leq 0.05$). Error bars indicate the standard error. Unit of measurement: g (grams).

of the species under study (Scavo et al. 2019). This fact was evidenced in this study, in which both the concentration and decomposition time of organic matter were decisive in intensifying the negative effects on the target species.

3.5 | Morphoanatomical Changes

Significant morphoanatomical variation was observed in the thickness of internal tissues in the radicle and hypocotyl regions of *H. impetiginosus* subjected to different concentrations of *R. communis* leaf litter (Table 7). In the hypocotyl, these changes included both increases and decreases in thickness depending on the region evaluated, with the cortex showing a decrease in thickness across all three treatments (T1, T2 and T3). The vascular system of the hypocotyl exhibited an increase in thickness at the 60 g/kg concentration of leaf biomass (Table 7). The epidermis showed no significant alteration in any of the treatments.

The radicle of *H. impetiginosus* also showed a significant response in the vascular system and cortex of the seedlings, with the effect varying by tissue region and leaf biomass concentration (Table 7). Regarding the cortex, a significant reduction in tissue thickness was observed in the T1 treatment (20 g/kg) compared to the control group (CK). The vascular system was negatively affected by treatments T1 (254.23 ± 16.81) and T2 (254.23 ± 16.81), but positively affected by treatment T3 (380.31 ± 15.34). The radicle epidermis, however, did not respond to the allelochemicals present in the substrate.

Qualitative analysis revealed morphoanatomical changes in the tissue growth of the radicle and hypocotyl of *H. impetiginosus* under different treatments (T1, T2 and T3) when compared to the control group (CK) (Figure 5). In seedlings subjected to the T2 treatment (40 g/kg), the hypocotyl exhibited alterations in the shape and organisation of cortical cells (Figure 5D), with evidence of plasmolysis and hyperplasia, resulting in irregularly shaped cells within the median cortex.

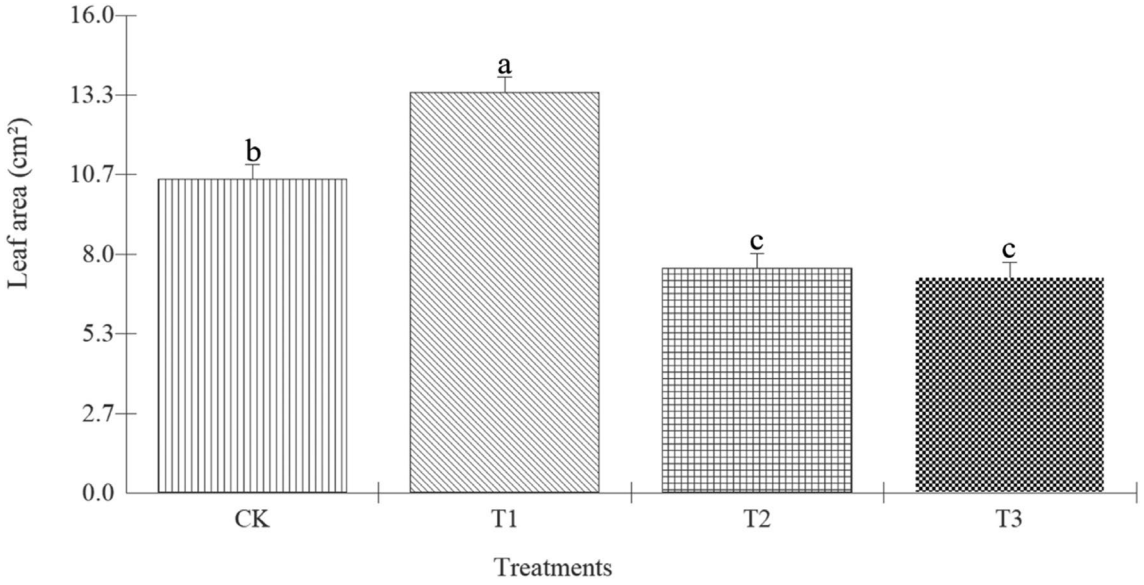

FIGURE 4 | Allelopathic effect of decomposing *Ricinus communis* leaf litter of young *Handroanthus impetiginosus* individuals. Values represent the mean ± standard error (SE) for 20 replicates. Bars with different letters indicate a significant difference as determined by a one-way ANOVA followed by Tukey's test ($p \leq 0.05$).

