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Effects of Aqueous Extracts of *Lantana camara* L. on Germination of *Setaria viridis* (L.) P.Beauv. Seeds with Different Degrees of Dormancy

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Abstract: *Setaria viridis* (green foxtail) is an invasive weed species in various agricultural systems, prompting the search for effective compounds to control its germination. The species has primary and secondary dormancy depending on the time elapsed since post-harvesting, making management strategies more difficult. Several weed plants, such as *Lantana camara* L., can be a source of allelochemicals with herbicidal effects, being a potential candidate for the control of *S. viridis*. We investigated the effects of *L. camara* extracts on the germination and initial growth of *S. viridis* seeds with different degrees of dormancy and revealed a dose-dependent bioherbicide effect. Aqueous extracts of *L. camara* were analyzed by HPLC-DAD and applied (0.1 to 5.0 mg/mL) to 12- and 110-day post-harvest *S. viridis* seeds. Seeds were evaluated daily and germination percentage (GP), speed germination index (SGI), and radicle length (RL) were calculated. Phenolic acids and flavonoids were major components of the extract. Lower concentrations (0.1 and 0.5 mg/mL) stimulated and accelerated the germination of *S. viridis*, breaking its dormancy. Both 1.0 and 5.0 mg/mL concentrations hindered germination, especially in 12 dph seeds. The 1.0 mg/mL concentration resulted in longer roots, whereas 5.0 mg/mL inhibited root development. *Lantana camara* extracts potentially stimulate germination and radicle growth of *S. viridis* at low concentrations while inhibiting these parameters at higher doses. These results may open new possibilities for using *L. camara* in weed-control strategies.

Keywords: allelopathy; aqueous extracts; bioherbicide; control strategies; green foxtail; invasive species

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1. Introduction

Weeds are one of the main threats to agricultural productivity, directly competing with crops for essential resources such as water, light, and nutrients, resulting in significant yield losses [1]. *Setaria viridis* (L.) P.Beauv. (green foxtail, Poaceae), a weedy C_4 grass is commonly found in fertile and well-drained soils, under warm and temperate climates. The species is widely distributed across several agroecosystems, such as in areas where maize, wheat,

and soybeans are cultivated [2]. This weed can cause significant yield losses in these areas, reducing crop productivity, and consequently resulting in economic losses [3–14].

Despite the intensive use of chemical herbicides, the persistence of dormant *S. viridis* seeds in the soil often results in ineffective weed eradication [15–17]. Dormancy is a mechanism that allows seeds to remain viable for extended periods, germinating over longer periods. This mechanism increases the success rate, making the control of this species difficult [18]. Seed dormancy in *S. viridis* is widely described, despite not being completely understood. According to some authors, the species has a primary dormancy, mainly dependent on the post-harvest length. At the same time, some environmental factors, such as temperature, may induce a secondary dormancy [18–21]. These factors facilitate the persistence of *S. viridis* in soil seed banks and contribute to its resistance to chemical control methods, resulting in seeds that often escape the effects of herbicides. Therefore, this mechanism is a key factor in the resilience of these weed populations, reinforcing the need for innovative management strategies [22].

The intensive and often indiscriminate use of synthetic herbicides has led to serious environmental problems, such as the emergence of herbicide-resistant weed populations, water contamination, and adverse effects on non-target organisms, compromising the sustainability of agricultural systems [16]. As a result, more sustainable alternatives have been sought, including natural compounds with herbicidal activity. These compounds, mostly products of plant secondary metabolism, fit into the concept of biological weed control as bioherbicides [23].

In this context, allelopathic compounds produced by plants have gained significant interest as potential tools for weed management. Allelopathy refers to the release of chemical substances by one plant affecting the growth and development of other plants, potentially having both inhibitory and stimulatory effects [23]. A notable species in this regard is *Lantana camara* L. (Verbenaceae), a common weed widely recognized for its allelopathic potential. Studies have shown that *L. camara* extracts contain a variety of secondary metabolites, such as phenolic compounds and terpenoids, which can directly interfere with the germination and development of other plant species [24,25]. Interestingly, the composition of these metabolites varies across different parts of the plant, with aerial parts often containing higher concentrations of compounds than roots. This variability suggests that the allelopathic potential of *L. camara* may depend on which part of the plant is used and indicates that the aerial parts might be suitable as a source of allelochemicals for bioherbicide development [24,25].

