

Identification of bioindicator species for the herbicide pendimethalin

Leila Lucia Camintia¹, Dieison Olescowicz¹, José Fernando Marquez¹, Lariane Fontana de Freitas¹, André Augusto Falchetti Volpato¹, Germano Maso Rissardi¹, Naiara Guerra², Antonio Mendes de Oliveira Neto¹

¹ Department of Agronomy, Santa Catarina State University (CAV/UFES), avenue Luiz de Camões, 2090, Conta Dinheiro, 88520-000, Lages, SC, Brazil.

² Special Coordination of Biological and Agronomic Sciences, Federal University of Santa Catarina (CBS-UFSC), highway Ulysses Gaboardi, 3000, 89520-000, Curitibanos, SC, Brazil.

*Corresponding author: leilacamintia@gmail.com

Submitted:
04/10/2025

Revised:
13/11/2025

Accepted:
18/02/2026

Abstract: The new formulation of pendimethalin modifies its physicochemical properties and, consequently, its dynamics in the environment. The behavior of pendimethalin in the soil can be analyzed by means of a bioindicator plant; however, there are few studies on selection of species for this purpose. Therefore, the objective of this work is to determine a bioindicator for pendimethalin through two studies: the first on some important crop species, and the second, using the species selected in the first study and *Urochloa plantaginea*. The experiments were carried out in a greenhouse in a completely randomized design, with four replications. The variables were phytointoxication and dry weight inhibition on the basis of pendimethalin doses (0, 625.63, 1,251.25, 1,876.88, 2,502.50, and 3,128.13 g ai ha⁻¹). The data were normalized to the control value and used to determine the C₅₀ and GR₅₀ values to identify the species most sensitive to the herbicide. In the first study, beet and lettuce were the selected species. In the second study, *U. plantaginea* was determined as the bioindicator species for pendimethalin, because it needs 193.0 g ha⁻¹ to achieve GR₅₀ of roots, while 56.6 g ai ha⁻¹ reduces shoot dry mass weight by 50%. C₅₀ at 28 DAS is 65.7 g ai ha⁻¹, which results in the lowest C₅₀ and GR₅₀ values compared to those of the other species assessed. The species *U. plantaginea* effectively indicates the presence of pendimethalin in the soil solution and can be used in bioassay studies with this herbicide.

Keywords: capsule suspension; bioassay; microtubule inhibitor; *Urochloa plantaginea*; *Beta vulgaris*; *Lactuca sativa*.

Abbreviations: DAA_days after emergence; C₅₀_dose that produces 50% of the effect (e.g., mortality, inhibition); CO₂_carbon dioxide; D_dose; DT₅₀_half-life (time to 50% degradation); GR₅₀_growth reduction by 50%; g_gram; g ai ha⁻¹_grams of active ingredient per hectare; ha_hectare; h_hour; K_d_sorption coefficient; km h⁻¹_kilometers per hour; K_{oc}_organic carbon-normalized sorption coefficient; L_liter; Log K_{ow}_octanol-water partition coefficient; SDW_shoot dry weight; RDW_root dry weight; m_meter; pK_a_electrolytic dissociation constant; SC_Santa Catarina; S_South; S_w_water solubility; W_west; °C_degrees Celsius.

Introduction

The use of herbicides at pre-emergence aids residual weed control during the critical phase of weed-crop interference, a period when there may be a significant reduction in productivity (Agostinetto et al., 2022; Ribeiro Junior et al., 2018). Microtubule assembly inhibitors stand out among these herbicides; for example, pendimethalin [N-(1-ethyl propyl)-2,6-dinitro-3,4-xylidine].

Pendimethalin inhibits the binding between α - β -tubulin heterodimers, which is the main component of microtubule assembly. Microtubules, in turn, are essential to boost cell growth and to form the mitotic spindle during cell division (Majumdar and Dastidar, 2016). Therefore, pendimethalin compromises root development in sensitive plants, especially in grasses, whose roots may ultimately have a swollen apex because of mitotic inhibition (Neal et al., 2016). Depending on the degree of phytointoxication, other possible symptoms are hypocotyl thickening, shoot shrinking, and smaller, wrinkled, and dark green leaves (Gazziero and Neumaier, 1985).

As a dinitroaniline herbicide, pendimethalin is applied before weed emergence, with advantages such as high efficiency, low toxicity, and long residual control. Pendimethalin has a broad control spectrum, which can effectively control annual grass weeds and some eudicotyledons (Chen et al., 2021). In addition to these characteristics, it is a contact herbicide, does not translocate within the plant, and is selective for crops such as cotton, garlic, peanuts, rice, potato, coffee, sugar cane, onion, citrus, beans, and apple (Vargas and Roman, 2006; BASF Corporation, 2023).

From the physicochemical point of view, pendimethalin has the following characteristics: water solubility (S_w) of 0.33 mg L⁻¹; octanol-water partition coefficient (Log K_{ow}) of 5.4; electrolytic dissociation constant (pK_a) – non-ionizable; vapor pressure at 20 °C of 3.24 mPa; half-life (DT₅₀) of 182.3 days; sorption coefficient (K_d) of 228 L kg⁻¹; standard organic carbon sorption coefficient (K_{oc}) of 17.49 L kg⁻¹ (PPDB, 2025).

Currently, there is increased application of pre-emergence herbicides, including pendimethalin in a capsule suspension formulation (BASF Corporation, 2023). This formulation provides a more efficient use of the active ingredient, prolongs the residual period, and reduces environmental losses because of slow product release (Mogul et al., 1996).

Because this formulation is highly persistent due a great potential for gradual release of pendimethalin, its environmental behavior needs to be studied. One of the available methodologies is the bioassay, which is using of plant species that are highly sensitive to the product. This technique offers advantages such as low cost, ease of cultivation, and rapid development, when compared to instrumental methods (Dias et al., 2017). For this reason, it is widely used for detection of herbicide residues (Nunes and Vidal, 2009).

