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Chemical Control of 'Prata Anã' Banana Suckers by Pseudostem Application: Efficacy and Subsequent Soil Bioassay Responses

Juan Antônio Borges Felipe [1], Carlos Henrique Milagres Ribeiro [2,*], Gabriele Padilha Schneider [1], Monalisa Gomes Barbosa [1], Denny Oswaldo Paéz Piñango [1], Daniel Leopoldino Dias [1], Pedro Henrique Reis Vilela [1], Paulina Celestino Silva [1], Ana Gabriela Resende da Silva [1], Isabel Roque de Oliveira [1] and Leila Aparecida Salles Pio [1]

[1] Department of Agriculture, Federal University of Lavras, University Campus, P.O. Box 3037, Lavras 37203-202, MG, Brazil; juan.felipe@estudanteufla.br (J.A.B.F.); gabrieleschneider120599@gmail.com (G.P.S.); monalisa.barbosa@estudante.ufla.br (M.G.B.); denny.pinango1@estudante.ufla.br (D.O.P.P.); daniel.dias2@estudante.ufla.br (D.L.D.); pedro.vilela4@estudante.ufla.br (P.H.R.V.); ps1190396@gmail.com (P.C.S.); anagabrielaresende23@gmail.com (A.G.R.d.S.); isabel.oliveira1@estudante.ufla.br (I.R.d.O.); leila.pio@ufla.br (L.A.S.P.)

[2] Department of Soil Science, Federal University of Lavras, University Campus, P.O. Box 3037, Lavras 37203-202, MG, Brazil

* Correspondence: chm.ribeiro8@gmail.com

Abstract

Effective banana sucker management is essential for plantation renewal because physical removal may allow regrowth from viable rhizome buds. This study compared localized pseudostem application of glyphosate (480 g a.e. L^{-1}; 1.8 mL $shoot^{-1}$), 2,4-D (720 g a.e. L^{-1}; 1.5 mL $shoot^{-1}$), and KH_2PO_4 + paclobutrazol (PBZ; 2.0 g + 1.0 g in 5 mL water $shoot^{-1}$) with untreated, cutting, and mechanical controls in 'Prata Anã' banana. Phytotoxicity, chlorophyll indices, relative water content (RWC), mortality, regrowth, growth, and biomass were evaluated for up to 120 days after application (DAA). Soils collected six months after treatment application were subsequently evaluated using lettuce and tomato as bioindicator species, together with soil chemical characterization. Glyphosate and 2,4-D progressively impaired banana sucker physiology and growth. At 120 DAA, both treatments resulted in 100% sucker mortality, completely suppressed new sucker emergence, and reduced shoot fresh and dry biomass by 100% compared with the untreated control. The response to 2,4-D was faster, reaching 100% mortality as early as 28 DAA. In contrast, KH_2PO_4 + PBZ caused temporary physiological impairment, with RWC decreasing to 63.83% at 60 DAA and recovering to 85.56% at 120 DAA. Six months after field application, seedling emergence was unaffected by soil origin, ranging from 86.32 to 89.84% in lettuce and from 94.53 to 95.70% in tomato, and chlorophyll indices were also unaffected. However, species-specific differences occurred in growth, biomass, and Dickson quality index, while soil chemical properties differed among field treatments. Overall, localized pseudostem application of glyphosate and 2,4-D provided sustained suppression of banana sucker regrowth, whereas KH_2PO_4 + PBZ produced only temporary suppression. No consistent biologically detectable effects were observed across the bioindicator responses six months after field treatment application under the conditions of this bioassay. However, these responses cannot be attributed exclusively to chemical residues because the compounds and their metabolites were not directly quantified and soil chemical properties differed among treatments. From a practical standpoint, localized pseudostem application of glyphosate or 2,4-D can provide sustained sucker suppression, but the present bioassay does not establish a safe rotation or replanting interval, which would require direct residue quantification and evaluation at multiple post-application times.

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1. Introduction

Banana (*Musa* spp.) is one of the most important fruit crops in tropical and subtropical regions, where its production plays a major role in food supply and income generation [1]. Global banana production reached approximately 139.4 million tons in 2024, with India as the world's largest producer (37.6 million tons) and Brazil ranking fifth, with approximately 7.0 million tons [2]. Unlike annual crops, banana plantations may remain in the same area for several production cycles because new shoots arise continuously from lateral buds in the underground rhizome [3]. This characteristic sustains crop succession within the mat but also requires careful management of sucker number and development to avoid excessive competition among plants [4].

Sucker management is particularly important for maintaining adequate plant density and productivity and becomes essential when established banana mats need to be removed during plantation rehabilitation or renewal [4,5]. Because banana suckers originate from buds associated with the underground rhizome, removal of the aboveground portion alone may allow subsequent regrowth. Conventional management therefore involves repeated desuckering or physical removal of unwanted shoots. These operations can increase labor requirements, particularly when regrowth occurs, and additional interventions are needed [4,5]. Under Brazilian production conditions, desuckering is a recurrent management operation and, during plantation establishment, is generally performed at approximately 4, 6, and 10 months after planting. Moreover, cutting the sucker at ground level requires the subsequent destruction of the apical growth point to prevent regrowth. The use of a specific tool for apical bud removal has been reported to increase operational efficiency by approximately 75% compared with traditional methods, illustrating the labor and operational demands associated with conventional sucker management [6].

Localized chemical application provides an alternative for suppressing or eliminating unwanted banana shoots while restricting product delivery to the target plant. In this approach, the chemical is delivered directly into the pseudostem rather than sprayed over the entire plant or soil surface. By confining the treatment to the target pseudostem, this application strategy can limit direct deposition of the applied product onto non-target plant surfaces and the surrounding soil [7]. Therefore, localized application may reduce the potential for off-target environmental exposure compared with broadcast foliar or soil-directed applications, although the extent of this reduction depends on the physicochemical properties and subsequent fate of each compound. Pseudostem injection has been used for banana plant destruction and can reduce the time and labor required for plant elimination [8]. Glyphosate applied directly into the pseudostem has shown effective control of banana regrowth [9], while 2,4-D has also been successfully used for chemical suppression of banana regrowth through localized application [10]. Other compounds have been evaluated for sucker control. Luo et al. [11], for example, reported effective suppression of sucker growth using a combination of monopotassium phosphate (KH_2PO_4) and paclobutrazol (PBZ). These products differ markedly in their modes of action and may consequently differ in the speed, intensity, and persistence of their effects on banana regrowth.

Agronomic efficiency alone is not sufficient to determine whether a chemical treatment is suitable for plantation renewal. Residues reaching the soil may remain biologically active and affect crops subsequently established in the same area, a phenomenon commonly referred to as herbicide carryover [12]. Persistence in soil depends on the physicochemical

properties of the compound as well as soil characteristics, temperature, moisture, and microbial activity [13]. Evidence from banana production systems also indicates that herbicide-related soil responses may depend on the exposure scenario. For example, in a banana plantation, a single application of a glufosinate-based herbicide did not significantly affect soil microbial diversity or function, whereas prolonged herbicide use was associated with indirect changes in soil functions related to vegetation differences [14]. This issue is especially relevant when chemical sucker control is followed by rapid replanting or a change in the crop grown in the area. Bioassays using sensitive plant species provide a practical means of detecting biologically active effects in treated soil and assessing potential injury to subsequent crops [15]. However, plant bioassays indicate biological responses to the tested soil and do not provide direct information on the identity, concentration, or persistence of specific chemical residues. Because bioassay responses may also be influenced by soil fertility and other chemical properties, soil chemical characterization can complement the interpretation of biologically detectable residual effects. However, little is known about the potential residual effects in soil following localized chemical treatments used for banana sucker control.