Aqueous extracts of *L. camara* have shown, in previous studies, to have variable allelopathic effects on different plant species [26], demonstrating an ability to inhibit germination and root growth. This effect is often attributed to phenolic compounds present in the extract that can interfere with essential physiological processes, such as enzymatic activity, cell membrane permeability, and increased production of reactive oxygen species [24,27]. Despite having known effects on the germination of seeds of several plants, the impact of *L. camara* extracts on seeds with dormancy has not been sufficiently explored [24]. Given the degrees of dormancy in *S. viridis* seeds, we hypothesize that seeds with distinct dph may be differently affected by the allelochemicals present in *L. camara* extracts. Addressing these different responses could represent a first step in the management strategy for *S. viridis*, a model plant for physiological and genetic studies [18,28–30].

This study aimed to evaluate the effects of aqueous extracts of aerial parts of *L. camara* on the germination of *S. viridis* seeds with different degrees of dormancy, verifying if the effects of the allelochemicals differ according to the seeds' dormancy status. We believe this study can advance the understanding of the action mechanisms of plant extracts as alternative tools in weed management, especially for weeds with seed dormancy, contributing to the use of *L. camara* as a bioherbicide.

2. Materials and Methods

2.1. Plant Harvesting and Aqueous Extracts Obtaining

Shoots of 20 *Lantana camara* plants grown at the Federal University of Rio de Janeiro, Brazil (22°50′24.0″ S 43°13′54.5″ W) were harvested on a sunny day. The one-year-old plants were immediately transported to the laboratory, washed, and oven-dried at 50 °C for 72 h. After drying, the shoots were weighed (SF-400 balance, Fullcommerce®, Hangzhou, China), ground in an electric blender (Mondial®, São Paulo, Brazil), and fine sieved. The aqueous extracts (20%, *w*/*v*) were obtained by immersing 40 g of powdered shoots in 200 mL of hot distilled water (boiled) for 10 min, with occasional stirring. The process was repeated three times. The extracts were successively filtered through filter paper and cotton to remove particulates. After filtration, the extracts were freeze-dried and weighed (BN1200, Coleman®, São Paulo, Brazil).

2.2. Chemical Characterization of the Extracts

The chemical composition of aqueous extracts of *L. camara* was analyzed by using High-Performance Liquid Chromatography (HPLC) with a Shimadzu® LC-20AT system coupled to a diode array detector (DAD, Shimadzu® SPD-M20A, Kyoto, Japan) operating within a wavelength range of 200–600 nm. Chromatographic separation was performed on a Merck® RP-18 reverse-phase column (5 µm, 250 × 4.6 mm, São Paulo, Brazil) kept at a constant temperature of 35 °C. The eluents were composed of (A) ultrapure water containing 0.1% formic acid and (B) acetonitrile. The elution gradient was 0–10 min (95–80% A), 10–20 min (80–78% A), 20–35 min (78–75% A), 35–40 min (75–70% A), 40–45 min (70–0% A); 45–60 min (0% A), 60–62 min (0–95% A), and 62–68 min (95% A). The flow rate was set at 0.8 mL/min, and the injection volume was 20 µL for each sample (10 mg/mL).

The chromatograms were acquired at 254, 330, and 350 nm. The main phenolic compounds were identified based on retention times, UV spectra, and comparisons to standards (syringic and chlorogenic acids) and published literature [31–34]. All the extracts were analyzed in triplicate.

2.3. Germination and Initial Growth of S. viridis

Five concentrations of *L. camara* aqueous extracts were used to evaluate the effects on germination and initial growth [35] of *S. viridis*: 0.1, 0.5, 1.0, and 5.0 mg/mL. Two experiments were conducted using *S. viridis* seeds with different degrees of dormancy. Seeds (A10.1 accession) were harvested from plants cultivated from seeds originally obtained from Thomas Brutnell's laboratory at the Donald Danforth Plant Science Center, St. Louis, Missouri. In *S. viridis*, the seed dormancy is directly dependent on the length of time post-harvest. The germination rate is low in freshly harvested seeds, and gradually increases from 0% to around 42% over 55 days, reaching around 56% after 115 days [18]. In this study, two different dormancy degrees were used: seeds 12 and 110 days post-harvest (dph) [18]. For both dormancy degrees, seeds were inspected under 2.5 times magnifying lenses, and only intact seeds were used in the experiment [18]; conducted in September 2024.