However, although the bioassay is an easily applicable technique, there are still few studies that evaluate potential indicator species for pendimethalin. Therefore, the objective of this work was to identify a bioindicator species for this herbicide.

Results

Phytointoxication

Phytotoxicity of the herbicide pendimethalin presented a dose-dependent relationship, in which, the percentage of injury was increased with higher doses applied at 21 DAS (Figure 1) and 28 DAS (Figure 2), corresponding to the first and second study, respectively. However, there was great variability in sensitivity among the tested species, reflecting different levels of herbicide tolerance. Among the characteristic symptoms, there was a reduction of shoot and root growth, wrinkle of the leaf blade and, particularly in the cucurbitaceae, the development of the typical “umbrella” effect, a morphological symptom associated with the action of herbicides that interfere with cell division (Shaw and Vineyard, 2014).

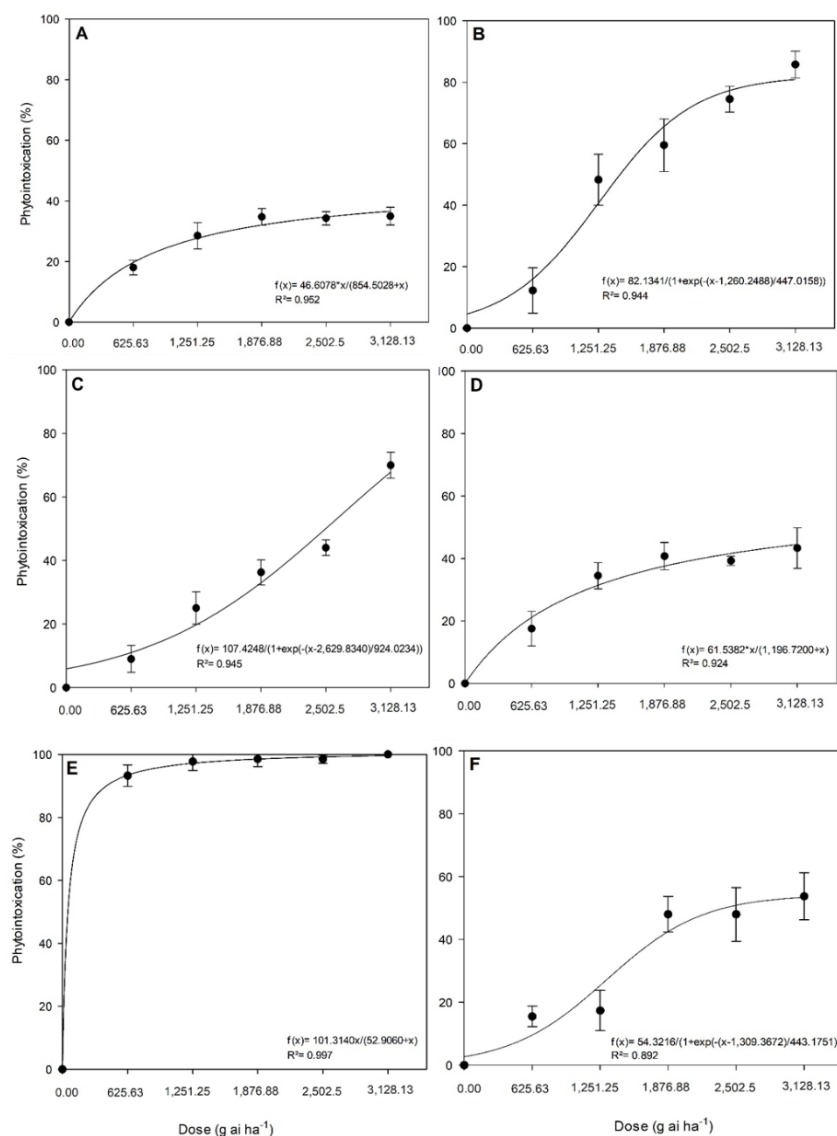


Figure 1. Dose-response curves of phytointoxication caused by the herbicide pendimethalin in different plant species at 21 days after sowing (DAS), in percentage terms (%). A: *Avena strigosa*; B: *Beta vulgaris*; C: *Cucumis sativus*; D: *Cucurbita moschata*; E: *Lactuca sativa*; F: *Sorghum bicolor*.