We hypothesized that localized chemical application into the banana pseudostem would provide more effective and persistent suppression of sucker regrowth than conventional physical removal methods, but that the magnitude and duration of this response would depend on the chemical treatment used. We further hypothesized that restricting application to the pseudostem would result in limited biologically detectable effects in the soil several months after treatment. Therefore, this study compared different strategies for managing 'Prata Anã' banana suckers, including the absence of intervention, conventional cutting, mechanical meristem destruction, and localized pseudostem application of glyphosate, 2,4-D, or KH_2PO_4 + PBZ. The field experiment was designed to determine whether localized chemical treatments could provide more persistent suppression of sucker regrowth than conventional physical removal methods. In addition, soils collected six months after treatment application were evaluated using lettuce and tomato as bioindicator species to assess potential biologically detectable effects associated with the previous treatments.

2. Materials and Methods

The study was conducted in two independent and complementary experimental stages: (i) a field experiment to evaluate the agronomic efficacy of different treatments for controlling banana regrowth; (ii) an experiment under controlled conditions to assess biologically detectable responses in soils collected six months after treatment application using bioindicator species.

2.1. Experiment 1—Agronomic Efficacy of Different Banana Sucker Management Strategies

2.1.1. Experimental Site and Plant Material

The experiment was conducted from October 2025 to April 2026 at the Fruit Science Sector of the Department of Agriculture, School of Agricultural Sciences, Federal University of Lavras (UFLA), Lavras, Minas Gerais, Brazil. The experimental site is located at approximately 918 m above sea level, at 21°14′ S and 45°00′ W.

According to the Köppen climate classification [16], the region has a Cwb climate, characterized as a highland humid subtropical climate with dry winters and rainy summers. Data on temperature, precipitation, and relative humidity recorded during the experimental period were obtained from the Brazilian National Institute of Meteorology (INMET) and are presented in Figure 1.

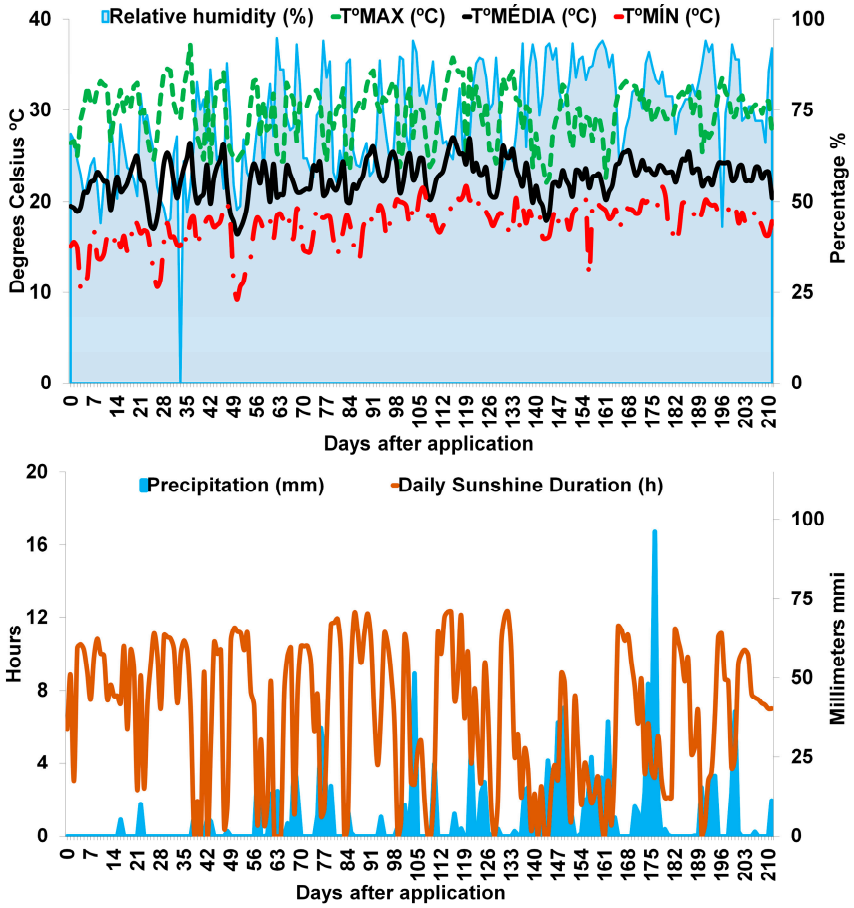


Figure 1. Air temperature, relative humidity, precipitation, and daily sunshine duration recorded during the experimental period in Lavras, Minas Gerais, Brazil. Source: Instituto Nacional de Meteorologia [17].

Before treatment application, a composite soil sample representative of the experimental area was collected from the 0–20 cm soil layer for chemical and particle-size characterization. The soil had a pH of 6.60; 48.61 mg dm^{-3} P; 298.25 mg dm^{-3} K; 7.33 cmolc dm^{-3} Ca; 1.40 cmolc dm^{-3} Mg; 0.10 cmolc dm^{-3} Al; 3.42 dag kg^{-1} organic matter; and 88.59% base saturation. The particle-size distribution consisted of 41.77% clay, 21.80% silt, and 36.42% sand.

Approximately six-year-old 'Prata-Anã' banana plants, Gorutuba clone, were used. Before the experiment was established, the plants were cut at ground level to standardize the emergence of new shoots. When the regrowth reached an average height of 50 ± 5 cm, six shoots were retained per mat.

The experimental units were grouped into four blocks according to their spatial position within the orchard, considering their distribution along the planting rows and spatial proximity. This blocking criterion was adopted to account for potential spatial heterogeneity within the experimental area. Within each block, the six treatments were randomly assigned to individual banana mats.

2.1.2. Treatments and Application

The experiment consisted of six treatments: an untreated control, cutting control, mechanical control using the "Nova Lurdinha" device, glyphosate, 2,4-D, and a combination of monopotassium phosphate (KH_2PO_4) + paclobutrazol (PBZ). For each chemical treatment, all six shoots retained within the corresponding banana mat received the same treatment. Each shoot was treated individually according to the application procedure described in

Table 1. Thus, treatments were assigned at the banana-mat level rather than independently to individual shoots.

Table 1. Description of the treatments used for banana regrowth control.

Treatment	Commercial Product/Formulation	Applied Dose	Application Method	Reference
Untreated control	-	-	Shoots maintained without intervention	-
Cutting control	-	-	Shoots cut at ground level using a machete	-
Mechanical control	Nova Lurdinha	-	Cutting at ground level followed by roto-compression of the meristematic region	[18]
Glyphosate	Roundup® (480 g a.e. L^{-1}, SL; Monsanto do Brasil Ltda., São Paulo, SP, Brazil)	1.8 mL $shoot^{-1}$	Injection into the pseudostem approximately 10 cm above the soil surface	[9]
2,4-D	2,4-D NORTOX® (720 g a.e. L^{-1}, SL, Nortox S/A, Arapongas, PR, Brazil)	1.5 mL $shoot^{-1}$	Injection into the pseudostem approximately 10 cm above the soil surface	[10]
KH_2PO_4 + PBZ	KH_2PO_4 + paclobutrazol (paclobutrazol (PBZ; TraceCERT®, ≥99.0% purity, Sigma-Aldrich, St. Louis, MO, USA)	2.0 g KH_2PO_4 + 1.0 g PBZ in 5 mL water per shoot	Injection into the pseudostem approximately 10 cm above the soil surface	[11]

For the KH_2PO_4 + PBZ treatment, the mixture was prepared immediately before application at a 2:1 (w/w) ratio, as adapted from Luo et al. [11].

Chemical treatments were applied using a graduated syringe fitted with a 10 cm metal needle, which was inserted into the pseudostem approximately 10 cm above the soil surface, directed toward the central region at an angle of approximately 45°. After application, the injection site was immediately sealed with melted commercial solid paraffin to minimize losses through exudation. Applications were performed in the morning, at air temperatures ranging from 22 to 24 °C and relative humidity above 50%.

