



ALOE VERA LEAF EXTRACT ENHANCES GERMINATION DYNAMICS AND SEEDLING VIGOR IN SWEET PEPPER (*CAPSICUM ANNUUM* L.)

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ABSTRACT

Objective: This study aimed to evaluate the effect of *A. vera* leaf extract on germination performance and seedling vigor in *C. annuum* under controlled laboratory conditions.

Theoretical Framework: Plant extracts are recognized as sustainable alternatives to synthetic inputs, acting as natural biostimulants and antifungal agents. Aloe vera contains polysaccharides, phenolics, anthraquinones and glycoproteins capable of modulating germination physiology and early seedling vigor.

Method: The experiment followed a completely randomized design with five extract concentrations (0–40%) and four replications. Germination percentage, germination speed index, root length, shoot height and stem diameter were measured. Data were submitted to ANOVA and means compared by the Scott–Knott test (5%).

Results and Discussion: No significant effects were detected for most variables. However, intermediate concentrations showed slight stimulation in shoot height and stem diameter, whereas higher concentrations reduced root elongation, indicating a dose-dependent (hormetic) trend. The absence of fungal contamination in treated seeds suggests an antifungal effect of the extract.

Research Implications: The findings indicate that Aloe vera extract can be safely incorporated into seed treatment protocols, but concentration thresholds must be optimized to avoid inhibitory responses, especially in root development.

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Originality/Value: This study provides one of the few systematic evaluations of Aloe vera leaf extract on *Capsicum annuum* germination, offering new insights into its hormetic behavior, antifungal potential and applicability as a natural biostimulant in sustainable horticulture.

Keywords: *Capsicum Annuum*, Natural Biostimulant, Germination, Hormesis, *Aloe Vera*.

EXTRATO FOLIAR DE ALOE VERA MELHORA A DINÂMICA DE GERMINAÇÃO E O VIGOR DE PLÂNTULAS DE PIMENTA-DOCE (*CAPSICUM ANNUUM* L.)

RESUMO

Objetivo: Este estudo objetivou avaliar o efeito do extrato foliar de *A. vera* no desempenho germinativo e no vigor de plântulas de *C. annuum* sob condições laboratoriais controladas.

Referencial Teórico: Os extratos vegetais são reconhecidos como alternativas sustentáveis aos insumos sintéticos, atuando como bioestimulantes naturais e agentes antifúngicos. A *Aloe vera* contém polissacarídeos, compostos fenólicos, antraquinonas e glicoproteínas capazes de modular a fisiologia da germinação e o vigor inicial das plântulas.

Método: O experimento seguiu um delineamento inteiramente casualizado (DIC) com cinco concentrações do extrato (0–40%) e quatro repetições. Foram mensurados a porcentagem de germinação, o índice de velocidade de germinação (IVG), o comprimento radicular, a altura da parte aérea e o diâmetro do caule. Os dados foram submetidos à análise de variância (ANOVA) e as médias comparadas pelo teste de Scott-Knott (5%).

Resultados e Discussão: Não foram detectados efeitos significativos para a maioria das variáveis. Entretanto, concentrações intermediárias apresentaram leve estímulo na altura da parte aérea e no diâmetro do caule, enquanto concentrações mais altas reduziram o alongamento radicular, indicando uma tendência dose-dependente (efeito hormético). A ausência de contaminação fúngica nas sementes tratadas sugere um efeito antifúngico do extrato.

Implicações da Pesquisa: Os resultados indicam que o extrato de *Aloe vera* pode ser incorporado de forma segura em protocolos de tratamento de sementes, porém os níveis de concentração devem ser otimizados para evitar respostas inibitórias, especialmente no desenvolvimento radicular.

Originalidade/Valor: Este estudo fornece uma das poucas avaliações sistemáticas do extrato foliar de *Aloe vera* na germinação de *Capsicum annuum*, oferecendo novas perspectivas sobre seu comportamento hormético, potencial antifúngico e aplicabilidade como bioestimulante natural na horticultura sustentável.

Palavras-chave: *Capsicum Annuum*, Bioestimulante Natural, Germinação, Hormese, *Aloe Vera*.