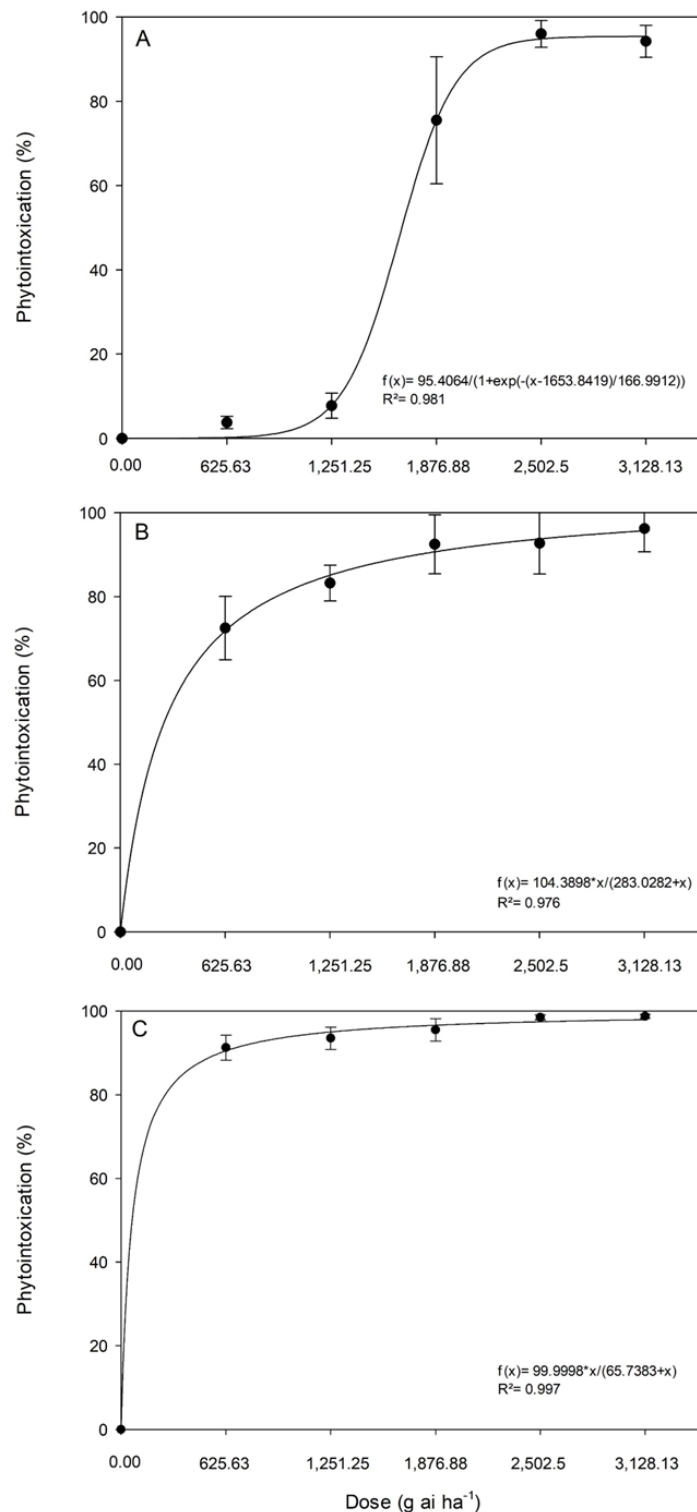


Figure 2. Dose-response curves of phytointoxication caused by the herbicide pendimethalin in different plant species at 28 days after sowing (DAS), in percentage terms (%). A: *Beta vulgaris*; B: *Lactuca sativa*; C: *Urochloa plantaginea*.

Phytointoxication – first study (21 DAS)

Beta vulgaris and *Lactuca sativa* were the most sensitive species (Figures 1B and 1E); therefore, they could be potentially used as efficient bioindicators for detection of pendimethalin at 21 DAS. By contrast, the other species presented low phytointoxication, which reduces their usefulness as bioindicators.

Avena strigosa showed an increase in phytointoxication up to the dose of 1,251.25 g ai ha⁻¹, and it stabilized around 30% at the higher concentrations, a pattern that suggests low sensitivity (Figure 1A). *Cucumis sativus* showed a varied response, ranging from 5% to 70% between minimum and maximum doses, thereby indicating moderate-dose sensitivity (Figure 1C). For *Curcubita moschata*, injury was stabilized at 1,251.25 g ai ha⁻¹; thus, it was disqualified as a reliable bioindicator (Figure 1D).

Sorghum bicolor showed similar phytotoxicity at the doses of 625.63 and 1,251.25 g ai ha⁻¹ (15.5% and 17.3%, respectively), but it reached higher levels (48–53.8%) at 1,876.88 g ai ha⁻¹.

The lowest value of C_{50} was found for *L. sativa* (51.56 g ai ha⁻¹), followed by *B. vulgaris* (1,457.85 g ai ha⁻¹), whose value was approximately 28 times higher (Table 1). *S. bicolor* and *C. sativus* showed values of 2,394.70 and 2,501.80 g ai ha⁻¹, respectively (Table 1). C_{50} could not be estimated for *A. strigosa* and *C. moschata*, since the highest dose tested resulted in less than 50% control (Table 1).

Table 1. Dose required (g ai ha⁻¹) for 50% phytointoxication (C_{50}) in the species assessed, and the respective mathematical equations describing their biological behavior.

Species	C_{50} 21 DAS	Mathematical model	Parameters of the equation		
			<i>a</i>	<i>x0</i>	<i>b</i>
<i>Avena strigosa</i>	>3,128.13	Hyperbole	46.6078	-	854.5028
<i>Beta vulgaris</i>	1,457.85	Sigmoid	82.1341	1,260.2488	447.0158
<i>Cucumis sativus</i>	2,501.80	Sigmoid	107.4248	2,629.8340	924.0234
<i>Cucurbita moschata</i>	>3,128.13	Hyperbole	61.5382	-	1,196.7200
<i>Lactuca sativa</i>	51.56	Hyperbole	101.3140	-	52.9060
<i>Sorghum bicolor</i>	2,394.70	Sigmoid	54.3216	1,309.3672	443.1751
Species	C_{50} 28 DAS	Mathematical model	Parameters of the equation		
			<i>a</i>	<i>x0</i>	<i>b</i>
<i>Beta vulgaris</i>	1,669.90	Sigmoid	95.4064	1,653.8419	166.9912
<i>Lactuca sativa</i>	260.20	Hyperbole	104.3898	-	283.0282
<i>Urochloa plantaginea</i>	65.74	Hyperbole	99.9998	-	65.7383

Phytointoxication – second study (28 DAS)

L. sativa showed 72.5% phytotoxicity (Figure 2B) at the lowest evaluated dose, while *B. vulgaris* and *Urochloa plantaginea* achieved 3.5% (Figure 2A) and 91.3% phytotoxicity (Figure 2C), respectively. Sensitivity of the species varied significantly according to the shape of the response curve and the dose required to achieve high levels of phytotoxicity.

B. vulgaris showed low phytotoxicity at lower doses. However, injury was close to 100% at the dose of 2,502.5 g ai ha⁻¹ or higher. For this reason, *B. vulgaris* is less sensitive at low doses. It requires a dose of 1,876.88 g ai ha⁻¹ or higher to produce a significant effect as a bioindicator of pendimethalin in the soil.