2.1.3. Evaluated Parameters

Shoot phytotoxicity was assessed at 7, 14, 21, 28, 60, 90, and 120 days after application (DAA) using the European Weed Research Council scale—EWRC [19], with scores ranging from 1 (no symptoms) to 9 (complete death). Assessments were performed by three previously trained evaluators, and the mean score for each experimental unit was used.

Chlorophyll *a*, chlorophyll *b*, and total chlorophyll (*a* + *b*) indices were determined at 7, 14, 21, 28, 35, 60, 90, and 120 DAA using a portable ClorofiLOG® CFL 1030 chlorophyll meter (Falker Automação Agrícola, Porto Alegre, RS, Brazil). Four fully expanded leaves per experimental unit were selected and identified before treatment application and were used for successive measurements while they remained physiologically viable. At the same evaluation times, relative water content (RWC) was determined according to Barrs and Weatherley [20], using 15 disks from fully expanded leaves per experimental unit. The disks were weighed to determine fresh weight (FW), maintained in distilled water for 24 h to determine turgid weight (TW), and then dried in a forced-air oven at 65 °C until constant weight to determine dry weight (DW). RWC was calculated as follows:

$$RWC\ (\%) = [(FW - DW)/(TW - DW)] \times 100$$

At 28 and 120 DAA, shoot mortality, number of new shoots, shoot height, and pseudostem diameter were determined. Mortality was expressed as the percentage of shoots classified with a score of 9 on the EWRC scale. The number of new shoots was determined by direct counting. Shoot height was measured from the base to the apex using a graduated measuring tape. To determine pseudostem diameter, pseudostem circumference was measured approximately 10 cm above the soil surface using a millimeter-graduated measuring tape, and diameter was subsequently calculated as

$$D = \frac{C}{\pi}$$

where D is the pseudostem diameter and C is the measured pseudostem circumference.

Aboveground biomass was determined at 28 and 120 DAA. At 28 DAA, the shoots were cut at ground level and immediately weighed to determine fresh weight. After this assessment, new shoots were allowed to grow freely until 120 DAA, when the aboveground biomass was again harvested and weighed. At both evaluation times, the plant material was dried in a forced-air oven at 65 °C until constant weight to determine dry weight.

2.1.4. Experimental Design and Statistical Analysis

The experiment was conducted in a randomized complete block design (RCBD) with six treatments and four blocks, totaling 24 independent experimental units. Each experimental unit consisted of one banana mat containing six shoots. Treatments were assigned to the banana mat as a whole, and all six shoots within a mat received the same assigned treatment. Therefore, the six shoots represented subsamples within the experimental unit and were not considered independent experimental replicates. For variables measured at the shoot level, values from the six shoots were aggregated at the banana-mat level before statistical analysis, resulting in four independent replicates per treatment.

When leaf tissue was absent following cutting or mechanical removal, chlorophyll indices and RWC could not be physiologically measured. Under these conditions, zero values were recorded to represent the absence of measurable leaf tissue and should not be interpreted as physiological values of zero in intact leaves.

For phytotoxicity, chlorophyll indices, and RWC, a split-plot-in-time design was adopted, with treatments considered as main plots and evaluation times as subplots. Shoot height, pseudostem diameter, and number of new shoots, evaluated at 28 and 120 DAA, were also analyzed considering the effects of treatment, evaluation time, and the treatment × evaluation time interaction. Aboveground fresh and dry weights were analyzed separately for each evaluation time because sampling at 28 DAA was destructive, and biomass at 120 DAA represented the growth that occurred after the first cutting.

Data were subjected to analysis of variance (ANOVA) after testing residual normality using the Shapiro–Wilk test and homogeneity of variances using Bartlett's test. When significant effects were detected, means were compared using Tukey's test at $p \leq 0.05$. Statistical analyses were performed using SISVAR® version 5.8 (Federal University of Lavras, Lavras, MG, Brazil) [21].

2.2. Experiment 2—Soil Bioassay Six Months After Treatment Application

2.2.1. Soil Sampling and Bioassay Conditions

Six months after field treatment application, soil samples were collected for evaluation using lettuce and tomato as bioindicator species. In each experimental unit, soil was sampled at six distinct points around the banana mat from the 0–20 cm soil layer using a Dutch auger. The samples were homogenized to obtain one composite sample per experimental unit, while soils from the four blocks were kept separate.

Soils from the untreated control, glyphosate, 2,4-D, and KH_2PO_4 + PBZ treatments were evaluated (Table 2). Soil collected from untreated field experimental units served as the negative reference control for the bioassay. No positive control consisting of soil amended with a known concentration of the evaluated compounds was included. Therefore, the bioassay was designed to compare biological responses among soils originating from the different field treatments rather than to validate the sensitivity of the bioindicator species to known residue concentrations.

Table 2. Soil origins evaluated in the bioassay conducted six months after field treatment application.

Treatment	Soil Origin
Control	Experimental units without chemical treatment application
Glyphosate	Experimental units subjected to glyphosate application to the pseudostem
2,4-D	Experimental units subjected to 2,4-D application to the pseudostem
KH_2PO_4 + PBZ	Experimental units subjected to KH_2PO_4 + PBZ application to the pseudostem

Lettuce (*Lactuca sativa* L.) and tomato (*Solanum lycopersicum* L.) were used as bioindicator species. The soil was air-dried to facilitate handling and homogenization, gently disaggregated, and passed through a 2-mm sieve to remove coarse fragments and obtain a more uniform substrate among experimental units before filling the 128-cell expanded polystyrene tray. Two commercial seeds of smooth-leaf lettuce or red cherry tomato were sown in each cell. At seven days after sowing, seedlings were manually thinned to one plant per cell.

The trays were maintained in an intermittent mist chamber for 30 days at a temperature of 25 ± 5 °C and a mean relative humidity of 72%. Irrigation was applied by misting for 20 s at 30-min intervals during the daytime.

2.2.2. Evaluated Parameters

Seedling emergence percentage was determined as the ratio between the number of emerged seedlings and the total number of seeds sown. At the end of the 30-day experimental period, the number of fully expanded leaves, seedling height, longest root length, and stem diameter were determined. Seedling height and root length were measured using a millimeter-graduated ruler, whereas stem diameter was measured at the root collar using a digital caliper.

The seedlings were separated into shoots and roots and immediately weighed to determine their respective fresh weights. Subsequently, the plant material was dried in a forced-air oven at 65 °C until constant weight to determine shoot and root dry weights. The Dickson Quality Index (DQI) [22] was calculated as follows:

$$DQI = \frac{TDW}{\frac{H}{D} + \frac{SDW}{RDW}}$$

where TDW is total dry weight; H is seedling height; D is stem diameter; SDW is shoot dry weight; and RDW is root dry weight.

Chlorophyll *a*, chlorophyll *b*, and total chlorophyll (*a* + *b*) indices were determined at the end of the experiment using a portable ClorofiLOG® CFL 1030 chlorophyll meter on two fully expanded leaves from each seedling.

A soil subsample from each experimental unit was used for chemical characterization according to the methods described by Teixeira et al. [23]. Soil pH was determined in water at a 1:2.5 soil-to-water ratio. Phosphorus (P), potassium (K), iron (Fe), and manganese (Mn)

were extracted using Mehlich-1, whereas calcium (Ca) and magnesium (Mg) were extracted using 1 mol L^{-1} KCl. Potential acidity (H + Al) was determined using the SMP method. Organic matter (OM) was determined by oxidation with 4 N $Na_2Cr_2O_7$ + 10 N H_2SO_4, and sulfur (S) was extracted using monocalcium phosphate in acetic acid. Base saturation (V) was calculated from the soil chemical analysis.

2.2.3. Experimental Design and Statistical Analysis

The bioassay was conducted in a completely randomized design (CRD) with four treatments and four replicates. Each replicate corresponded to soil collected from an independent experimental unit of the field experiment. For each bioindicator species, each experimental unit consisted of 32 cells, which were treated as subsamples. Data from these cells were averaged to obtain a single value per experimental unit before statistical analysis.