EL EXTRACTO FOLIAR DE ALOE VERA MEJORA LA DINÁMICA DE GERMINACIÓN Y EL VIGOR DE PLÁNTULAS DE PIMIENTO DULCE (*CAPSICUM ANNUUM* L.)

RESUMEN

Objetivo: Este estudio tuvo como objetivo evaluar el efecto del extracto foliar de *A. vera* sobre el desempeño germinativo y el vigor de las plântulas de *C. annuum* bajo condiciones controladas de laboratorio.

Marco Teórico: Los extractos vegetales son reconocidos como alternativas sostenibles a los insumos sintéticos, actuando como bioestimulantes naturales y agentes antifúngicos. El *Aloe vera* contiene polisacáridos, compuestos fenólicos, antraquinonas y glicoproteínas capaces de modular la fisiología de la germinación y el vigor inicial de las plântulas.

Método: El experimento siguió un diseño completamente al azar (DCA) con cinco concentraciones de extracto (0–40%) y cuatro repeticiones. Se midieron el porcentaje de germinación, el índice de velocidad de germinación (IVG), la longitud radicular, la altura de la parte aérea y el diámetro del tallo. Los datos fueron sometidos a análisis de varianza (ANOVA) y las medias se compararon mediante la prueba de Scott-Knott (5%).



Resultados y Discusión: No se detectaron efectos significativos para la mayoría de las variables. Sin embargo, las concentraciones intermedias mostraron una leve estimulación en la altura de la parte aérea y el diámetro del tallo, mientras que las concentraciones más altas redujeron la elongación radicular, indicando una tendencia dosis-dependiente (efecto hormético). La ausencia de contaminación fúngica en las semillas tratadas sugiere un efecto antifúngico del extracto.

Implicaciones de la Investigación: Los hallazgos indican que el extracto de *Aloe vera* puede incorporarse de manera segura en protocolos de tratamiento de semillas, pero los umbrales de concentración deben optimizarse para evitar respuestas inhibitorias, especialmente en el desarrollo radicular.

Originalidad/Valor: Este estudio proporciona una de las pocas evaluaciones sistemáticas del extracto foliar de *Aloe vera* en la germinación de *Capsicum annuum*, ofreciendo nuevas perspectivas sobre su comportamiento hormético, potencial antifúngico y aplicabilidad como bioestimulante natural en la horticultura sostenible.

Palabras clave: *Capsicum Annuum*, Bioestimulante Natural, Germinación, Hormesis, *Aloe Vera*.

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1 INTRODUCTION

Plant extracts have emerged as sustainable alternatives to synthetic agrochemicals, serving as bioinsecticides, fungicides, and seed biostimulants (Maciel, 2010; Bermejo *et al.*, 2013; Pannacci *et al.*, 2022). These natural compounds optimize metabolic pathways and nutrient absorption, promoting early plant growth (Soares, 2023). Among these, *Aloe vera* (L.) Burm.f. (Asphodelaceae), known as “babosa,” stands out due to its rich biochemical profile. Its succulent leaves store a complex mixture of bioactive compounds, including polysaccharides, anthraquinones, amino acids, and minerals, that play distinct roles in plant metabolism (Hes *et al.*, 2019; Nalimu *et al.*, 2021).

While primarily recognized for medicinal use, *A. vera* has shown significant potential in agriculture. Studies indicate that its extracts can mitigate abiotic stress and exhibit bioregulatory activity (Romagna *et al.*, 2019). For instance, Bendjedid *et al.* (2022) reported allelopathic effects of *A. vera* on *Triticum durum* and *Amaranthus hybridus*. However, the efficacy of plant-derived compounds is often dose-dependent, capable of exerting either stimulatory or inhibitory effects on germination depending on concentration and exposure time (Costa and Freire, 2018; Lopes *et al.*, 2025).

The sweet pepper (*Capsicum annuum* L.) is an economically strategic crop globally (FAO, 2020). Despite its importance, successful cultivation relies heavily on seed quality and rapid stand establishment (Carvalho and Nakagawa, 2012). Propagation is frequently limited



by seed dormancy and the mechanical resistance of the micropylar endosperm, which restricts embryo elongation and delays emergence (Watkins and Cantliffe, 1983).