L. sativa and *U. plantaginea* showed a rapid increase in phytotoxicity at low doses, followed by gradual stabilization (Figures 2B and 2C). This indicates greater sensitivity to the herbicide, especially *U. plantaginea*, which showed a very asymptotic curve. This response confirms high sensitivity, since 25% of the recommended dose provided 91.25% toxicity, suggesting that *U. plantaginea* is the most susceptible species compared to the others.

C_{50} values were 260.20; 1,669.90, and 65.74 g ai ha⁻¹ for *L. sativa*, *B. vulgaris*, and *U. plantaginea*, respectively (Table 1). Therefore, approximately 2.10% of the maximum dose recommended on the label is sufficient to achieve C_{50} in *U. plantaginea*.

Root and shoot dry weight

Root and shoot dry weight values were reduced in all species with increased doses of pendimethalin, although its response varied in magnitude among species.

Root dry weight and canopy dry weight – first study (21 DAS)

L. sativa showed high sensitivity in the shoot, with an GR_{50} of 111.4 g ai ha⁻¹, while a dose of 388.8 g ai ha⁻¹ was necessary to reach the root GR_{50} (Table 2). In *B. vulgaris*, the GR_{50} values were 283.8 g ai ha⁻¹ for the roots and 612.6 g ai ha⁻¹ for the shoots. In general, the reduction in root biomass may precede the reduction in shoot biomass. However, species respond differently to this attribute, which suggests that biometric analysis of the roots constitutes a complementary assessment to determine if shoot inhibition is sufficient to indicate the presence of herbicide in the soil (Figure 3).

Table 2. Dose required for 50% inhibition of root and shoot dry weight (g ai ha⁻¹) in the species assessed, and the respective coefficients and mathematical equations describing their biological behavior.

21 DAS					
Species	Component	GR_{50}	Mathematical model	<i>a</i>	<i>b</i>
<i>Beta vulgaris</i>	Root	283.8	Hyperbole	110.1712	339.7597
<i>Lactuca sativa</i>	Root	388.8	Hyperbole	124.3935	579.7144
<i>Beta vulgaris</i>	Shoot	612.6	Hyperbole	127.3355	957.3727
<i>Lactuca sativa</i>	Shoot	111.4	Hyperbole	103.9036	117.5681
28 DAS					
Species	Component	GR_{50}	Mathematical model	<i>a</i>	<i>b</i>
<i>Beta vulgaris</i>	Root	359.0	Hyperbole	120.9112	511.9907
<i>Lactuca sativa</i>	Root	322.9	Hyperbole	118.4309	440.6325
<i>Urochloa plantaginea</i>	Root	193.0	Hyperbole	100.5397	195.1026
<i>Beta vulgaris</i>	Shoot	967.0	Hyperbole	181.7472	2,549.0111
<i>Lactuca sativa</i>	Shoot	703.0	Hyperbole	142.4107	1,293.9926
<i>Urochloa plantaginea</i>	Shoot	56.6	Hyperbole	96.1284	54.3843