For each experiment conducted, 750 seeds were used: 150 for each extract concentration and 150 for control (distilled water). Before treatment, seeds were disinfected in a 20% commercial sodium hypochlorite solution with 0.1% Tween-20 for 20 min, followed by three washes in distilled water [36]. The seeds were placed in 9 cm diameter Petri dishes between two discs of germitest paper (Germilab, Passo Fundo, Brazil) [36]. The experiment was conducted under controlled laboratory conditions, with daytime temperatures between 30 and 33 °C, nighttime temperatures between 28 and 30 °C, and a photoperiod of 16/8 h light/darkness, following optimal conditions for germination and growth previously established for the species [36].

At the beginning of the experiment, 4 mL of distilled water or *L. camara* extracts at four different concentrations (0.1, 0.5, 1.0, and 5.0 mg/mL) were added to each Petri dish with seeds followed by 1 mL of each solution for the seven consecutive days.

Germination (protrusion of the radicle) was evaluated at 00 h, 20 h, 38 h, 44 h, 65 h, 108 h, and 192 h over eight days, according to the BBCH scale [36]. Each time, pictures were taken, and the seeds were observed under a Leica® MZ8 stereomicroscope (Leica Microsystems, Wetzlar, Germany). At the end of the 8th day, the germination percentage (GP), germination speed index (GSI), and root length (RL) were calculated as follows [37]. The stereomicroscope was used to count the seeds and seedlings, while the radicles were measured with ImageJ® software V 1.54k. Pictures were taken using a Leica® DFC 500 camera attached to a Leica® M205C stereomicroscope (Leica Microsystems, Wetzlar, Germany) and equipped with the Leica® Application Suite LASV3.6 software.

2.3.1. Germination Percentage (GP)

The germination percentage was calculated as GP (%) = (number of germinated seeds/total number of seeds) × 100.

2.3.2. Germination Speed Index (GSI)

The Germination speed index was calculated as

$$IVG = G_1/N_1 + G_2/N_2 \ldots + G_n/N_n$$

where

$G_1, G_2, \ldots, G_n$: number of seeds germinated in each count (on different days), and
$N_1, N_2, \ldots, N_n$: number of days since sowing until each count.

2.4. Statistical Analysis

The data obtained to calculate GP, IVG, and RL for green foxtail seeds under the different treatments with *L. camara* aqueous extracts were analyzed using SigmaPlot software (version 15, Systat Software®). Data were initially tested by the same program for normality (Shapiro–Wilk test) and homogeneity of variance (Brown–Forsythe test). The data were then subjected to a One-way ANOVA to ascertain significant differences between treatments at a significance level of 5% ($p < 0.05$). When significant differences were found ($p \leq 0.05$), the post-hoc pairwise multiple comparison Holm–Sidak test was applied to compare the means of the different treatments (0 mg/mL—control, 0.1 mg/mL, 0.5 mg/mL, 1.0 mg/mL, and 5.0 mg/mL; [38–40]). Graphs were constructed using Prisma software (version 8.0.2, GraphPad®).

3. Results and Discussion

3.1. Chemical Composition

HPLC-DAD analysis of aqueous extracts of *L. camara* aerial parts revealed the presence of 14 main peaks, with the specific compounds belonging to three different classes of phenolics (Table 1, Supplementary Figure S1). Among the compounds detected, peaks 2, 3, and 5 had retention times and UV spectra typical of *p*-hydroxybenzoic acid derivatives, while peak 4 was identified as syringic acid and peak 9 as chlorogenic acid. Peaks 12 to 14 had $UV_{máx}$ absorption characteristics of flavonoids. All these compounds were identified based on their UV spectra and comparison with the literature [31–34]. Although the allelopathic activity of most compounds identified in *L. camara* has not yet been determined, some may possess phytotoxic activity [24].

Table 1. Peaks detected by HPLC-DAD analysis in *L. camara* aqueous extracts, showing the retention time, the UV máx, and the putative identification.