In this scenario, natural biostimulants may overcome germination barriers and enhance seedling vigor (Moterle *et al.*, 2008; Romagna *et al.*, 2019). Although the bioactive potential of *A. vera* is well-documented, its specific influence on *C. annuum* germination dynamics remains poorly elucidated. Therefore, this study aimed to evaluate the effect of *A. vera* leaf extract on germination performance and seedling vigor in *C. annuum* under controlled laboratory conditions.

2 JUSTIFICATION

Rapid and uniform germination is pivotal for sweet pepper stand establishment, directly affecting seedling vigor, early growth, and crop yield. Nevertheless, producers still lack efficient natural alternatives to substitute synthetic growth promoters. Vegetable extracts, particularly from *Aloe vera*, exhibit biostimulant potential due to their high content of bioactive compounds; however, their specific effects on *Capsicum annuum* seeds remain largely unexplored. Therefore, it is crucial to objectively assess the impact of different extract concentrations on germination and seedling vigor, thereby establishing a technical framework for an agronomic application that is safe, sustainable, and economically viable.

3 METHODOLOGY

3.1 EXPERIMENTAL SITE AND DESIGN

The experiment was carried out at the Applied Laboratory for Phytosanitary Teaching of the Tocantina Amazon (LAFAT), located at the Federal University of Pará (UFPA), Cametá campus, Pará, Brazil, from August 26 to September 11, 2024.

A completely randomized design (CRD) was adopted, consisting of five treatments and four replicates. Each experimental unit comprised 25 seeds, totaling 100 seeds per treatment and 500 seeds overall. The plant material used was sweet pepper (*C. annuum* L.), with seeds obtained from a local commercial source and selected for uniform size, color, and health.



3.2 PREPARATION OF THE PLANT EXTRACT

Adult leaves of *A. vera* (including the epidermis) were collected from plants growing on the UFPA/Cametá campus. The leaves were washed under running water, cut into pieces, and homogenized in a blender without the addition of solvents. The resulting pulp was filtered through a plastic sieve to obtain a crude extract free from solid residues.

The crude extract was then diluted in distilled water to prepare four concentrations: 10%, 20%, 30%, and 40% (v/v). The control treatment consisted of distilled water (0%). Accordingly, the treatments were defined as follows: Control; AVPD1 – 10%; AVPD2 – 20%; AVPD3 – 30%; and AVPD4 – 40% *A. vera* leaf extract.

3.3 SEED TREATMENT AND GERMINATION PROCEDURE

Pepper seeds were immersed in each solution for 30 minutes using 50 mL plastic cups. After soaking, the seeds were evenly distributed in 250 mL plastic containers with lids and placed in a germination chamber (BOD – Biochemical Oxygen Demand) under controlled temperature and light conditions. Germination was monitored daily until the 16th day, when all treatments showed complete emergence and satisfactory seedling vigor.

3.4 EVALUATED PARAMETERS

Normal seedlings from each treatment were evaluated for shoot height (SH), root length (RL), and stem diameter (SD) using a digital caliper with millimeter precision. Measurements were taken for all normal seedlings in each replicate.

The germination percentagem (GP) was calculated using the following equation 1.

$$G(\%) = \left(\frac{N}{100} \right) \times 100 \quad (1)$$

Where:

N = number of germinated seeds at the end of the experiment, expressed as a percentage.

Germination speed was determined by the Germination Speed Index (GSI), calculated according to Maguire (1962), na equation 2.



$$GSI = \sum \left(\frac{n}{t} \right) \quad (2)$$

Where:

n is the number of normal seedlings counted at each evaluation, and t is the number of days elapsed from sowing to the respective count.

3.5 STATISTICAL ANALYSIS

All data were subjected to analysis of variance (ANOVA), and treatment means were compared using the Scott–Knott test at the 5% significance level. Statistical analyses were performed using the GENES software (Cruz, 2025).