TABLE 7 | Thickness of tissues in the radicle and hypocotyl of *Handroanthus impetiginosus* in transverse section, subjected to different concentrations of *Ricinus communis* leaf litter.

		Control (CK)	T1	T2	T3
Organ	**Variable**	**Thickness (μm)**			
Young stems	Epidermis	44.25 ± 1.07 [a]	41.85 ± 1.62 [a]	45 001 ± 2.13 [a]	44.33 ± 2.65 [a]
	Cortex	1445 ± 94 [b]	1163 ± 86.31 [c]	1169.67 ± 77.33 [a]	1168.57 ± 110.73 [c]
	Vascular system	532 203 ± 38.26 [ab]	480.28 ± 14.77 [b]	589.18 ± 38.30 [ab]	663.99 ± 43.29 [c]
Radicle	Epidermis	41.43 ± 1.84 [a]	42.91 ± 2.89 [a]	42.80 ± 3.1 [a]	45.45 ± 3.61 [a]
	Cortex	766.12 ± 20.57 [a]	548.33 ± 42.36 [b]	804.89 ± 25.94 [a]	763.80 ± 18.56 [a]
	Vascular system	331.67 ± 19.82 [b]	254.23 ± 16.81 [c]	254.23 ± 16.81 [c]	380.31 ± 15.34 [a]

Note: CK: Control; T1: 20 g/kg; T2: 40 g/kg; T3: 60 g/kg. Values represent the mean ± standard error (SE) for 20 replicates. Means followed by different letters are significantly different according to a one-way ANOVA followed by Tukey's test ($p \leq 0.05$). All measurements are in micrometres (μm).