Peak Number	Rt (Min)	UV Máx (nm)	Class Identification
1	3.2	240	N/D [1]
2	3.9	258	*p*-hydroxybenzoic acid derivative
3	4.2	261	*p*-hydroxybenzoic acid derivative
4	4.6	276	Syringic acid
5	5.9	264	*p*-hydroxybenzoic acid derivative
6	9.2	228	N/D
7	10.0	229	N/D
8	10.9	N/D	N/D
9	13.3	sh 300, 328	Chlorogenic acid
10	15.3	N/D	N/D
11	16.6	N/D	N/D
12	20.0	267, 335	Flavonoid
13	30.2	273, 333	Flavonoid
14	47.8	273, 321	Flavonoid

[1] N/D: not determined. For these compounds, it was not possible to identify the phenolic class based on the UV spectra; sh: shoulder.

These results are consistent with a study conducted by Jain et al. [34], which characterized 14 phenolic compounds in extracts of *L. camara* leaves, identifying them as *p*-hydroxybenzoic acid derivatives and cinnamic acid derivatives, such as coumaric acid, ferulic acid, and caffeic acid, all of which demonstrated significant allelopathic activities [34]. In addition, other studies described the presence of these and other phenolic compounds in extracts of *L. camara* [34,41,42].

The phenolic compounds identified in the extract of *L. camara*, particularly *p*-hydroxybenzoic derivatives and syringic acid, are often associated with allelopathic effects that interfere with the germination and growth of neighboring plants [34]. In the study conducted by Jain et al. [34], acidic and neutral extracts of *L. camara* strongly inhibited the growth of *Lemna minor* L. (common duckweed or lesser duckweed).

Phenolic compounds generally act as allelochemicals, interfering in critical physiological processes, such as seed germination and plant growth [43,44]. For example, compounds like benzoic acid alter the plant's hormonal balance, impairing growth and normal development [43,44]. These changes often occur due to the ability of phenolics to modify the polarity of cell membranes, affecting their structure and permeability [43,44].

Additionally, phenolic compounds such as vanillic acid, *p*-coumaric acid, and *p*-hydroxybenzoic acid act as inhibitors of the activity of several enzymes [45]. Such inhibition suggests that a decrease in enzymatic activity may be a secondary effect, possibly due to protein damage [45].

Moreover, flavonoids, such as the compounds represented by peaks 12–14, exhibit strong antioxidant and allelopathic activity [46]. These compounds are recognized for their ability to interact with plant hormones, such as auxins and gibberellins, modulating seedling growth and directly influencing germination [47].

3.2. Effects of L. camara Extracts on S. viridis Germination and Initial Growth

The germination of 12 dph and 110 dph *S. viridis* seeds was affected by the treatments with *L. camara* aqueous extracts (0.1, 0.5, 1.0, and 5.0 mg/mL) when compared to the control ($p_{12dph} < 0.001$, $p_{110dph} < 0.001$; Figure 1). A concentration of 0.1 mg/mL of *L. camara* aqueous extracts stimulated the germination of 12 dph seeds. Seeds treated with this concentration showed the highest germination percentage (GP% = 15.3 ± 2.3), being significantly higher than the control ($p < 0.001$) and the other treatments ($p_{0.5} = 0.040$; $p_{1.0} = 0.009$; $p_{5.0} < 0.001$). When the concentration increased to 0.5 mg/mL, the germination percentage (GP% = 11.3 ± 1.2) remained higher than that of the control ($p = 0.040$). The ger-

mination began to decrease at the concentration of 1.0 mg/mL, being drastically inhibited and reaching zero at 5.0 mg/mL (Figure 1a, Supplementary Figure S2).