Bioassay and soil chemical characterization data were subjected to analysis of variance (ANOVA) after testing residual normality using the Shapiro–Wilk test and homogeneity of variances using Bartlett's test. When significant treatment effects were detected, means were compared using Tukey's test at $p \leq 0.05$. Statistical analyses were performed using SISVAR® version 5.8 (Federal University of Lavras, Lavras, MG, Brazil) [21].

Pearson correlation analysis was additionally performed to explore associations between soil chemical attributes and the growth, biomass, quality, and chlorophyll indicators of lettuce and tomato seedlings. Correlations were calculated using the individual experimental units (n = 16 for each bioindicator species), and statistical significance was considered at $p \leq 0.05$. Correlation analyses were interpreted as exploratory associations and not as evidence of causal relationships.

3. Results

3.1. Agronomic Effectiveness of Banana Sucker Management Strategies

There was a significant interaction between treatments and evaluation times ($p \leq 0.05$) for phytotoxicity, chlorophyll *a*, *b*, and total chlorophyll indices, and relative water content (RWC). Phytotoxicity progressively increased in plants treated with glyphosate and 2,4-D, whereas the other treatments remained at score 1 on the EWRC scale throughout the experimental period (Table 3). The response to 2,4-D was faster, reaching score 9 at 28 DAA, whereas glyphosate reached this score at 60 DAA; both remained at score 9 through 120 DAA.

Table 3. Visual phytotoxicity scores of banana plants as affected by the interaction between treatments and days after application (DAA). Means followed by the same lowercase letter within a row and uppercase letter within a column do not differ according to Tukey's test ($p \leq 0.05$).

Days After Application	Untreated Control	Cutting Control	Mechanical Control	Glyphosate	KH_2PO_4 + PBZ	2,4-D
7	1.00 aC	1.00 aC	1.00 aC	4.25 eB	1.00 aC	7.00 cA
14	1.00 aC	1.00 aC	1.00 aC	6.10 dB	1.00 aC	8.25 bA
21	1.00 aC	1.00 aC	1.00 aC	8.00 cB	1.00 aC	8.75 aA
28	1.00 aC	1.00 aC	1.00 aC	8.50 bB	1.00 aC	9.00 aA
60	1.00 aB	1.00 aB	1.00 aB	9.00 aA	1.00 aB	9.00 aA
90	1.00 aB	1.00 aB	1.00 aB	9.00 aA	1.00 aB	9.00 aA
120	1.00 aB	1.00 aB	1.00 aB	9.00 aA	1.00 aB	9.00 aA
CV (%)	Cv_1 (installments) = 5.02; Cv_2 (subplots) = 6.80					

3.2. Chlorophyll Indices

Chlorophyll indices were mainly reduced by the glyphosate and 2,4-D treatments (Table 4). The reduction occurred more rapidly with 2,4-D, with chlorophyll *a*, *b*, and total

chlorophyll reaching zero from 28 DAA onward, whereas in the glyphosate treatment, values reached zero from 60 DAA onward. The KH_2PO_4 + PBZ treatment showed a reduction in chlorophyll indices between 60 and 90 DAA, followed by recovery at 120 DAA, while the zero values recorded for the cutting and mechanical controls at 7 DAA reflected the absence of measurable leaf tissue following shoot removal rather than physiological chlorophyll values of zero. Leaf tissue subsequently regenerated, allowing chlorophyll measurements at later evaluation times.

Table 4. Treatment × days after application (DAA) interaction for chlorophyll indices in banana leaves. Means followed by the same lowercase letter within a row and uppercase letter within a column do not differ significantly according to Tukey's test ($p \leq 0.05$).

Chlorophyll *a* Index (SPAD)						
Days After Application	**Untreated Control**	**Cutting Control**	**Mechanical Control**	**Glyphosate**	**KH_2PO_4 + PBZ**	**2,4-D**
7	38.47 abcA	0.00 cD	0.00 cD	40.44 aA	29.90 cB	23.65 aC
14	34.36 cA	21.83 bB	39.32 aA	18.64 bB	37.08 bA	12.88 bC
21	36.92 bcA	39.98 aA	30.09 bB	10.13 cB	36.25 bA	10.56 bB
28	42.99 aAB	37.65 aB	44.71 aA	14.85 bcC	43.44 aA	0.00 cD
60	38.59 abcA	41.06 aA	41.25 aA	0.00 dC	26.28 cB	0.00 cC
90	40.39 abA	40.39 aA	41.45 aA	0.00 dC	30.09 cB	0.00 cC
120	36.03 bcA	36.60 aA	39.22 aA	0.00 dB	36.39 bA	0.00 cB
CV (%)	Cv_1 (plots) = 9.01; Cv_2 (subplots) = 10.19					
Chlorophyll *b* Index (SPAD)						
Days After Application	**Untreated Control**	**Cutting Control**	**Mechanical Control**	**Glyphosate**	**KH_2PO_4 + PBZ**	**2,4-D**
7	27.54 abA	0.00 eC	0.00 cC	26.71 aA	13.51 dB	9.10 aB
14	24.86 abAB	9.78 dC	25.73 aA	7.11 bCD	19.21 bcdB	2.87 abD
21	24.29 bB	31.58 aA	12.10 bC	4.12 bcD	21.86 bB	2.71 bD
28	31.04 aA	17.93 dB	29.89 aA	4.02 bcC	29.11 aAB	0.00 bC
60	28.37 abA	24.90 bA	26.89 aA	0.00 cC	14.00 dB	0.00 bC
90	30.36 abA	30.36 abA	26.19 aA	0.00 cC	15.11 cdB	0.00 bC
120	25.93 abAB	27.48 abA	25.51 aAB	0.00 cC	20.97 bcB	0.00 bC
CV (%)	Cv_1 (plots) = 16.86; Cv_2 (subplots) = 18.72					
Total Chlorophyll Index (SPAD)						
Days After Application	**Untreated Control**	**Cutting Control**	**Mechanical Control**	**Glyphosate**	**KH_2PO_4 + PBZ**	**2,4-D**
7	66.01 abcA	0.00 dC	0.00 cC	63.72 aA	44.31 cB	34.86 aB
14	59.23 cA	31.61 cB	65.05 aA	25.75 bBC	56.29 bA	15.76 bC
21	61.21 bcB	71.56 aA	42.19 bC	14.25 cD	58.11 bB	13.28 bD
28	74.03 aA	55.58 bB	74.61 aA	18.87 bcC	72.55 aA	0.00 cD
60	66.97 abcA	65.97 abA	68.14 aA	0.00 dC	40.28 cB	0.00 cC
90	70.75 abA	70.75 aA	67.65 aA	0.00 bC	45.20 cB	0.00 cC
120	61.98 bcA	64.08 abA	64.73 aA	0.00 bB	57.37 bA	0.00 cB
CV (%)	Cv_1 (plots) = 11.53; Cv_2 (subplots) = 11.70					

3.3. Relative Water Content

Relative water content (RWC) was also affected by the interaction between treatments and evaluation times (Table 5). The 2,4-D treatment caused a marked reduction in RWC during the initial evaluations, reaching zero at 28 DAA, whereas in the glyphosate treatment, RWC reached zero at 60 DAA. At 7 DAA, the zero values recorded for the cutting and mechanical controls reflected the absence of measurable leaf tissue following shoot removal rather than physiological RWC values of zero. Leaf tissue subsequently regenerated,

allowing RWC measurements at later evaluation times. The KH_2PO_4 + PBZ treatment showed a temporary reduction, reaching its lowest value at 60 DAA (63.83%), followed by recovery to 85.56% at 120 DAA.