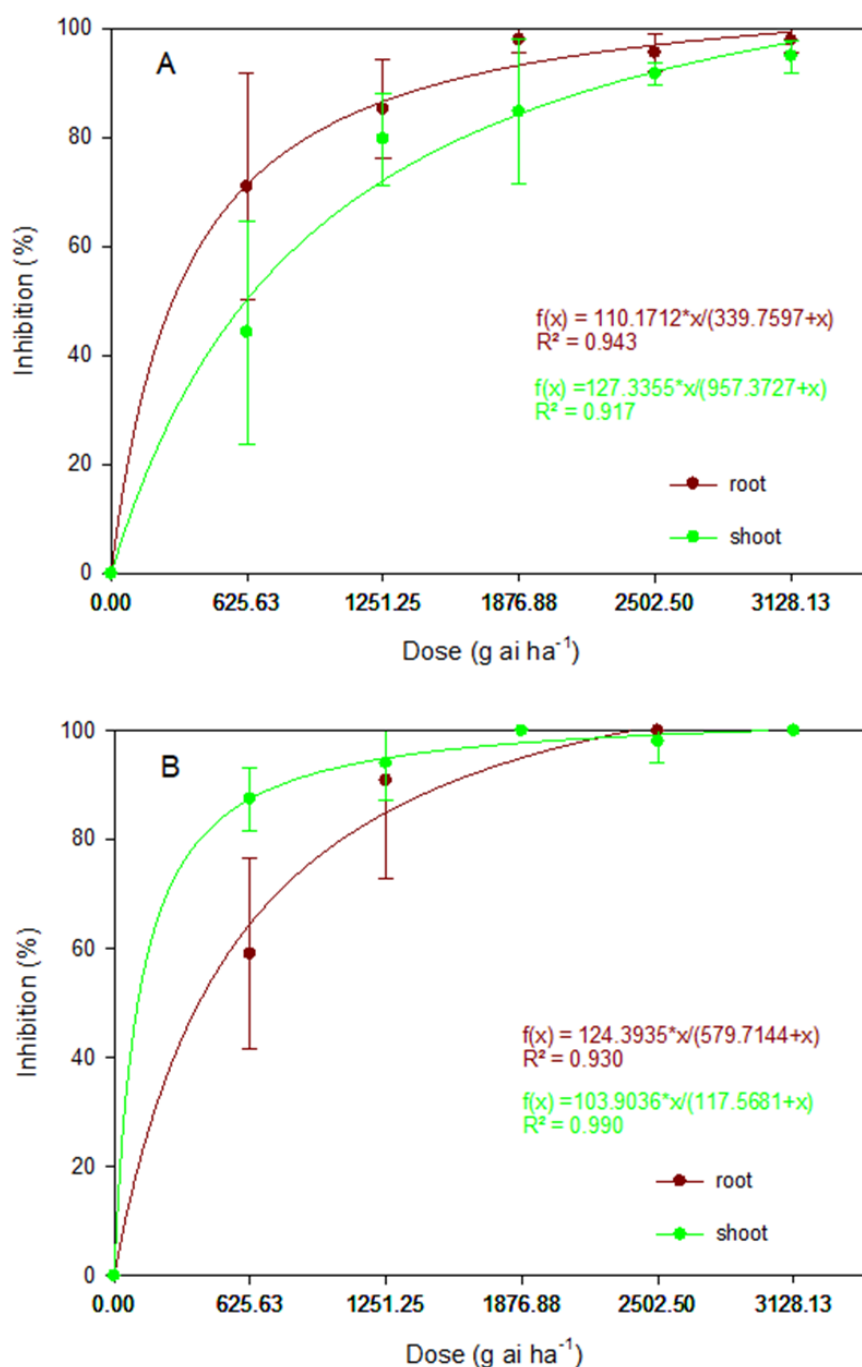


Figure 3. Percentage of shoot and root inhibition caused by application of pendimethalin at 21 days after application (DAA). A: *Beta vulgaris*; B: *Lactuca sativa*.

Root dry weight and canopy weight – second study (28 DAS)

GR₅₀ of the roots was 359.0, 322.9, and 193.0 g ai ha⁻¹ for *B. vulgaris*, *L. sativa* and *U. plantaginea*, respectively (Table 2). For GR₅₀ of the shoots, there was a similar behavior: *U. plantaginea* showed the lowest value, namely 56.6 g ai ha⁻¹, compared to 967.0 g ai ha⁻¹ (*B. vulgaris*) and 703.0 g ai ha⁻¹ (*L. sativa*). Thus, the sensitivity of *U. plantaginea*, based on the GR₅₀ value of the roots, is 1.9 times higher than that of *B. vulgaris* and 1.7 higher than that of *L. sativa*. For the shoots, *U. plantaginea* is 12.4 times and 17.1 times more sensitive than *L. sativa* and *B. vulgaris*, respectively (Figure 4).

Figure 4 shows the inhibition of shoots and roots in comparison to the control for *B. vulgaris* L. *sativa*, and *U. plantaginea*. As reported previously, the high sensitivity of *U. plantaginea* allowed inhibitions of 72.50% and 88.13% for the roots and the shoots, respectively, in the lowest dose used in this study (625.63 g ai ha⁻¹). The plateau was reached for the other doses, with mean inhibition ranging between 90% and 95% in both shoots and roots.

Comparatively, *B. vulgaris* and *L. sativa* did not show the same sensitivity. At the dose of 625.63 g ai ha⁻¹, root inhibition was 63.75% in *B. vulgaris* and 66.25% in *L. sativa*, while shoot inhibition was 37.47% and 47.47%, respectively. However, both species reached 100% inhibition of root and shoot dry weights at a dose of 2,502.5 g ai ha⁻¹, and this pattern was maintained at the maximum dose tested (3,128.13 g ai ha⁻¹).

Visual comparison of the sensitivity of the evaluated species

Figures 5 and 6 present the possible bioindicator species at 21 and 28 DAS, respectively, showing the potential sensitivity of lettuce and beet during the preliminary study and the confirmation of *U. plantaginea* as a bioindicator plant in the final study.

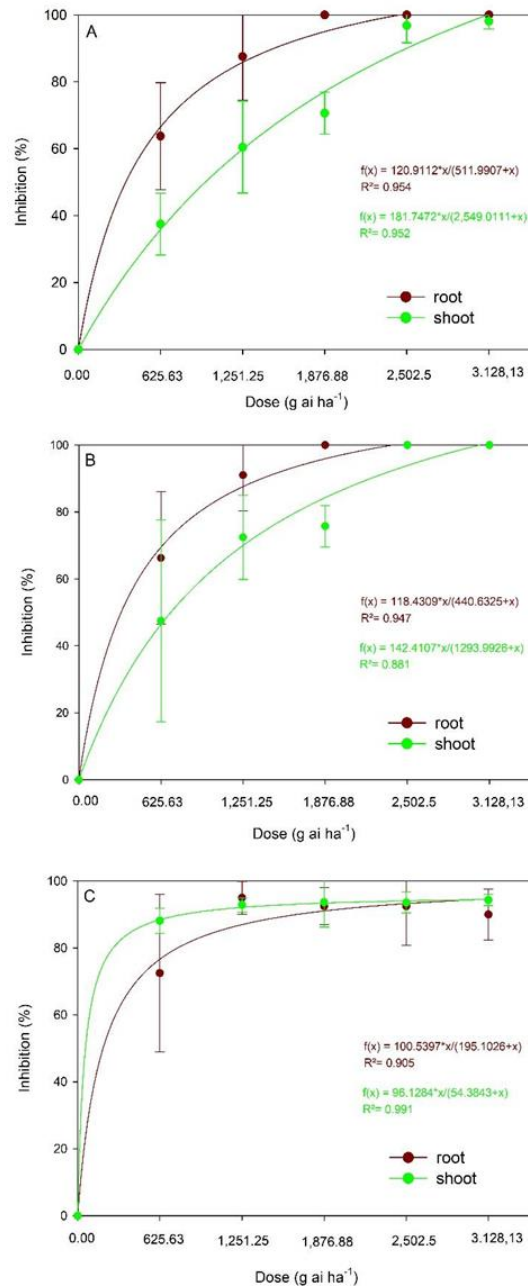


Figure 4. Percentage of shoot and root inhibition after application of pendimethalin at 28 days after sowing (DAS). A: *Beta vulgaris*; B: *Lactuca sativa*; C: *Urochloa plantaginea*.