4 RESULTS AND DISCUSSIONS

No significant effects or interactions were observed among treatments for any of the evaluated variables, as indicated by the analysis of variance (Table 1). Therefore, the parameters were analyzed independently. For the Germination Speed Index (GSI), the mean value was 4.13, with a coefficient of variation (CV) of 26.9%, indicating moderate data dispersion and variability among replicates. This level of variation suggests that uncontrolled environmental factors may have influenced germination performance during the experimental period.



Table 1

Analysis of variance (ANOVA) for germination speed index (GSI), germination percentage (GP), root length (RL), shoot height (SH), and stem diameter (SD) of sweet pepper (C. annuum) seedlings under different concentrations of A. vera leaf extract. Lower Tocantins region, Pará, Brazil, 2025.

FV	GL	MS				
		GSI	GP (%)	RL	SH (mm)	SD
Treatment	4	1.75 ^{ns}	8.83 ^{ns}	120.9 ^{ns}	16.8 ^{ns}	0.013 ^{ns}
Residual	15	1.24	7.22	68.7	14.1	0.008
Mean	-	4.13	98.2	30.6	25.9	0.86
CV(%)	-	26.9	2.73	27.1	14.5	10.5

ns = not significant. Mean square (MS); CV (%) = coefficient of variation. Significant at the 5% probability level according to the F-test. **Note:** germination speed index (GSI), germination percentage (GP), root length (RL), shoot height (SH), stem diameter (SD) (n = 100). Source: Authors, 2025.

The analysis of variance (ANOVA) revealed no significant differences among treatments for any evaluated parameter (Table 1), indicating that the observed variation resulted from natural experimental heterogeneity rather than the *A. vera* extract concentrations.

Germination percentage (GP) remained high (mean = 98.2%) with a low coefficient of variation (CV = 2.73%). This stability demonstrates that the extract did not impair seed viability and that intrinsic seed vigor predominated over external biochemical stimuli, a behavior consistent with *C. annuum* responses under favorable conditions (Carvalho and Nakagawa, 2012).

Similarly, seedling growth metrics, root length (RL), shoot height (SH), and stem diameter (SD), showed no significant response to the treatments. Means were 30.6 mm, 25.9 mm, and 0.86 mm, respectively. The moderate variability observed in RL (CV = 27.1%) likely reflects microenvironmental fluctuations or seed-to-seed variability rather than biochemical modulation by the extract.

The absence of significant effects contrasts with findings by Sousa et al. (2024), who reported inhibition in soybean germination at high *A. vera* concentrations due to saponin accumulation. In the present study, the tested range (10–40%) exerted a neutral effect, suggesting a balance between potential stimulatory and inhibitory compounds. Furthermore, the variability in physiological attributes aligns with the wide phenotypic plasticity reported for

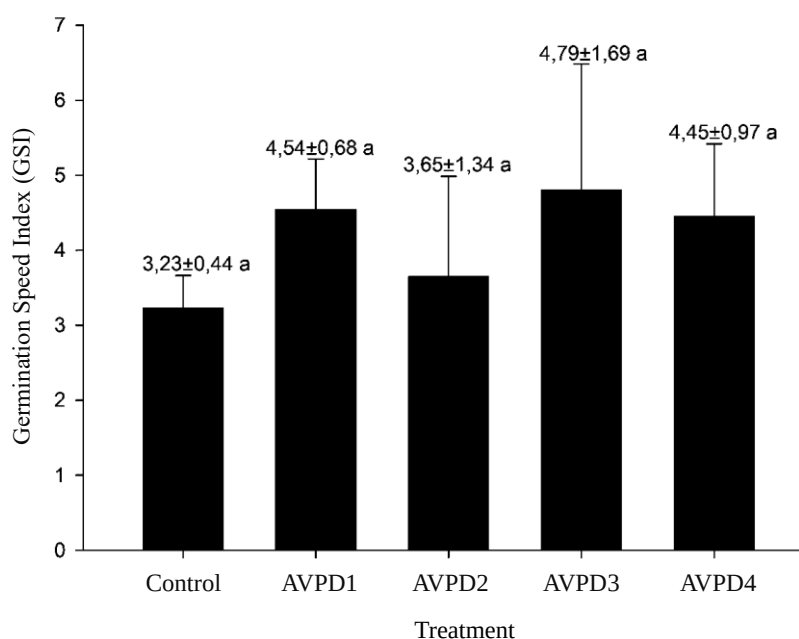


the genus *Capsicum* (Liu et al., 2023). Overall, the extract did not alter germination dynamics, emphasizing the high physiological quality of the seed lot used.