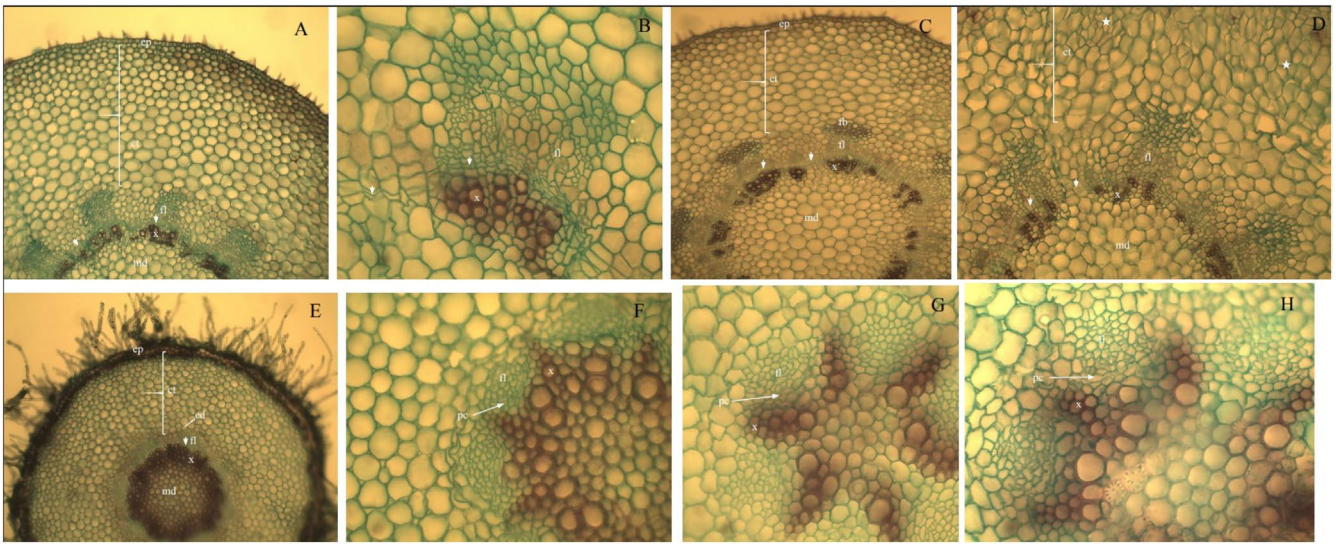

FIGURE 5 | Morphoanatomy of the hypocotyl (A–D) and radicle (E–H) of *Handroanthus impetiginosus* seedlings, in transverse sections, subjected to different concentrations of *Ricinus communis* leaf litter. (A, B) Hypocotyl of the control group (CK), in secondary growth; (C) Hypocotyl from the 20 g/kg treatment (T1), in secondary growth; (D) Hypocotyl from the 40 g/kg treatment (T2), in secondary growth, showing a disorganised cortex with hypertrophied cells. (E) Radicle of the control group (CK), in secondary growth; (F) Radicle from the 20 g/kg treatment (T1), in primary growth; (G) radicle from the 40 g/kg treatment (T2), in primary growth; (H) radicle from the 60 g/kg treatment (T3), in primary growth. ep: Epidermis; ct: Cortex; fl: Phloem; x: Xylem; md: Pith; pc: Procambium; arrowhead: Vascular cambium; fb: Fibre; asterisk: Cluster of hypertrophied cells.

Regarding the qualitative results, all tested treatments (T1 at 20 g/kg, T2 at 40 g/kg, and T3 at 60 g/kg) exhibited a significant delay in vascular system development when compared to the control group (CK). In contrast, the control group exhibited secondary growth (Figure 5E).

Regarding lateral root formation, an increase in these structures was observed in treatments T1 (20g/kg) and T2 (40g/kg), whereas no secondary roots were present in the control group (CK). The development of these structures in allelopathy studies has been cited as a response in receptor species to hormonal alterations resulting from absorbed allelochemicals (Pina 2008; Feitoza et al. 2020; Alcântara et al. 2023). Hormonal imbalances caused by the allelopathic potential of a donor species can induce the formation of secondary roots, a process primarily associated with low levels of the hormones auxin and ethylene, which are essential for the development of these structures (Aloni et al. 2006).

In their study, Alcântara et al. (2023) evaluated the phytotoxic potential of an aqueous extract of *Commelina benghalensis* L. on the morphoanatomy of *Lonchocarpus sericeus* (Poir.) Kunth ex DC. seedlings. They observed the development of secondary roots and a decrease in the mean seedling length, findings that are similar to the results of our own study. These outcomes were attributed to alterations in key hormonal pathways, caused by allelochemicals released from the donor species, which resulted in the premature formation of these structures.

4 | Conclusions

The adverse effects on the germination and post-germination development of *H.* impetiginosus support the hypothesis of a negative allelopathic effect from compounds released by the decomposition of *R. communis* leaf litter. The released allelochemicals persist in the substrate, with their longevity depending on time and environmental conditions. The impacts are most pronounced on germination during the initial post-decomposition stage, while higher concentrations of the compounds affect average growth during the final stages of decomposition.

In conclusion, the presence or introduction of *R. communis* into a natural environment directly impacts the successional process of *H. impetiginosus*, causing reductions of over 90% in its germination rate at higher concentrations of leaf biomass. Over the medium and long term, this species interaction may lead to the decline or extinction of the target species within the ecosystem, as it negatively affects both its germination and subsequent plant growth.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1111/wre.70079.

References

Alcântara, B. M., D. F. Antunes, J. A. S. Silva, et al. 2023. "Phytotoxic Potential and Chemical Composition of *Commelina benghalensis* L. (Commelinaceae) on *Lonchocarpus sericeus* (Poir.) Kunth ex DC. (Fabaceae)." *South African Journal of Botany* 163: 531–540.

Almeida, A. R. P. 1993. "Efeito Alelopático de Espécies de Brachiárias Griseb, Sobre Algumas Leguminosas Forrageiras Tropicais." *Piracicaba*, ESALQ 73, (Dissertação).

Almeida-Bezerra, J. W., V. B. Silva, M. A. P. Silva, et al. 2022. "Leaf Decomposition of *Mesosphaerum suaveolens* Affects the Growth of Cactaceae Species in the Brazilian Seasonally Dry Tropical Forest." *Journal of Arid Environments* 198: 104681.