Table 5. Treatment × days after application (DAA) interaction for relative water content in banana leaves. Means followed by the same lowercase letter within a row and uppercase letter within a column do not differ significantly according to Tukey's test ($p \leq 0.05$).

Days After Application	Untreated Control	Cutting Control	Mechanical Control	Glyphosate	KH_2PO_4 + PBZ	2,4-D
7	77.71 dA	0.00 cD	0.00 bD	51.81 aB	73.36 cA	36.84 aC
14	85.59 bcAB	82.63 bAB	80.34 aB	48.00 aC	85.90 aA	23.14 bD
21	91.41 abA	89.71 aA	79.53 aB	14.30 bC	80.07 abB	1.16 cD
28	94.45 aA	87.54 abB	83.22 aB	11.92 bD	76.15 bcC	0.00 cE
60	87.47 bcA	84.79 abAB	81.37 aB	0.00 cD	63.83 dC	0.00 cD
90	90.05 abA	90.05 aA	80.78 aB	0.00 cD	75.03 bcC	0.00 cD
120	82.48 cdA	86.97 abA	82.53 aA	0.00 cB	85.56 aA	0.00 cB
CV (%)	Cv_1 (plots) = 6.05; Cv_2 (subplots) = 4.70					

3.4. Mortality, Regrowth, Growth, and Biomass

The visual progression of symptoms showed chlorosis, necrosis, and progressive death of suckers treated with glyphosate and 2,4-D (Figure 2). In contrast, the control treatments and KH_2PO_4 + PBZ maintained a greater amount of green tissue and regrowth capacity throughout the experimental period.

For mortality, number of new suckers, plant height, and pseudostem diameter, there was a significant interaction between treatments and evaluation times (Figure 3A–D). Glyphosate and 2,4-D resulted in the highest mortality rates and markedly reduced sucker emergence and vegetative growth. Shoot fresh and dry biomass, analyzed separately at each evaluation time because of destructive sampling at 28 DAA, were also lower under glyphosate and 2,4-D (Figure 3E,F). The control treatments showed greater regrowth and vegetative growth, whereas KH_2PO_4 + PBZ exhibited an intermediate response, with initial growth suppression followed by partial recovery.

3.5. Lettuce Bioassay

In the lettuce bioassay, the treatments did not affect emergence percentage, number of leaves, stem diameter, shoot dry mass, or chlorophyll indices (Table 6). Plant height was greater under 2,4-D than under the control and glyphosate treatments, whereas KH_2PO_4 + PBZ showed an intermediate value. In contrast, KH_2PO_4 + PBZ resulted in the lowest values for maximum root length and shoot fresh mass. Root fresh mass was lower under KH_2PO_4 + PBZ than under the control and 2,4-D treatments. For root dry mass and DQI, the control showed the highest values, whereas the three chemical treatments did not differ from one another.

3.6. Tomato Bioassay

In the tomato bioassay, the treatments did not affect emergence percentage, number of leaves, or chlorophyll indices. However, differences were observed in growth and biomass variables and in the Dickson quality index. The KH_2PO_4 + PBZ treatment resulted in the highest values for plant height and maximum root length, whereas KH_2PO_4 + PBZ and 2,4-D resulted in the highest values for stem diameter, shoot fresh mass, shoot dry mass, root dry mass, and DQI. For root fresh mass, KH_2PO_4 + PBZ showed the highest value, followed by 2,4-D. In contrast, glyphosate resulted in the lowest values for shoot dry mass, root dry mass, and DQI.



Figure 2. Visual progression of phytotoxicity symptoms and sucker emergence in banana plants subjected to the different treatments over the evaluation periods following treatment application. Source: Author (2026).

3.7. Soil Chemical Properties

Soil chemical properties assessed six months after treatment application differed among treatments for most of the evaluated attributes (Table 7). Soil pH, potential acidity (H + Al), and base saturation (V) were not affected by the treatments. Glyphosate resulted in the highest K, P, Mn, and S concentrations, whereas KH_2PO_4 + PBZ generally showed intermediate values for these nutrients. The untreated control showed the highest Ca and Mg concentrations, although Ca did not differ from glyphosate or KH_2PO_4 + PBZ, and Mg did not differ from KH_2PO_4 + PBZ. The 2,4-D treatment resulted in the highest Fe concentration. Organic matter was highest in the untreated control and lowest in the glyphosate treatment.

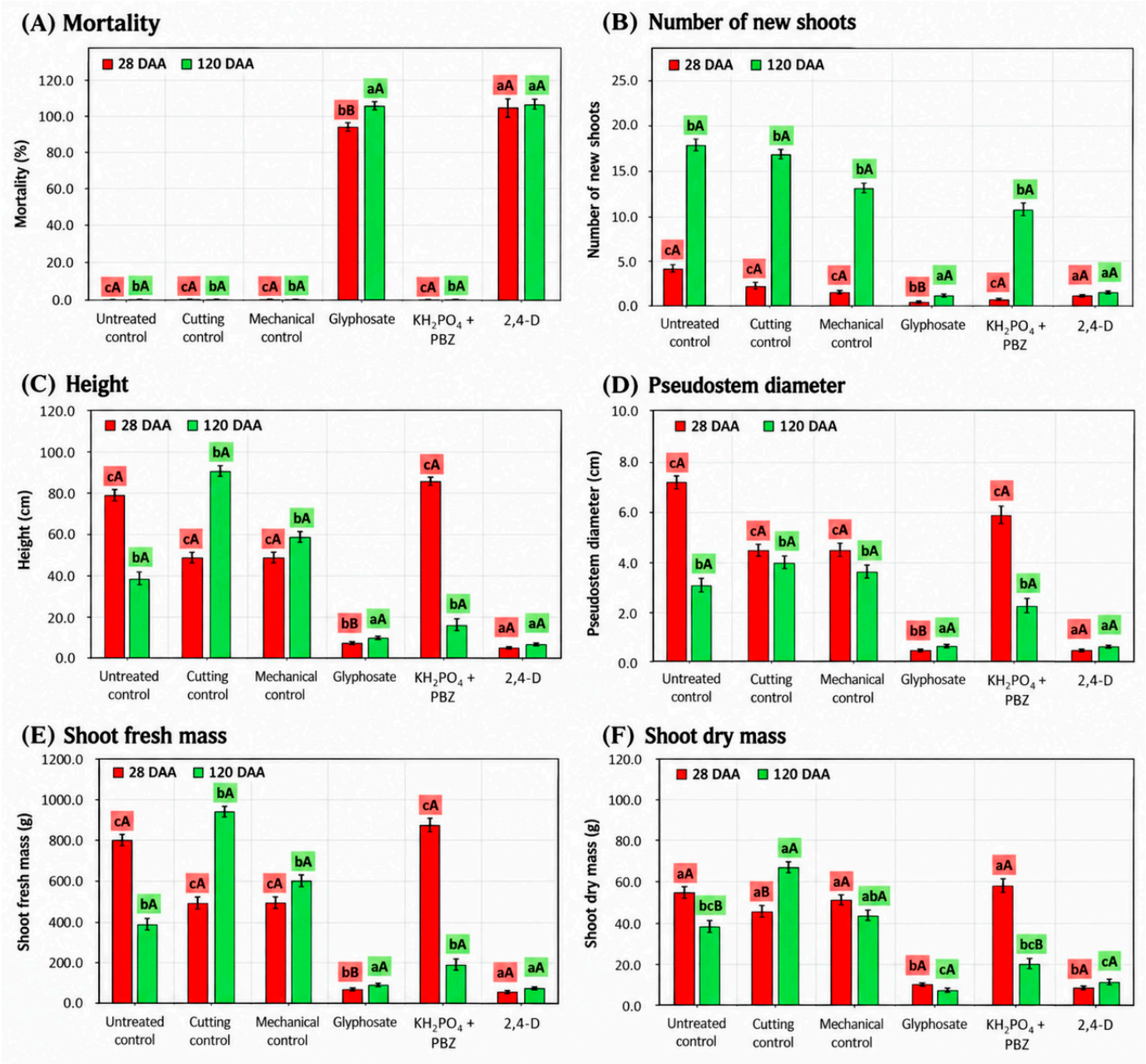


Figure 3. Mortality and growth attributes of banana plants subjected to different control methods at 28 and 120 days after application (DAA): (**A**) mortality; (**B**) number of new shoots; (**C**) height; (**D**) pseudostem diameter; (**E**) shoot fresh mass; and (**F**) shoot dry mass. Means followed by the same letter do not differ according to Tukey's test ($p \leq 0.05$). Bars represent the standard error of the mean.