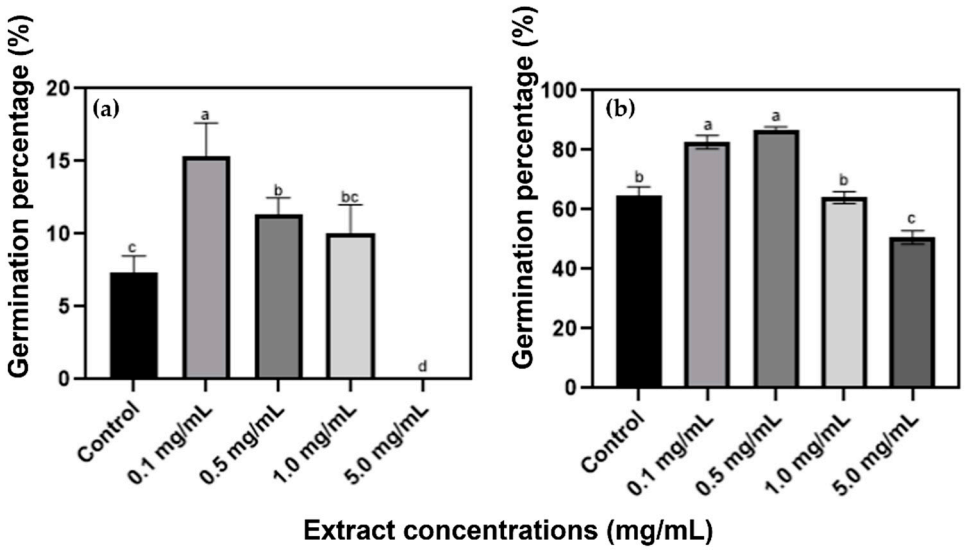

Figure 1. Effects of *L. camara* aqueous extracts on the germination rate of *S. viridis* seeds. (**a**) 12 dph seeds; (**b**) 110 dph seeds. Values are represented as means and the bars represent the standard deviation. Different letters indicate values that differ significantly at $p < 0.05$, according to One-way ANOVA, followed by the Holm-Sidak test.

For 110 dph seeds, the two lowest concentrations (0.1 and 0.5 mg/mL) have been shown to stimulate germination, being significantly greater compared to the control and the extract concentrations of 1.0 and 5.0 mg/mL (Figure 1b, $p < 0.05$). At the concentration of 1.0 mg/mL, the germination rate declined again, reaching levels comparable to the control ($p = 0.119$). Significant reduction in germination was observed for the treatment with the highest concentration of *L. camara* extracts (5.0 mg/mL, GP% = 50.67 ± 2.31; Figure 1b), but not reaching zero, as observed for the 12 dph seeds (Figure 1a). Our results indicate that the lower concentrations of *L. camara* aqueous extracts (0.1 mg/mL) stimulate the germination of *S. viridis* seeds, while extracts at higher concentrations significantly inhibit this process. This dual behavior of the extracts rich in phenolic compounds is well documented [34,42,48].

Several studies have shown that extracts obtained from different plant species can exert opposite effects, either stimulating or inhibiting seeds' germination, depending on the species tested and the concentration of the extract used [42]. Concerning *L. camara* extracts, Ahmed et al. [48] found similar results to those observed here, reporting that aqueous extracts of leaves of *L. camara* have dual effects on the germination of different crop species, including *Cicer arietinum* L. (chickpea), *Raphanus sativus* L. (radish), *Vigna unguiculata* (L.) Welp. (cowpea), *Cucumis sativus* L. (cucumber), *Brassica juncea* (L.) Czern. (Chinese mustard), and *Phaseolus mungo* L. (mungo bean). The extracts stimulated the germination of the species at low concentrations (20.0 mg/mL) while inhibiting it at higher concentrations (150 mg/mL). Additionally, Gindri et al. [49] demonstrated that *L. camara* extracts inhibited the germination of *Avena sativa* L. seeds at concentrations at or above 2.78 mg/mL [48].

Lantana camara extracts inhibited germination and/or growth of various grasses, including *Lolium multiflorum* Lam. (annual ryegrass), *Triticum aestivum* L. (common wheat), *Hordeum vulgare* L. (barley), *Zea mays* L. (corn), and *Pennisetum americanum* (L.) Leeke (pearl millet) [47,50–53]. In addition, the extracts of leaves, stems, and fruits of *L. camara* L. decreased the growth of *S. italica* (L.) P.Beauv., another species of *Setaria* genus [50]. However, none of these studies evaluated the effects of *L. camara* extracts on *S. viridis* germination, nor investigated differences related to the degree of seed dormancy.