Aloni, R., E. Aloni, M. Langhans, and C. I. Ullrich. 2006. "Role of Cytokinin and Auxin in Shaping Root Architecture: Regulating Vascular Differentiation, Lateral Root Initiation, Root Apical Dominance and Root Gravitropism." *Annals of Botany* 97: 883–893.

Anwar, S., S. Naseem, S. Karimi, and M. R. Asi. 2021. "Bioherbicidal Activity and Metabolic Profiling of Potent Allelopathic Plant Fractions Against Major Weeds of Wheat – Way Forward to Lower the Risk of Synthetic Herbicides." *Frontiers in Plant Science* 12: 632390.

Babita, M., M. Maheswari, L. M. Rao, A. K. Shanker, and D. G. Rao. 2010. "Osmotic Adjustment, Drought Tolerance and Yield in Castor (*Ricinus communis* L.) Hybrids." *Environmental and Experimental Botany* 69: 243–249.

Bartz, R., and I. Kowarik. 2019. "Assessing the Environmental Impacts of Invasive Alien Plantas: A Review of Assessment Approaches." *NeoBiota* 43: 69–99.

Bellard, C., P. Cassey, and T. M. Blackburn. 2016. "Alien Species as a Driver of Recente Extinctions." *Biology Letters* 12: 20150623.

Brasil. 2009. "Regras Para Análise de Sementes: Ministério da Agricultura, Pecuaría e Abastecimento." Secretária de Defesa Agropecuária. Mapa/ACS. 1nd edition, 399.

Cavalcanti, M. L. F., P. D. Fernandes, H. R. Gheyi, G. B. Júnior, F. A. L. Soares, and E. C. Siqueira. 2005. "Tolerância da Mamoneira BRS 149 à Salinidade: Germinação e Características de Crescimento." *Revista Brasileira de Engenharia Agricola e Ambiental* 9, no. 1: 57–61.

Chapin, F. S., III, P. A. Matson, and P. M. Vitousek. 2011. *Principles of Terrestial Ecosystem Ecology*. 2nd ed, 529. Springer.

Chen, B. M., H. X. Liao, W. B. Chen, H. J. Wei, and S. L. Peng. 2017. "Role of Allelopathy in Plant Invsion and Control of Invasive Plants." *Allolopathy Journal* 41, no. 2: 155–166.

Cheng, H. H., and W. C. Koskinen. 2010. "Effects of "Aging" in Bioreactive Chemical Retention, Transformation, and Transporte in Soil." In *Molecular Environmental Soils Science at the Interferences in the Earth's Critical Zone*, edited by P. M. Huang, 184–186. Springer Berlin Heidelberg.

Coleman, D. C. 2008. "From Peds to Paradoxes: Linkages Between Soil Biota and Their Influences on Ecological Processes." *Soil Biology and Biochemistry* 40, no. 2: 271–289.

Coolbear, P., A. Francis, and D. Grierson. 1984. "The Effect of Low Temperature Pre-Sowing Treatment on the Germination Performance and Embrane Integrity of Artificially Agend Tomato Seeds." *Journal of Experimental Botany* 35, no. 11: 1609–1617.

Cronan, C. S. 2018. *Ecosystem Biogeochemistry: Element Cycling in the Forest Landscape*, 203. Springer.

Dally, E. Z., O. Chabrerie, F. Massol, et al. 2023. "A Synthesis of Biological Invasion Hypotheses Associated With the Introduction–Naturalisation–Invasion Continuum." *Nordic Society Oikos* 5: e09645.

Donagema, G. K., D. B. Campos, S. B. Calderano, W. G. Teixeira, and J. M. Viana. 2011. "Manual de Métodos de Análise de Solo." Embrapa Solos-Documentos (INFOTECA-E).

Duke, S. O. 2010. "Allelopathy: Current Status of Research and Future of the Discipline: A Commentary." *Allelopathy Journal* 25, no. 1: 17–30.