Figure 4 shows the visual development of lettuce and tomato seedlings at 30 days after sowing in soil collected from the different treatments. Overall, no severe visual phytotoxicity symptoms were observed in seedlings grown in soils collected from the glyphosate and 2,4-D field treatments.

Pearson correlation analysis revealed species-specific associations between soil chemical attributes and bioindicator responses (Figure 5). In lettuce, soil P was negatively correlated with root dry mass (MSR; $r = -0.71$, $p \leq 0.01$) and Dickson quality index (IQD; $r = -0.70$, $p \leq 0.01$), whereas Ca and Mg showed positive correlations with several growth and biomass-related variables. Organic matter was also positively correlated with MSR ($r = 0.72$, $p \leq 0.01$) and IQD ($r = 0.71$, $p \leq 0.01$). In tomato, soil P was not significantly correlated with any of the evaluated growth, biomass, quality, or chlorophyll indicators.

Significant negative correlations were observed between root dry mass and pH ($r = -0.65$, $p \leq 0.01$), K ($r = -0.61$, $p \leq 0.05$), Mn ($r = -0.62$, $p \leq 0.05$), and S ($r = -0.61$, $p \leq 0.05$). Overall, the correlation patterns indicate that bioindicator responses were associated with multiple soil chemical attributes and differed between lettuce and tomato.

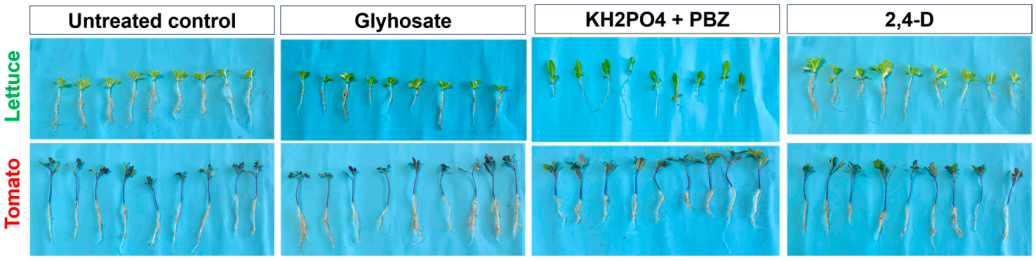


Figure 4. Visual appearance of lettuce and tomato seedlings at 30 days after sowing in soil collected six months after treatment application to banana pseudostems. Source: Author (2026).

Table 6. Physiological and biometric variables of lettuce and tomato seedlings grown in soil collected six months after treatment application to banana pseudostems. Means followed by the same letter within a column do not differ according to Tukey's test ($p \leq 0.05$). PSE, seedling emergence percentage; NF, number of leaves; ALT, plant height; CMR, maximum root length; DIA, stem diameter; MFPA, shoot fresh mass; MFR, root fresh mass; MSPA, shoot dry mass; MSR, root dry mass; DQI, Dickson quality index; Chl *a*, chlorophyll *a* index; Chl *b*, chlorophyll *b* index; Chl total, total chlorophyll index.

Lettuce							
Treatments	PSE	NF	ALT	CMR	DIA	MFPA	MFR
Untreated control	89.84 a	4.80 a	2.09 b	7.21 a	1.48 a	0.15 a	0.12 a
Glyphosate	87.10 a	4.50 a	2.23 b	7.05 a	1.36 a	0.17 a	0.11 ab
KH_2PO_4 + PBZ	88.28 a	4.30 a	2.58 ab	3.30 b	1.50 a	0.08 b	0.03 b
2,4-D	86.32 a	4.40 a	3.06 a	6.87 a	1.76 a	0.17 a	0.15 a
CV (%)	2.49	2.84	7.77	11.90	8.23	8.71	9.43
Treatments	MSPA	MSR	IQD	Clor *a*	Clor *b*	Clor *total*	
Untreated control	0.02 a	0.05 a	0.04 a	25.12 a	9.0 a	34.12 a	
Glyphosate	0.03 a	0.01 b	0.01 b	25.12 a	8.9 a	34.02 a	
KH_2PO_4 + PBZ	0.01 a	0.01 b	0.01 b	25.15 a	8.8 a	33.95 a	
2,4-D	0.02 a	0.01 b	0.009 b	25.22 a	9.1 a	34.32 a	
CV (%)	10.13	7.44	7.34	0.68	2.36	0.73	
Tomato							
Treatments	PSE	NF	ALT	CMR	DIA	MFPA	MFR
Untreated control	95.70 a	4.44 a	7.19 c	7.34 b	0.80 b	0.06 b	0.03 c
Glyphosate	94.53 a	4.70 a	6.47 c	6.88 b	0.81 b	0.04 b	0.02 c
KH_2PO_4 + PBZ	95.32 a	5.56 a	10.21 a	10.14 a	1.59 a	0.15 a	0.07 a
2,4-D	95.31 a	4.57 a	8.76 b	7.05 b	1.35 a	0.11 a	0.05 b
CV (%)	2.50	8.89	7.28	10.08	12.06	10.21	7.26
Treatments	MSPA	MSR	IQD	Clor *a*	Clor *b*	Clor *total*	
Untreated control	0.0030 b	0.014 b	0.0020 b	27.85 a	10.95 a	38.80 a	
Glyphosate	0.0010 c	0.003 c	0.0005 c	27.80 a	10.94 a	38.74 a	
KH_2PO_4 + PBZ	0.0055 a	0.027 a	0.0050 a	27.89 a	10.96 a	38.85 a	
2,4-D	0.0045 a	0.025 a	0.0042 a	27.90 a	10.96 a	38.86 a	
CV (%)	7.33	13.72	10.30	2.27	0.40	1.63	

Table 7. Chemical properties of soil collected six months after the application of different treatments to banana pseudostems. Means followed by the same letter within a column do not differ according to Tukey's test ($p \leq 0.05$). K, potassium; P, phosphorus; Ca, calcium; Mg, magnesium; H + Al, potential acidity; V, base saturation; OM, organic matter; Fe, iron; Mn, manganese; S, sulfur; CV, coefficient of variation.