The speed index (GSI) of *S. viridis* seeds was also altered by treatment with *L. camara* aqueous extracts (Figure 2). In 110 dph seeds, the concentration of 1.0 mg/mL of *L. camara* extracts exhibited the highest GSI (GSI = 4.3 ± 1.0), being significantly higher than both the control ($p = 0.008$) and the 5.0 mg/mL treatments ($p < 0.001$). Seeds treated with 0.1 mg/mL also showed an elevated GSI (GSI = 3.5 ± 1.0), indicating a positive effect on the initial growth rate of seedlings. In contrast, at a concentration of 5.0 mg/mL, there was a marked decrease in GSI, with complete inhibition of germination (Figure 2a).

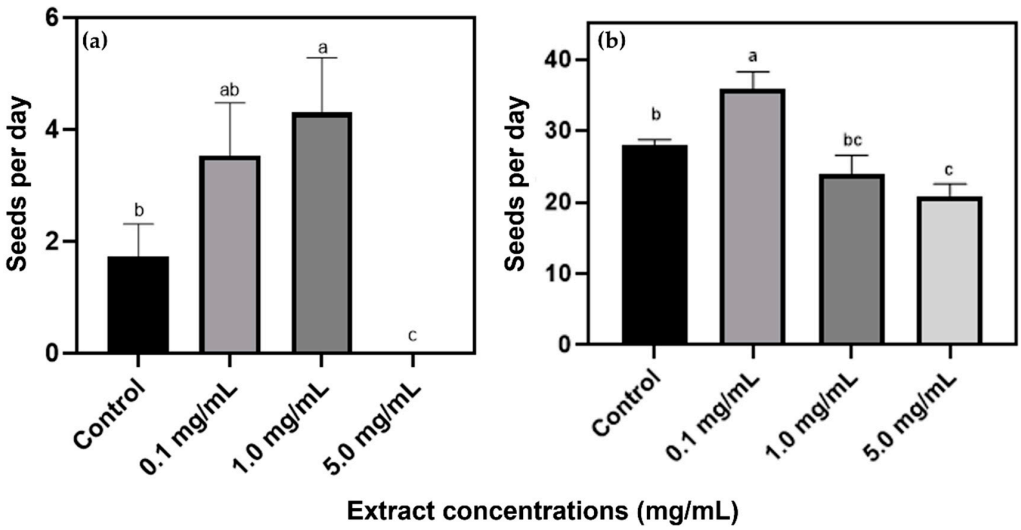

Figure 2. Effects of *L. camara* aqueous extracts on germination speed index—GSI: (**a**) 12 dph seeds; (**b**) 110 dph seeds. Different letters indicate values that differ significantly at $p < 0.05$, according to One-way ANOVA, followed by the Holm–Sidak test.

For 110 dph seeds, the highest GSI was observed in seeds treated with extracts of shoots of *L. camara* at a concentration of 0.1 mg/mL (GSI = 35.8 ± 2.5), being significantly higher than the control (GSI = 27.9 ± 0.8, $p = 0.002$) and the concentrations of 1.0 mg/mL (GSI = 23.9 ± 2.6, $p < 0.001$) and 5.0 mg/mL (GSI = 20.9 ± 1.7, $p < 0.001$). At the concentrations of 1.0 and 5.0 mg/mL, the GSI significantly decreased, with the lowest value recorded at 5.0 mg/mL (Figure 2b).

In our study, the increase in GSI at lower concentrations of the extracts indicates a stimulatory effect. However, the inhibitory action of the extracts at higher concentrations might be linked to high amounts of phenolics, promoting a phytotoxic environment and limiting the development of *S. viridis* seeds [43]. The results on the germination speed align with the findings of Ujjwal et al. [54], who demonstrated that plant extracts can accelerate the germination process at appropriate concentrations. However, a threshold concentration seems to exist, as higher concentrations can lead to toxicity, reducing the germination speed, as observed in this study.

Regarding root length, the application of the extracts of *L. camara* at a concentration of 1.0 mg/mL resulted in the longest root size for 12 dph seeds (RL_{cm} = 7.8 ± 1.0). The root length at this concentration was significantly higher than the control ($p_{control} = 0.006$) and the other treatments ($p_{0.1} = 0.005$; $p_{0.5} = 0.031$; $p_{5.0} < 0.001$). Seeds treated with 0.1 and 0.5 mg/mL showed similar root lengths and were equivalent to the control (RL_{cm} = 4.9 ± 1.3; 5.8 ± 0.3; 5.1 ± 0.2, respectively) (Figure 3a).