The GSI of *C. annuum* seeds exhibited no significant differences among treatments with *A. vera* leaf extract (Figure 1). Although slight numerical variations were observed, values ranged narrowly from 3.23 ± 0.44 to 4.79 ± 1.69 , indicating a uniform germination performance across all concentrations. The highest mean GSI was obtained at 30% leaf extract concentration (AVPD3), whereas the lowest occurred in the control. However, these differences were not statistically significant, suggesting that *A. vera* leaf extract did not enhance or inhibit the rate of seed germination under the tested conditions.

Figure 1

Germination speed index (GSI) of sweet pepper (*C. annuum* L.) seeds treated with different concentrations of *A. vera* leaf extract. Lower Tocantins region, Pará, Brazil, 2025.



*Mean $\pm$ standard deviation (n = 100). Means followed by the same letter do not differ significantly according to the Scott-Knott test ($p > 0.05$). Source: Authors, 2025.

The Germination Speed Index (GSI) displayed a non-significant upward trend in treated seeds, peaking in treatment AVPD3 (4.79 ± 1.69) compared to the control (3.23 ± 0.44) (Figure 1). However, this response was not linear, as AVPD2 showed a reduction compared to other treatments. The notable standard deviation in AVPD3 indicates a heterogeneous response among replicates, contrasting with the physiological stability observed in the control group.

The slight acceleration in germination speed may be attributed to the priming effect of bioactive compounds present in *A. vera*, such as saponins and glycoproteins. These molecules



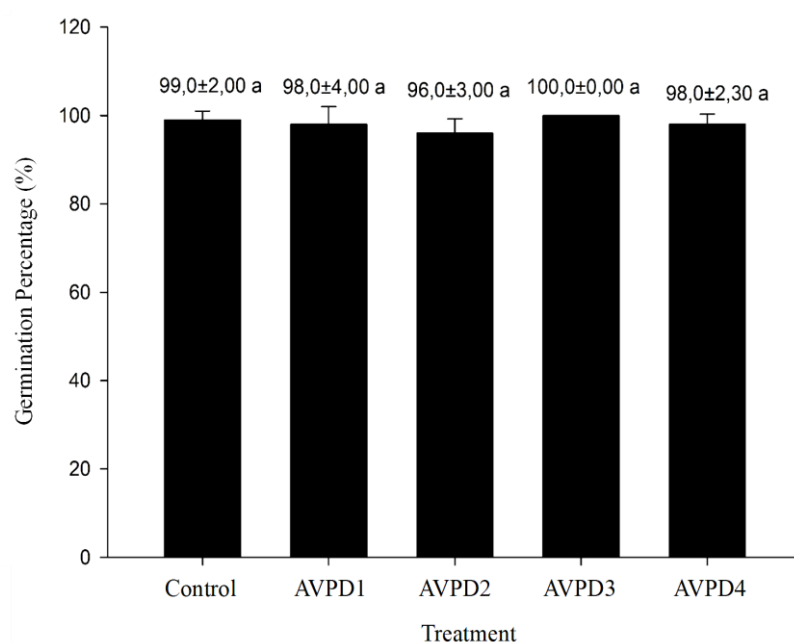
can modulate membrane permeability and activate hydrolytic enzymes essential for embryo protrusion (Nalimu et al., 2021). This hypothesis is supported by Sousa et al. (2024) and Dourado Neto et al. (2014), who described the capacity of natural extracts to act as physiological enhancers.