Treatments	pH	K	P	Ca	Mg	H + Al
	-	mg dm^{-3}			cmolc dm^{-3}	
Untreated control	6.56 a	203.42 c	29.80 d	7.80 a	1.58 a	1.70 a
Glyphosate	6.69 a	481.33 a	69.61 a	7.37 ab	1.33 b	1.68 a
KH_2PO_4 + PBZ	6.59 a	341.65 b	49.73 b	7.44 ab	1.49 a	1.70 a
2,4-D	6.59 a	176.41 d	45.51 c	6.86 b	1.13 c	1.69 a
CV (%)	0.26	0.19	1.05	3.58	4.08	1.64
Treatments	**V**	**OM**	**Fe**	**Mn**	**S**	
	%	dag kg^{-1}		mg dm^{-3}		
Untreated control	85.35 a	4.10 a	26.80 c	51.59 c	7.59 c	
Glyphosate	85.08 a	2.65 d	27.16 b	66.19 a	22.18 a	
KH_2PO_4 + PBZ	85.23 a	3.40 c	26.82 c	58.50 b	14.97 b	
2,4-D	87.81 a	3.50 b	43.26 a	50.06 d	5.20 d	
CV (%)	3.10	5.02	3.37	2.42	3.10	

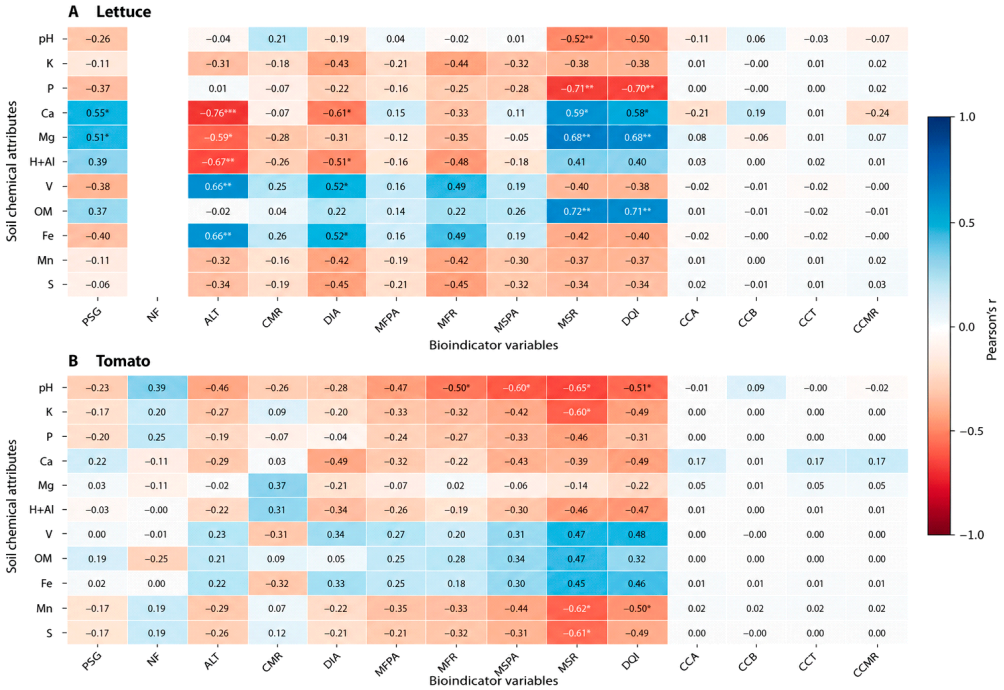


Figure 5. Pearson correlation matrix between soil chemical attributes and bioindicator responses of lettuce (**A**) and tomato (**B**) seedlings grown in soils collected six months after field treatment application. Values within cells represent Pearson's correlation coefficients (*r*), ranging from −1 to +1. Asterisks indicate significant correlations: * $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$. PSG, percentage of seed germination; NF, number of leaves; ALT, plant height; CMR, maximum root length; DIA, stem diameter; MFPA, shoot fresh mass; MFR, root fresh mass; MSPA, shoot dry mass; MSR, root dry mass; IQD, Dickson quality index; CCA, chlorophyll a index; CCB, chlorophyll b index; CCT, total chlorophyll index; CCRR, chlorophyll a/b ratio; H + Al, potential acidity; V, base saturation; OM, organic matter; K, potassium; P, phosphorus; Ca, calcium; Mg, magnesium; Fe, iron; Mn, manganese; S, sulfur. Source: Author (2026).

4. Discussion

The contrasting responses among control methods demonstrate that the efficiency of banana sucker suppression depends not only on injury to aerial tissues but also on damage to structures responsible for plant regeneration. Glyphosate and 2,4-D caused a progressive increase in phytotoxicity, high mortality, and reduced emission of new suckers, whereas the controls showed a greater capacity for vegetative recovery. This behavior is particularly important in banana plants because buds associated with the rhizome may remain viable even after pseudostem damage and give rise to new suckers [24]. Thus, the high level of regrowth observed in the controls indicates that removal or injury of the aerial portion alone was insufficient to prevent plant regeneration. Similar results were reported by Okurut [10], Gasparotto [18], and Mendes [9], who observed the effectiveness of chemical control in banana plants.

Although glyphosate and 2,4-D were highly effective, the progression of phytotoxicity differed between the herbicides. Glyphosate produced a more gradual response, consistent with inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), which disrupts the shikimate pathway and progressively compromises the synthesis of aromatic amino acids, proteins, and other essential metabolites [25,26]. In contrast, 2,4-D reached high levels of phytotoxicity more rapidly. As a synthetic auxin, this herbicide disrupts hormonal signaling, promotes uncontrolled growth, vascular and metabolic disturbances, and loss of cellular integrity, ultimately leading to tissue necrosis and death [27,28]. Therefore, the different temporal patterns observed are consistent with their distinct modes of action, although both ultimately impaired plant survival and regrowth capacity.

The reduction in chlorophyll *a*, chlorophyll *b*, and total chlorophyll indices in plants treated with glyphosate and 2,4-D demonstrates that the progression of injury also compromised photosynthetic functioning. Pigment degradation, together with chloroplast alterations and secondary oxidative stress, may reduce light energy capture and limit photosynthetic activity [29,30]. At the same time, the decline in relative water content indicates a reduced ability to maintain tissue water status, possibly because of impaired cellular integrity and water transport [31]. Thus, the simultaneous reductions in chlorophyll indices and relative water content, accompanied by increasing phytotoxicity, indicate progressive and integrated deterioration of plant metabolism [32].

These physiological effects were directly reflected in reduced growth, biomass accumulation, and emission of new suckers. Because the banana rhizome functions as an important storage organ and contains buds capable of sustaining new sucker emergence, the high level of regrowth in the controls confirms that these regenerative structures remained active [33]. In contrast, the low sucker emission under glyphosate and 2,4-D suggests that herbicide activity was not restricted to tissues near the application site but also impaired processes required for plant regeneration.

The KH_2PO_4 + PBZ treatment showed a different response, with an initial reduction in growth but without severe injury or sustained suppression of regrowth. Paclobutrazol inhibits gibberellin biosynthesis and primarily reduces cell elongation and vegetative growth without necessarily causing direct death of meristematic tissues [34,35]. This may explain the partial recovery of plants and physiological indicators during the final evaluations. This response contrasts with that reported by Luo et al. [11], who obtained up to 100% sucker mortality within 3 days and no subsequent regrowth after treatment with KH_2PO_4 + PBZ. Although both studies used a 2:1 KH_2PO_4:PBZ ratio, important methodological and biological differences existed between the experiments. Luo et al. [11] evaluated suckers arising from 5-month-old *Musa* × *paradisiaca* (AA) plants and first removed the aboveground portion of the suckers at ground level before injecting the KH_2PO_4 + PBZ mixture into the remaining tissue. In contrast, in the present study, 2.0 g

KH_2PO_4 + 1.0 g PBZ in 5 mL of water per shoot was injected directly into the intact pseudostem of 'Prata Anã' suckers approximately 10 cm above the soil surface. The experiments were also conducted under different production environments, with Luo et al. [11] conducting their study in Hainan, China, whereas the present experiment was conducted under field conditions in Lavras, Minas Gerais, Brazil. Differences in application procedure, genotype, sucker developmental stage, environmental conditions, and rhizome reserve status may therefore have contributed to the contrasting responses [36,37]. Under the conditions of the present study, KH_2PO_4 + PBZ acted predominantly as a temporary growth suppressor rather than as an effective method for sustained sucker control.

Soil Bioassay Responses Six Months After Treatment Application

The bioassays conducted six months after treatment application allowed the assessment of whether products applied to the pseudostem produced biologically detectable effects in the soil. The absence of differences in the emergence percentage of lettuce and tomato indicates that soils collected six months after treatment application did not exert biologically detectable effects sufficient to impair seedling emergence and initial establishment under the conditions of the bioassay. Localized application directly into the pseudostem likely contributed to limiting direct deposition of the compounds onto the soil compared with applications made directly to the soil surface [38].