Embrapa – Empresa Brasileira De Pesquisa Agropecuária. 1997. *Manual de Métodos de Análises de Solo*. 2nd ed, 212. EMBRAPA-CNPS.

Feitoza, B. B. R., R. M. Varela, A. Torres, et al. 2020. "Evaluation of the Phytotoxicity of *Urochloa humidicola* Roots by Bioassays and Microscopic Analysis. Characterization of New Compounds." *Journal of Agricultural and Food Chemistry* 68, no. 17: 4851–4864.

Fernando, E. M. P., K. G. Campos, M. L. Mamede, and M. F. A. Lucena. 2022. "Floristic Survey of a Caatinga Area of High Biological Importance in the Mesoregion of Paraíba Backlands, Northeast Brazil." *Hoehnea* 49: e642021.

Flora e Funga do Brasil. 2026. "*Ricinus communis*. Flora e Funga do Brasil. Jardim Botânico do Rio de Janeiro." https://floradobrasil.jbrj.gov.br/FB17659.

Gniazdowska, A., and R. Bogatek. 2005. "Allelopathic Interactions Between Plants. Multisite Action of Allelochemiclas." *Acta Physiologiae Plantarum* 27, no. 3: 395–407.

Haque, M. M., A. K. M. M. Islam, M. P. Anwar, and S. Yeasmin. 2020. "Evaluation of Allelopathic Potential of *Ricinus communis* on the Growth of Seven Field Crops." *Research Journal of Medicinal Plants* 14, no. 2: 79–87.

Hossain, G. M., S. A. Khan, S. S. Shetu, M. S. Rahman, F. A. Ahmed, and M. H. Ali. 2022. "Floristic Survey of Vascular Plants in Coastal District Bagerhat of Bangladesh." *Bangladesh Journal of Plant Taxonomy* 29, no. 1: 43–78.

Huang, W., T. Hu, H. Chen, et al. 2013. "Impact of Decomposing *Cinnamomum septentrionale* Leaf Litter on the Growth of *Eucalyptus grandis* Saplings." *Plant Physiology and Biochemistry* 70, no. 9: 411–417.

Islam, A. K. M. M., and H. Kato-Noguchi. 2013. "Allelopathic Prospective of *Ricinus communis* and *Jatropha curcas* for Bio-Control of Weeds." *Acta Agriculturae Scandinavica* 63, no. 8: 731–739.

Jan, H. A., I. Surina, A. Zaman, A. S. Al-Fatesh, F. Ramin, and R. L. Al-Otaibi. 2022. "Synthesis of Biodiesel From *Ricinus communis* L. Seed Oil, a Promising Non-Edible Feedstock Using Calcium Oxide Nanoparticles as a Catalyst." *Energies* 15: 6425.

Johansen, D. A. 1940. "Pant Microtechnique." *Nature* 147, no. 222: 523.

Jones, B. A., and S. M. McDermott. 2017. "Health Impacts of Invasive Species Through Na Altered Natural Environment: Assessing Air Pollution Sinks as a Causal Pathway." *Environmental and Resource Economics* 71: 23–43.

Khan, M. N., and L. Badshah. 2019. "Floristic Diversity and Utility of Flora of District Charsadda, Khyber Pakhtunkhwa." *Acta Ecologica Sinica* 39: 306–320.

Laboriau, L. G. 1983. *Germinação de Sementes*. 1st ed. Secretaria Geral da Organização dos Estados Americanos.

Labouriau, L. G., and A. Pacheco. 1978. "On the Frequency of Isothermal Germination in Seeds of *Dolichos biflorus* L." *Plant and Cell Physiology* 19, no. 3: 507–512.

Li, Y. P., Y. L. Feng, Y. J. Chen, and Y. H. Tian. 2015. "Soil Microbes Alleviate Allelopathy of Invasive Plants." *Science Bulletin* 60, no. 12: 1083–1091.

Linima, V. K., R. Ragunathan, and J. Johney. 2023. "Biogenic Synthesis of *Ricinus communis* Mediated iron and Silver Nanoparticles and Its Antibacterial and Antifungal Activity." *Heliyon* 9: e15743.