For the 110 dph seeds, the concentration of 0.1 mg/mL (RL_{cm} = 7.1 ± 0.9) resulted in root lengths similar to the control (RL_{cm} = 6.4 ± 0.3; $p = 0.163$). However, the concentration of 0.5 mg/mL (RL_{cm} = 8.6 ± 0.7; $p_{control} = 0.003$; $p_{0.1} = 0.023$; $p_{5.0} < 0.001$) and 1.0 mg/mL (RL_{cm} = 9.7 ± 0.4; $p_{control} < 0.001$; $p_{0.1} = 0.001$; $p_{5.0} < 0.001$) significantly promoted root growth, resulting in longer roots compared to the other treatments. At 5.0 mg/mL, the root length (RL_{cm} = 3.1 ± 0.1) significantly decreased, showing the lowest values across all treatments (Figure 3b, Supplementary Figure S3).

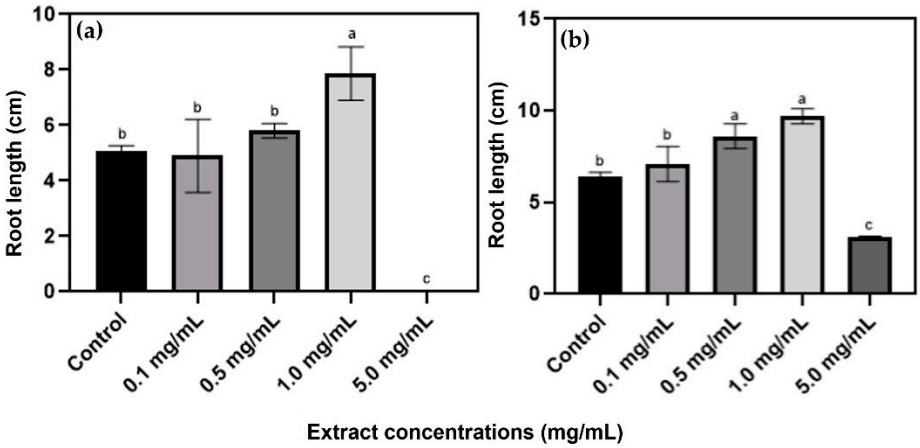

Figure 3. Effects of *L. camara* aqueous extract on root length. (**a**) 12 dph seeds; (**b**) 110 dph seeds. Different letters indicate values that differ significantly at $p \leq 0.05$, according to One-way ANOVA, followed by the Holm–Sidak test.

Our results showed that lower concentrations of *L. camara* extracts effectively stimulate root growth in both dormancy degrees of *S. viridis* seeds, whereas the highest concentration (5.0 mg/mL) has a strong inhibitory effect, which can be considered allelopathic. Studies conducted by Ahmed et al. [48] and Ujjwal et al. [54] support these results, also showing that *L. camara* extracts can influence root development, promoting growth at moderate concentrations while inhibiting this process at higher concentrations. This effect might be attributed to phenolic compounds and alkaloids, known for their allelopathic properties [49].

For all the responses evaluated, stimulation was caused by low doses and inhibition by high doses of *L. camara* extracts. These findings align with the phenomenon of hormesis, a dose-dependent response in which low doses of a compound stimulate biological activity, whereas high doses are inhibitory [55,56]. Therefore, the hormetic effect highlights the fine balance between compounds' beneficial and inhibitory effects depending on dosage [57–60].

It is noteworthy that the 1.0 mg/mL treatment with *L. camara* extracts tested here showed an intriguing effect on both degrees of dormancy of *S. viridis* seeds. Although the germination rate was similar to the control and showed a slight inhibition compared to the lower concentrations (0.1 and 0.5 mg/mL), the root growth was significantly stimulated. Therefore, the dynamic effects of *L. camara* extracts on germination and seedling root development must be carefully considered before the application of these extracts. If the primary purpose is to employ *L. camara* extracts as bioherbicide, they are appropriate for pre-emergence applications, minimizing the number of weeds that sprout. The use of *L. camara* extracts at a dosage of 1.0 mg/mL in post-emergence applications could trigger weed growth. Notably, the highest concentration tested (5.0 mg/mL) proved the most effective as a potential bioherbicide for dormant and non-dormant seeds of *S. viridis*, inhibiting all relevant parameters in germination and root growth.