Discussion

These results are consistent with the mechanism of action of pendimethalin, which inhibits tubulin polymerization and, consequently, microtubule assembly, compromising the division and elongation of cells (Hatzinikolaou et al., 2004). Because the herbicide is absorbed predominantly by the roots and presents low mobility in the xylem, it accumulates in the root tissues, severely affecting early root development. Li et al. (2021) found that pendimethalin significantly reduced ginger biomass, an effect attributed to root injury. In addition, the authors reported significant accumulation of the herbicide in the roots, but not in the rhizomes, which indicates that it has low translocation. This structural limitation compromises the absorption of water and nutrients, reflecting lower shoot growth, which is the most pronounced pattern in *U. plantaginea* and, to a lesser extent, in *L. sativa* and *B. vulgaris*. These findings corroborate the premise that different species have varying degrees of sensitivity, and specific tests must be performed to validate their efficacy as herbicide bioindicators (Guerra et al., 2014). The species *U. plantaginea* stood out as the most sensitive bioindicator to pendimethalin, confirming the potential

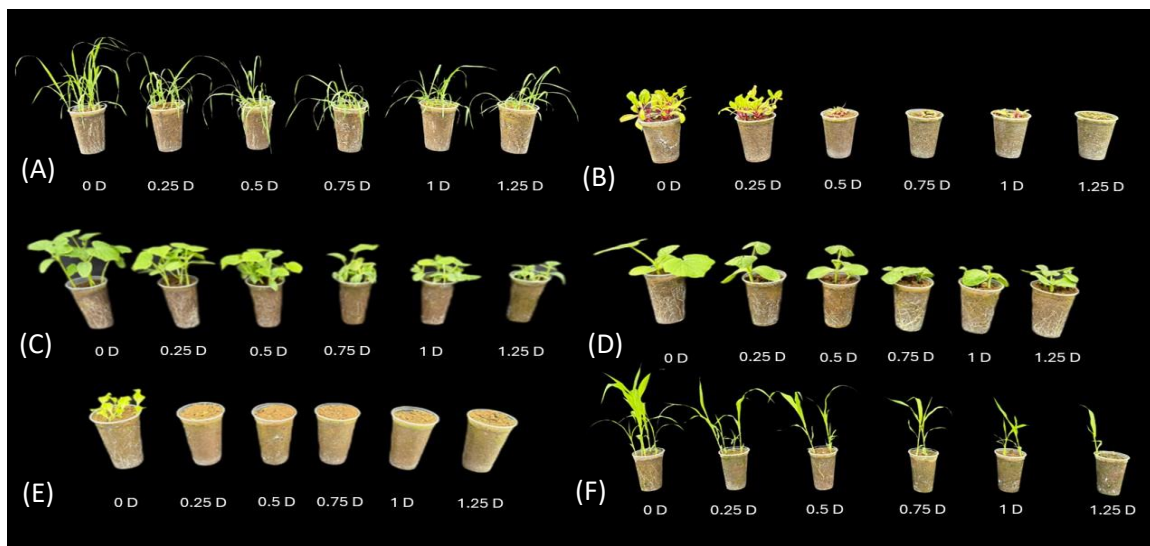


Figure 5. Reduction of growth caused by the herbicide pendimethalin in different plant species at 21 days after sowing (DAS), in increasing doses from left to right. A: *Avena strigosa*; B: *Beta vulgaris*; C: *Cucumis sativus*; D: *Cucurbita moschata*; E: *Lactuca sativa*; F: *Sorghum bicolor*.

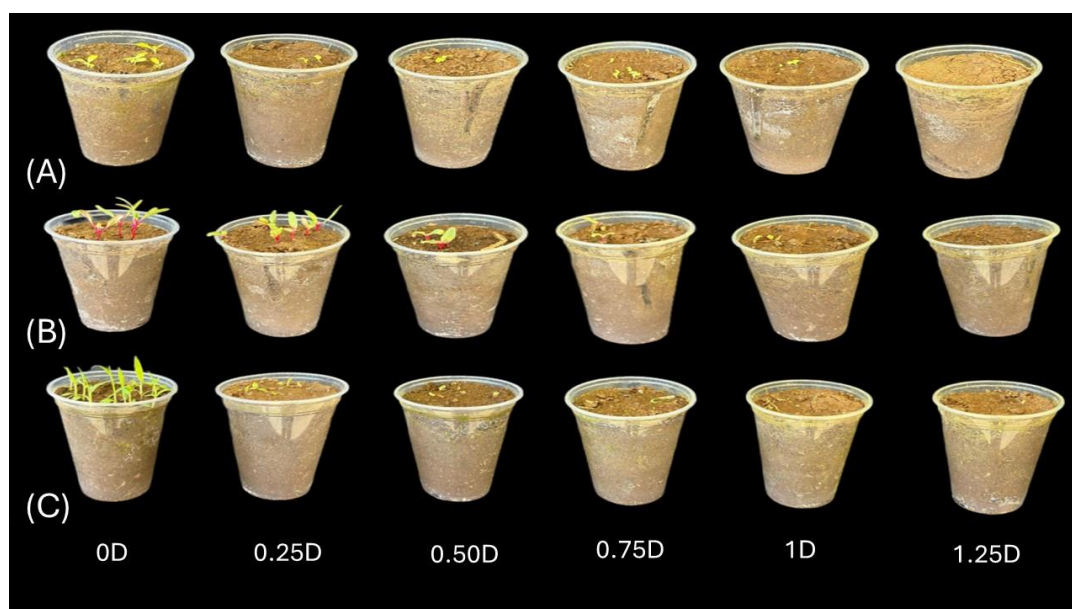


Figure 6. Reduction of growth caused by the herbicide pendimethalin in different plant species at 28 days after sowing (DAS), in increasing doses from left to right. A: *Beta vulgaris*; B: *Lactuca sativa*; C: *Urochloa plantaginea*.

of grasses as experimental models, since the herbicide acts on seeds of grasses that are germinating in the soil (BASF Corporation, 2023).

Still, vegetable seeds are also recommended for toxicological evaluations of soil residues, according to the United States Environmental Protection Agency (1996) and the Organization for Economic Co-operation and Development (2006), because physiological characteristics, such as short cycle and consistent responses to chemical stresses, make these species particularly suitable for monitoring (Gopalan, 1999; Valerio, Garcia, and Peinado, 2007).