Nevertheless, the lack of statistical differentiation suggests that the concentration thresholds used were insufficient to trigger a consistent biostimulant effect in *C. annuum*. While a numerical trend exists, it likely reflects a subtle metabolic interaction rather than a robust bioactivation process. Future studies involving enzymatic profiling (e.g., amylase activity) are required to determine if these variations stem from specific biochemical pathways or stochastic experimental factors.

The GP of *C. annuum* seeds remained consistently high across all treatments, ranging from $96.0 \pm 3.0\%$ (AVPD2) to $100.0 \pm 0.0\%$ (AVPD3) (Figure 2). No significant differences were observed among treatments, indicating that the application of *A. vera* leaf extract did not affect total seed germination. These results suggest that the physiological potential of the seeds was sufficiently high to achieve near-complete germination, regardless of treatment concentration.

Figure 2

Germination percentage (GP) of sweet pepper (*C. annuum* L.) seeds treated with different concentrations of *A. vera* leaf extract. Lower Tocantins region, Pará, Brazil, 2025.



Mean $\pm$ standard deviation (n = 100). Means followed by the same letter do not differ significantly according to the Scott-Knott test ($p > 0.05$). Source: Authors, 2025.



The low variability ($CV = 2.73\%$) and high mean germination percentages confirm the uniform viability and vigor of the seed lot used. The control treatment ($99.0 \pm 2.0\%$) and the leaf extract-treated seeds (ranging from 96.0 to 100.0%) displayed comparable performance, reinforcing that *A. vera* extract neither enhanced nor inhibited germination percentage under the tested conditions.

Comparable findings were reported by Sousa *et al.* (2024), who observed that moderate concentrations of *A. vera* leaf extract exerted minimal influence on total germination but could slightly modify germination speed, possibly due to osmotic and enzymatic adjustments. Similarly, Nalimu *et al.* (2021) emphasized that *A. vera* contains bioactive polysaccharides and phenolic compounds capable of modulating water uptake and enzymatic activity during early germination; however, the magnitude of these effects depends strongly on concentration, exposure time, and the species' physiological sensitivity.

In the present study, the absence of significant effects on GP suggests that the leaf extract concentrations tested (10–40%) were within a neutral range, neither phytotoxic nor sufficiently stimulatory to induce detectable changes in germination rate or percentage. This stability highlights the intrinsic vigor of sweet pepper seeds and supports the hypothesis that *A. vera* leaf extract exerts limited physiological influence on germination success under optimal laboratory conditions.

Shoot height (SH) and stem diameter (SD) of *C. annuum* seedlings exhibited slight numerical variation among treatments, with means ranging from $22.5 \pm 6.95\text{mm}$ (Control) to 27.4 mm (AVPD3) for SH, and from 0.81 mm to 0.94 mm for SD (AVPD2) (Table 2). Despite the increasing trend in SH with the application of *A. vera* leaf extract, no statistically significant differences were detected among treatments, indicating that the extract concentrations did not markedly influence early seedling growth.



Table 2

Shoot height (SH) and stem diameter (SD) of sweet pepper (C. annuum L.) seedlings treated with different concentrations of A. vera leaf extract. Lower Tocantins region, Pará, Brazil, 2025.

Treatment	SH	SD
	(mm)	
Control	22.5 ± 6.95	0.81 ± 0.12
AVPD1	25.6 ± 2.15	0.81 ± 0.07
AVPD2	26.9 ± 2.27	0.84 ± 0.02
AVPD3	27.4 ± 2.49	0.89 ± 0.13
AVPD4	27.2 ± 2.53	0.94 ± 0.03
Mean	25.9	0.86
CV (%)	13.2	8.71

Mean ± standard deviation (n = 100). CV (%) = coefficient of variation. Significant at the 5% probability level according to the Scott-Knott test ($p > 0.05$). Source: Authors, 2025.

For Shoot Height (SH), a progressive but non-significant increase was observed with rising extract concentrations (Table 2). This behavior suggests a dose-related stimulatory trend, consistent with the hormetic effects described by Mairesse *et al.* (2007). The presence of phenolic derivatives and amino acids in the extract likely facilitated nutrient absorption and metabolic regulation, promoting cell elongation in the hypocotyl.