It is important to note that *L. camara* has been well-documented as an invasive species in several regions, often considered a weed [61]. Using weeds, such as *L. camara*, to develop bioherbicides represents a potentially sustainable and innovative strategy for managing invasive plants. Utilizing plant material that would otherwise be discarded and transforming it into sustainable products with the potential for biological control offers an environmentally friendly and economically viable alternative for underdeveloped areas [62]. This approach contributes to a circular economy by minimizing plant waste and promoting the use of bioactive compounds with inherent allelopathic properties capable of inhibiting the growth of other weeds [63].

Additionally, our study evaluated different degrees of dormancy of *S. viridis* seeds (i.e., 12 and 110 dph), an aspect that research focused on bioherbicides and allelopathy typically does not evaluate nor specify [24,64–70]. The dormancy is a well-known aspect of

S. viridis seeds and is primarily related to the length of time post-harvest [18]. Studies have shown that the seeds from the parent plant shed variable germinability in *S. viridis* [71]. In addition, the dormancy observed in green foxtail is also related to the morphophysiological aspects of the seeds [19–21]. The hull of *S. viridis* seeds is a firmly connected structure formed by two lemmas, two glumes, and one palea, which encloses the caryopsis, made of the embryo and endosperm [72]. All these enveloping layers control the entrance of water and dissolved gases, directly affecting seed dormancy [19]. Therefore, analyzing dormant seeds allows for a better understanding of the allelopathic potential of plant extracts in weed control since these seeds pose a significant problem for weed management because they remain viable longer in the soil [73].

The use of *S. viridis* as a research object is important, considering the species is a weed in various regions, including several European countries, where it threatens agricultural systems due to its rapid growth and herbicide resistance [74]. Moreover, a study conducted on *S. viridis*, widely known as a model species for C_4 monocots [15], facilitates the extrapolation of our results to other agronomically relevant weeds, especially other grasses.

4. Conclusions

The results obtained in this study demonstrated that aqueous extracts of *Lantana camara* have a significant dual effect, exhibiting a typical hormesis response on the germination and the initial development of *Setaria viridis*, an invasive grass and a model plant for C_4 species research. The results of germination showed some differences according to the degree of dormancy. At moderate concentrations, *L. camara* extracts acted as a biostimulant, enhancing germination rate and speed, and promoting root growth, highlighting its potential for applications designed to stimulate early plant growth and/or break dormancy. Conversely, at higher concentrations, the extracts exhibited allelopathic effects, significantly inhibiting germination and root development, suggesting its potential use as a bioherbicide.

These findings align with other studies that report the versatility of *L. camara* extracts and their potential for dual use, as a bioherbicide or biostimulant, depending on the concentration applied. In addition, using weeds such as *L. camara* to manage other invasive species offers a more sustainable and economically viable alternative, reducing our reliance on synthetic herbicides and minimizing environmental impacts associated with the use of chemicals in agriculture. This approach aligns with regenerative agricultural practices and contributes to implementing a circular economy, leveraging the bioactive potential of plants that would otherwise be discarded.

Future research should focus on more detailed investigations into the chemical composition of *L. camara* extracts, aiming to identify and quantify all the potential bioactive compounds responsible for the observed hormeses effects. Additionally, it is crucial to explore the underlying molecular mechanisms that drive the biostimulant and/or allelopathic actions of these extracts, gaining a deeper understanding of how different compounds influence plant physiological processes. Finally, developing optimized formulations that enhance the biological effects while minimizing impacts on non-target plants will be essential for the practical and efficient application of *L. camara* extracts in agriculture.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/seeds3040044/s1; Figure S1: Chromatogram (254 nm) of *Lantana camara* aqueous extracts; Figure S2: Effects of *L. camara* extracts in *S. viridis* germination; Figure S3: Effects of *L. camara* extracts in *S. viridis* root length.

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