Lunardi, V. O., E. E. M. Silva, S. T. A. Silva, and D. G. Lunardi. 2019. "*Handroanthus impetiginosus* (Bignoniaceae) as Na Important Floral Resource for Synanthropic Birds in the Brazilian Semiarid." *Oecologia Australis* 23, no. 1: 137–144.

Maguire, J. D. 1962. "Speed of Germination Aid in Selection and Evalution for Seedling Emergence and Vigor." *Crop Science* 2, no. 2: 176–177.

Matthews, S. 2005. *América do Sul Invadida: A Crescente Ameaça Das Espécies Exóticas Invasoras*, 80. GISP.

Oliveira Junior, R. S., J. Constantin, and M. H. Inoue. 2011. *Biologia e Manejo de Plantas Daninhas*. 1st ed, 348. Omnipax.

Pacheco, M. V., V. P. Matos, A. L. P. Feliciano, and R. L. C. Ferreira. 2008. "Germinação de sementes e crescimento inicial de plântulas de *Tabebuia aurea* (Silva Manso) Benth. & Hook f. ex S. Moore." *Ciência Florestal* 18, no. 2: 143–150.

Parreno, J., B. Cempron, N. Bucog, M. M. Pepito, and C. Zamora. 2020. "Allelopathic Potential of Castor Plant (*Ricinus communis* L.) Aqueous Extracts on Germination on Selected Crop Species." *International Research Journal of Science and Technology* 1, no. 2: 120–125. https://doi.org/10.46378/irjst.2020.010207.

Pina, G. O. 2008. "Efeito Alelopático do Extrato Aquoso Foliar de *Eugenia dysenterica* DC. (Myrtaceae – Cagaita) na Germinação, Crescimento e Morfo-Anatomia de *Sesamum indicum* L. (Pedaliacea – Gergelim) e *Raphanus sativus* L. (Brassicaceae – rabanete)." Universidade de Brasília Universidade de Brasília, Brasília, 30. Dissertação de mestrado (Pós-graduação em Botânica).

Richardson, D. M., P. Pysek, M. Rejmánek, M. G. Barbour, F. D. Panetta, and C. J. Oeste. 2000. "Naturalization and Invasion od0 Alien Plants: Concepts and Definitions." *Diversity and Distributions* 6, no. 2: 93–107.

Riesenfeld, C. S., P. D. Schloss, and J. Handelsman. 2004. "Metagenomics: Genomic Analysis of Microbial Communities." *Annual Review of Genetics* 38: 525–552.

Rocha, F. V., R. B. Lima, and D. D. Cruz. 2019. "Conservation Priorities for Woody Species Used by a Quilombo Commnity on the Coast of Northeastern Brazil." *Journal of Ethnobiology* 39, no. 1: 158–179.

Roeser, K. R. 1962. "Die Nadel der Schwarzkiefer-Massenprodukt und kunstwerk der Natur." *Mikrokosmos* 61, no. 1: 33–36.

Saadaoui, E., J. J. Martín, N. Ghazel, C. B. Romdhane, N. Massoudi, and E. Cervantes. 2015. "Allelopathic Effects of Aqueous Extracts of *Ricinus communis* L. on the Germination of Six Cultivated Species." *International Journal of Plant & Soil Science* 7, no. 4: 220–227.

Sala-Carvalho, W. R., F. P. Montessi-Amaral, M. P. Esposito, et al. 2022. "Metabolome of *Ceratodon purpureus* (Hedw.) Brid., a Cosmopolitan Moss: The Influence of Seasonality." *Planta* 255: 77.

Santana, O. A., and J. L. Encinas. 2008. "Levantamento das espécies exóticas arbóreas e seu impacto nas espécies nativas em áreas adjacentes a depósitos de resíduos domiciliares." *Revista Biotemas* 21, no. 4: 29–38.

Santos Filho, L. A. F., and T. Messina. 2012. "*Handroanthus impetiginosus* (BIGNONIACEAE)." Lista Vermelha da Flora Brasileira: Centro Nacional de Conservação da Flora/ Instituto de Pesquisas Jardim Botânico Do Rio de Janeiro.