The identification of highly sensitive species, such as *U. plantaginea*, provides a sensitive tool for the detection of pendimethalin residues in agricultural soils. However, the existence of tolerant species requires a cautious selection of bioindicators to avoid false negatives in monitoring studies. Such information is especially relevant for the use of pendimethalin in crops such as cotton, peanuts, sugarcane, coffee, citrus, beans, apple, and vegetables (Agrofit, 2025), which reinforces the importance of reliable methods for evaluating its effects on the agroecosystem.

Materials and methods

Experimental design

The experiment was conducted in two stages, between April and June 2025, in a greenhouse at Santa Catarina State University, Center for Agroveterinary Sciences (CAV/UDESC), located in the municipality of Lages, SC (27°47'34.52" S, 50°18'5.4" W, 904 m altitude). The soil used as substrate was collected in an area without a history of herbicide application,

in the municipality of Ituporanga, SC (27°31'47.81" S, 49°33'38.55" W, 612 m altitude). The physicochemical characteristics of the soil were as follows: pH (H₂O) = 5.4; K⁺ = 0.156 cmol_c dm⁻³; Ca²⁺ = 12.56 cmol_c dm⁻³; Mg²⁺ = 3.26 cmol_c dm⁻³; P = 12.0 mg dm⁻³; Al³⁺ = 0.46 cmol_c dm⁻³; CEC at pH 7.0 = 21.48 cmol_c dm⁻³; base saturation = 74.38%; organic matter = 2.8%; and clay content = 44.0%. The soil received 4.7 t ha⁻¹ of limestone and 300 kg ha⁻¹ of standard fertilization in the 7-28-14 formulation.

The study used a completely randomized experimental design, and it was carried out in two stages: the first experiment used olericultural and grasses species; the second experiment was aimed at confirming the bioindicator species. In the first stage, seeds of pumpkin (*Cucurbita moschata*), lettuce (*Lactuca sativa*), beet (*Beta vulgaris*), black oats (*Avena strigosa*), cucumber (*Cucumis sativus*), and sorghum (*Sorghum bicolor*) were sown. The second stage used lettuce, beet, and the weed *Urochloa plantaginea*, a species belonging to the family Poaceae, aiming to improve detection accuracy and obtain a more representative biological response.

The doses of pendimethalin were 0D, 0.25D, 0.5D, 0.75D, 1.0D and 1.25D (D = 2,502.5 g ai ha⁻¹), with four replications per treatment. Prowl® H₂O is a microencapsulated formulation of pendimethalin widely marketed in Brazil, and it contains three components: a pendimethalin core coated by a polyurea shell, suspended in an aqueous solution (Asher and Schuh, 2005). Initially registered for the cotton market, Prowl® H₂O is now available for more than 100 crops owing to its convenience, performance, and safety (BASF Corporation, 2025).

The experimental unit consisted of a container with a capacity of 500 cm³, filled with the substrate. Eight seeds were sown per experimental unit, except for sorghum (12 seeds, owing to its lower germination percentage). For *U. plantaginea*, each experimental unit received 0.2 g of seed. Sowing was performed at 1-2 cm depth. After sowing, the experimental units were irrigated, and the herbicide was applied about 2 hours later.

Pre-emergence spraying was carried out at 0.5 m above the experimental units, with a CO₂-pressurized backpack sprayer fitted with a spraying rod and four flat jet tips (TT 110 015) spaced at 0.5 m, at a pressure of 189 kPa, which resulted in an application rate equivalent to 150 L ha⁻¹. During the application, the climatic conditions were: air temperature between 13.4 and 18.3 °C, relative humidity between 62.6 and 85.7%, and wind speed of 1.3 to 4.0 km⁻¹ h.

Data collection

The variables were phytointoxication, root dry weight, (RDW) and shoot dry weight (SDW). The percentage of phytointoxication was measured at 21 days after application (DAA) in the preliminary study and at 28 DAA in the final study, because of low temperatures and lower availability of solar radiation, which prolonged the development of the plants. The evaluation was based on a visual scale of 0 to 100%, where 0% represents the absence of symptoms and 100% plant death (Kuva, Salgado and Revoredo, 2016). After phytointoxication was assessed, the plants were separated into shoots and roots and dried in a forced air circulation oven at 65 °C for 72 h (Lucadema, Sao José do Rio Preto, SP, Brazil). Then, SDW and RDW were determined on a previously calibrated precision balance with 0.001 g readability (Exacta Balanças, Porto Alegre, RS, Brazil). After that, the values were expressed as a percentage in comparison to the control, according to the equation:

$$\text{Inhibition (\%)} = 100 - \left[\left(\frac{\text{DW treatment}}{\text{DW control}} \right) \times 100 \right]$$

Where:

Inhibition (%) = inhibition percentage for shoot and/or root dry weight.

DW treatment = shoot and/or root dry weight of the treatment

DW control = shoot and/or root dry weight of the control

Statistical analysis

The data underwent analysis of variance by the F test ($p \leq 0.05$); when significant, they were adjusted by regression analysis, considering the statistical significance of the coefficients and the respective biological interpretation. Statistical analyses were performed with the software SISVAR (Ferreira et al., 2019), and the graphs were designed with SigmaPlot®, version 14.5 (Systat Software Inc., San Jose, CA, USA).

The resulting equations were used to estimate the doses that provide 50% phytointoxication (C₅₀) and 50% reduction of SDW and RDW (GR₅₀); they were both normalized to the values found for the control. Thus, the sensitivity of the species is determined with the C₅₀ and GR₅₀ values; the species with the lowest coefficients is considered a possible bioindicator.

Conclusion

The species *U. plantaginea* has the highest sensitivity to the herbicide pendimethalin compared to the other species analyzed in this study. Although vegetable species such as *L. sativa* and *B. vulgaris* are traditionally used as bioindicators in ecotoxicological studies, the results showed that weeds can present an equal or even higher potential for studies of herbicide behavior in the soil.