However, the absence of effects on emergence does not imply the complete absence of subsequent responses. In lettuce, soil originating from the KH_2PO_4 + PBZ treatment was associated with reduced root length and biomass accumulation, whereas the untreated control resulted in higher root dry mass and Dickson quality index values. Interpretation of these responses requires particular caution because KH_2PO_4 is also a source of P and K, introducing a potential nutritional effect in addition to any possible biological activity associated with PBZ. Although PBZ interferes with gibberellin biosynthesis and cell elongation [38,39], the experimental design did not allow the effects of KH_2PO_4 and PBZ to be separated. Therefore, the observed responses cannot be specifically attributed to PBZ residues or to the nutritional contribution of KH_2PO_4.

The correlation analysis further supports the need for caution when attributing bioindicator responses exclusively to residual chemical effects. Notably, soil P was not significantly correlated with any of the evaluated growth, biomass, quality, or chlorophyll indicators in tomato, indicating that the higher P concentration observed in soil from the KH_2PO_4 + PBZ treatment does not, by itself, explain the improved performance of tomato seedlings. In lettuce, soil P was negatively correlated with root dry mass and Dickson quality index, further demonstrating that higher P availability was not consistently associated with improved bioindicator performance. Significant associations with other soil attributes, including Ca, Mg, organic matter, pH, K, Mn, and S, varied according to the bioindicator species and response variable. These species-specific and multivariate patterns suggest that seedling responses were associated with the combined chemical characteristics of the soils rather than with variation in a single nutrient. However, because correlation does not establish causality and several soil attributes varied simultaneously among field treatments, the contribution of nutrient availability cannot be separated from potential residual effects of the applied compounds.

In tomato, the response pattern was different. KH_2PO_4 + PBZ and 2,4-D resulted in higher values for several growth and biomass traits, whereas glyphosate produced lower shoot dry mass, root dry mass, and DQI values. This contrasting response between species shows that the bioassay did not reveal a uniform pattern of residual phytotoxicity. Lettuce and tomato may differ in physiological sensitivity and in their capacity to respond to the

chemical conditions of the root environment, contributing to distinct responses even when grown in soils originating from the same treatments [40,41].

Despite differences in some biometric traits, the treatments did not affect chlorophyll *a*, chlorophyll *b*, or total chlorophyll indices in lettuce and tomato seedlings. This indicates that soil conditions six months after application were not sufficiently restrictive to cause detectable changes in chlorophyll status. This response contrasts with that observed directly in the treated banana plants, in which glyphosate and 2,4-D reduced chlorophyll indices during the progression of phytotoxicity. Thus, the intense physiological effects observed in the target plants were not reproduced in the bioindicator species subsequently grown in the soil.

Soil chemical characterization provides an additional context for interpreting these responses. No differences among treatments were observed for pH, H + Al, or base saturation, whereas K, P, Ca, Mg, Fe, Mn, S, and organic matter varied among soils. Soil from the glyphosate treatment, for example, had higher K, P, Mn, and S contents, whereas soil from the 2,4-D treatment had higher Fe and lower Ca and Mg contents. These differences indicate that the bioindicator species were exposed to distinct soil chemical environments, which may also have influenced their growth and biomass accumulation. Although KH_2PO_4 supplies both P and K, the soil originating from the KH_2PO_4 + PBZ treatment did not show the highest concentrations of these nutrients six months after application. Therefore, the present data do not allow the nutritional contribution of KH_2PO_4 to be isolated from other sources of soil variability or from potential PBZ-related effects.

Importantly, the chemical properties of the soils differed among field treatments, which represents an additional factor influencing the responses of the bioindicator species. Differences in nutrient availability and organic matter may directly affect plant growth and biomass accumulation independently of any residual activity of the compounds previously applied to the banana pseudostems. Therefore, the treatment-related differences observed for some growth, biomass, and DQI variables in lettuce and tomato cannot be attributed exclusively to chemical residues. Instead, they should be interpreted as integrated responses to the soils originating from different field treatments, reflecting both their chemical properties and any potential biologically active compounds that may have been present.

However, these differences should not be interpreted as direct treatment effects. Because the fertility of each experimental unit was not individually characterized before and after treatment application, a causal relationship cannot be established between product application and the chemical differences observed six months later. Soil spatial variability, differential nutrient uptake, mortality or reduced growth of banana plants, nutrient cycling, and decomposition of plant tissues may also have contributed to the values observed.

This consideration is particularly important for glyphosate. Despite the higher K, P, Mn, and S contents in soil associated with this treatment, tomato seedlings showed lower shoot dry mass, root dry mass, and DQI values. Therefore, differences in soil fertility alone do not explain plant performance. The possible presence of glyphosate or AMPA could have contributed to this response [42,43]; however, because these compounds were not directly quantified in the soil, this hypothesis cannot be confirmed.

Similarly, the greater tomato growth observed for some traits under KH_2PO_4 + PBZ and 2,4-D indicates that prior application of these products did not necessarily result in negative effects on the subsequently cultivated species. These increases may result from interactions among species sensitivity, soil nutritional conditions, and any biologically active compounds that may have been present. Therefore, the results should be interpreted as biologically detectable responses associated with soils originating from the different treatments rather than as direct evidence of the presence or absence of specific residues.

Accordingly, the bioassay cannot establish the persistence, concentration, or chemical identity of glyphosate, 2,4-D, PBZ, or their metabolites in the soil. Direct chemical residue analysis would be required to determine the environmental persistence and fate of these compounds. In addition, although soil air-drying and sieving were used to standardize substrate preparation for the bioassay, these procedures may alter soil biological activity and compound bioavailability compared with undisturbed field conditions and should therefore be considered when interpreting the bioassay responses.

Several additional limitations should be considered when interpreting the present results. Although an initial composite soil characterization was available for the experimental area, individual experimental units were not chemically characterized before treatment application, which limits causal attribution of the differences in soil properties observed six months later to the field treatments. In addition, the experiment included four independent experimental units per treatment. Although this replication was incorporated into the randomized complete block design, the relatively small number of independent units limits statistical power, particularly for exploratory associations between soil chemical attributes and bioindicator responses. Accordingly, the correlation analysis should be interpreted as exploratory rather than causal. Together with the absence of direct quantification of the applied compounds and their metabolites and the potential effects of soil processing for the bioassay, these limitations define the scope within which the present findings should be interpreted.

Taken together, the bioassays showed no consistent biologically detectable effects across lettuce and tomato six months after field treatment application, as seedling emergence and chlorophyll indices were not impaired. However, changes in some growth, biomass, and DQI traits indicate that species-specific sublethal responses occurred. Because the tested compounds and their metabolites were not directly quantified, these responses cannot be attributed specifically to chemical residues or used to infer their persistence in soil.

5. Conclusions

Pseudostem application of glyphosate and 2,4-D was more effective than mechanical methods for controlling 'Prata Anã' banana suckers, resulting in severe phytotoxicity, reduced vegetative growth and regrowth, and high plant mortality. The response to 2,4-D occurred more rapidly than that to glyphosate, whereas KH_2PO_4 + PBZ may have contributed only temporary growth suppression followed by partial recovery and was therefore ineffective for sustained sucker control under the conditions evaluated.

Six months after field application, soils originating from the different treatments did not consistently impair lettuce or tomato performance, and seedling emergence and chlorophyll indices were unaffected. However, species-specific changes in growth, biomass accumulation, and Dickson quality index indicate that sublethal responses occurred. Because soil chemical properties also differed among field treatments, these responses cannot be attributed exclusively to chemical residues and may partly reflect differences in soil fertility. Because the compounds and their metabolites were not directly quantified in soil, these bioassay responses should not be interpreted as evidence of the presence, absence, or persistence of specific chemical residues. Direct chemical analyses are required to determine the environmental persistence and fate of these compounds.

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