Scavo, A., C. Abbate, and G. Maurimicale. 2019. "Plant Allelochemicals: Agronomic, Nutritional and Ecological Relevance in the Soil System." *Plant and Soil* 442: 23–48.

Silva, E. F., D. G. Zoca, G. N. A. Silva, et al. 2022. "Avaliação In Vivo da Atividade Analgésica e Anti-Inflamatória de Extratos Hidroalcoólicos de *Handroanthus impetiginosus* e Sua Composição Química por Análise UPLC/MS." *Pesquisa de Produtos Naturais* 37, no. 16: 2801–2807.

Silva, L. A., J. S. Pereira, A. S. Meira, and M. S. S. Farias. 2017. "Estudo Fitossociológico de Fragmento de Área de Preservação Permanente." *Espacios* 38, no. 38: 6–16.

Silva, P. S. S. 2012. "Atuação dos Aleloquímicos no Organismo Vegetal e Foras de Utilização da Alelopatia na Agronomia." *Biotemas* 25, no. 3: 65–74.

Silva, R. F., R. T. Bressan, B. M. Zilli, M. A. Pilatti, S. N. M. Souza, and R. F. Santos. 2016. "Allelopathic Effect of Aqueous Extract of Fresh Leaf castor Beans (*Ricinus communis* L.) Applied to the Beginning Stage of Soy (*Glycine max* L.) and Safflower (*Carthamus tinctorius* L.)." *African Journal of Biotechnology* 15: 2787–2793.

Silva, V., J. W. Almeida-Bezerra, E. S. Brito, et al. 2021. "Effect of Decomposition of Leaves of *Azadirachta indica* A. Juss. On Germination and Growth of *Myracrodruon urundeuva* Allemão." *South African Journal of Botany* 142: 42–52.

Silva, V. B., J. W. Almeida-Bezerra, B. M. Alcântara, and M. A. P. Silva. 2022. "Avaliação da Germinação de Diásporos de *Myracrodruon urundeuva* Allemão (Anacardiaceae) Submetidos a Diferentes Métodos de Armazenamento." *Revista Brasileira de Meio Ambiente* 10, no. 1: 85–96.

Souza Filho, A. P. S., and S. M. Alves. 2002. *Alelopatia: Princípios Básicos e Aspectos Gerais*, 260. Embrapa Amazônia Oriental.

Tropicos.org. Missouri Botanical Garden. March 5, 2026, https://tropicos.org.

Wagay, N. A., V. R. Deshmukh, and S. P. Rothe. 2015. "A Floristic Survey of Flowering Plants From Vidyabharati Mahavidyalya Campus, Amravati (Maharashtra) India." *International Journal of Life Sciences* 3, no. 3: 249–254.

Wall, D. H., G. Adams, and A. N. Parsons. 2001. "Soil Biodiversity." In *Global Biodiversity in a Changing Environment: Scenarios for the 21st Century*, edited by F. S. Chapin III, O. E. Sala, and E. Huber-Sannwald, 47–82. Springer-Verlag.

Warra, A. A. 2015. "Physico-Chemical and GC-MS Analysis of Castor Brean (*Ricinus communis* L.) Seed Oil." *Chemistry and Materials Research* 7, no. 2: 56–60.

Williams, B. A., O. Venter, J. R. Allan, et al. 2020. "Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems." *One Earth* 3: 371–382. https://doi.org/10.1016/j.oneear.2020.08.009.

Yahia, Y., M. A. Benabderrahim, N. Tlili, M. Bagues, and K. Nagaz. 2020. "Bioactive Compounds, Antioxidant and Antimicrobial Activities of Extracts From Different Plant Parts of Two *Ziziphus* Mill. Species." *PLoS One* 15, no. 5: e0232599.

Yan, F., S. Schubert, and K. Mengel. 1996. "Soil pH Changes During Legume Growth and Application of Plant Material." *Biology and Fertility of Soils* 23, no. 3: 236–242.

Zhang, C., and S. Fu. 2009. "Allelopathic Effects of eucalyptus and the Establishment of Mixed Stands of eucalyptus and Native Species." *Forest Ecology and Management* 258, no. 7: 1391–1396.