Acknowledgements

This study was supported by Santa Catarina State University (UDESC), the Santa Catarina Research and Innovation Support Foundation (FAPESC), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the National

Council for Scientific and Technological Development (CNPq), through the provision of scholarships and research funding. The authors wish to express their appreciation to the team of the Weed Science and Herbicide Laboratory (CAV/UDESC) for their support during the conduct of this study.

References

- Agostinetto D, Ulguim AR, Vargas L (2022) Weed Management in No-Tillage Systems. In: No-Tillage System in Brazil. 1st edn. *E-book*. 106-118.
- Asher S, Schuh J (2005) Prowl® H2O - a novel water-based formulation of pendimethaline. Paper presented at the Beltwide Cotton Conferences, New Orleans, 4-7 January 2005.
- BASF Corporation (2023) PROWL® H2O Herbicide. Available from: <https://agriculture.basf.us/crop-protection/products/herbicides/prowl.html>
- BASF Corporation (2025) How Prowl H2O Herbicide Works. Available from: <https://agriculture.basf.us/crop-protection/products/herbicides/prowl.html>
- Chen J, Yu Q, Patterson E, Sayer C, Powles SB (2021) Dinitroaniline herbicides: resistance and mechanisms in weeds. *Front Plant Sci.* 12:634018.
- Dias RC, Mendes KF, Oliveira CR, Pucci LF, Reis MR (2017) Methods of analysis and behavior of herbicides in soil. In: Lopes EA et al. (eds). *Chemistry in plant production*. 1st edn. Authors' Publisher, Rio Paranaíba. 372-373.
- Ferreira DF (2019) Sisvar: a computer analysis system to fixed effects split plot type designs. *Braz J Biom.* 2019;37(4):529-535.
- Gazziero DLP, Neumaier N. Symptoms and diagnosis of herbicide phytotoxicity in soybean, 1st edn, Embrapa, Londrina. 1985. p. 16-17.
- Gopalan HNB (1999) Ecosystem health and human wellbeing: the mission of the international programme on plant bioassays. *Mutat Res.* 426(2):99-102.
- Guerra N, Oliveira Neto AM, Oliveira Jr RS, Constantin J, Takano HK (2014) Sensibility of plant species to herbicides aminocyclopyrachlor and indaziflam. *Planta Daninha.* 32(3):609-617.
- Hatzinikolaou AS, Eleftherohorinos IG, Vasilakoglou IB (2004) Influence of formulation on the activity and persistence of pendimethalin. *Weed Techn.* 18(2):397-403.
- Kuva MA, Salgado TP, Revoredo TTO (2016) Herbicide efficiency and agronomic practicability experiments. In: Monquero PA (ed) *Experimenting with herbicides*, 1st edn. Rima, São Carlos. 2016. p. 75-98.
- Li Y, Wang K, Kong Y, Lv Y, Xu K (2021) Toxicity and tissue accumulation characteristics of the herbicide pendimethalin under silicon application in ginger (*Zingiber officinale* Roscoe). *Environ Sci Pollut Res.* 29(25):25263-25275.
- Majumdar S, Dastidar SG (2016) Ligand Binding Swaps between Soft Internal Modes of α,β -Tubulin and Alters Its Accessible Conformational Space. *J. Phys. Chem.* 121(1):118-128.
- Ministry of Agriculture and Livestock (BR). Agrofite - Phytosanitary Pesticides System. PROWL - Leaflet. Brasília, DF: MAPA. Available from: https://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons
- Mogul MG, Akin H, Hasirci N, Trantolo DJ, Gresser JD, Wise DL (1996) Controlled release of biologically active agents for purposes of agricultural crop management. *Resour Conserv Recycl.* 16(1):289-320.
- Neal J, Goodale D, Jennings K (2016) Root Inhibitors. Raleigh, NC: North Carolina State University. Available from: content.ces.ncsu.edu/root-inhibitors
- Nunes AL, Vidal RA (2009) Selection of plants for quantifying residual herbicides. *Pesticides: Journal of Ecotoxicology and Environmental Sciences.* 19(1):19-28. Portuguese.
- Organisation for Economic Co-operation and Development (2006) Test No. 208: Terrestrial Plant Test: Seedling Emergence and Seedling Growth Test. Paris: OECD Publishing; (OECD Guidelines for the Testing of Chemicals, Section 2). Available from: <https://doi.org/10.1787/9789264070066-en>
- Pesticide Properties Database (PPDB) - University of Hertfordshire (2025). Pendimethalin (Ref: AC 92553). Available from: <http://sitem.herts.ac.uk/aeru/ppdb/en/Reports/511.htm>
- Ribeiro Junior LF, Gonçalves TP, Sousa BF, Da Costa JLB (2018) Tolerância inicial de feijão-caupi a herbicidas aplicados em pré-emergência. *Weed Control J.* 17(3):e603.
- Shaw SL, Vineyard L (2014) Cortical Microtubule Array Organization and Plant Cell Morphogenesis. In: Fukuda, H (ed) *Plant Cell Wall Patterning and Cell Shape*, 1st edn. Wiley, New York.
- United States Environmental Protection Agency (1996) Seedling emergence and seedling growth [Internet]. Washington, D.C.: U.S. Environmental Protection Agency; (OCSPP Harmonized Test Guidelines; No. 850.4100). Available from: <https://www.epa.gov/sites/default/files/2015-07/documents/850-4100.pdf>
- Valerio ME, Garcia JF, Peinado FM (2007) Determination of phytotoxicity of soluble elements in soils, based on a bioassay with lettuce (*Lactuca sativa* L.). *Sci Total Environ.* 378(1-2):63-66.
- Vargas L, Roman ES (2006) Weed resistance to herbicides: concepts, origin, and evolution. *Online Documents* - No. 58. Portuguese. Available from: <https://www.infoteca.cnptai.embrapa.br/bitstream/doc/852512/1/pdo58.pdf>