Stem Diameter (SD) followed a similar pattern, with AVPD4 displaying the highest mean (0.94 ± 0.03 mm). Despite the lack of statistical significance, the low coefficient of variation ($<10\%$) confirms experimental precision. The numerical superiority of treated seedlings mirrors findings in *Solanum lycopersicum* by Buthane *et al.* (2025), where *A. vera* applications enhanced secondary thickening via auxin-cytokinin signaling pathways.

The absence of significant variation suggests that the extract concentrations used were within a "safe window", insufficient to cause the osmotic stress or phenolic toxicity often associated with high-dose applications (Borella, 2011). Consequently, while the extract did not significantly boost morphometric traits under these conditions, it proved to be non-phytotoxic, supporting its potential use as a safe, natural amendment for seedling production.

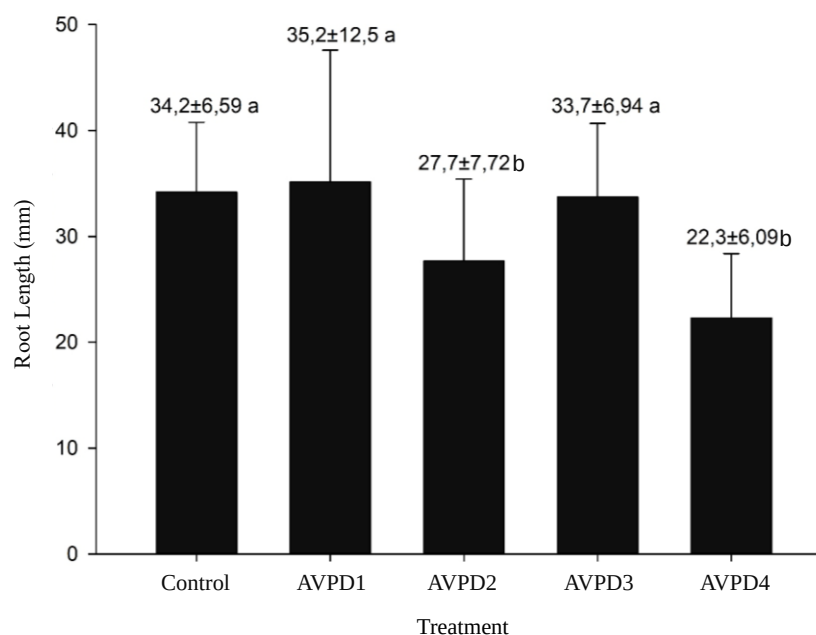
Root length (RL) exhibited greater sensitivity to *A. vera* treatments compared to other vegetative parameters (Figure 3). Significant differences were observed among treatments, with mean values ranging from 22.3 ± 6.09 mm (AVPD4) to 35.2 ± 12.5 mm (AVPD1). The longest roots were recorded in the control (34.2 ± 6.59 mm) and AVPD1 (35.2 ± 12.5 mm) treatments, both statistically superior to AVPD2 and AVPD4, which showed reduced root elongation. The



treatment AVPD3 (33.7 ± 6.94 mm) maintained an intermediate response, statistically similar to the control.

Figure 3

Root length (RL) of sweet pepper (*C. annuum*) seedlings treated with different concentrations of *A. vera* leaf extract. Lower Tocantins region, Pará, Brazil, 2025.



Mean $\pm$ standard deviation ($n = 100$). Means followed by the same letter do not differ significantly according to the Scott-Knott test ($p > 0.05$). Source: Authors, 2025.

The reduction in Root Length (RL) at high concentrations (AVPD4) suggests a phytotoxic or allelopathic effect. Elevated levels of phenolics and anthraquinones, specifically aloin, likely altered the substrate's osmotic potential and disrupted enzymatic activities essential for cell elongation (Borella, 2011; Sausen *et al.*, 2009). As noted by Shao *et al.* (2013), anthraquinones can suppress DNA synthesis and mitotic activity in meristematic tissues, leading to the observed radicle constraint.

Conversely, lower concentrations (AVPD1) exhibited a mild biostimulatory trend, potentially mediated by auxin and cytokinin-like signaling pathways that enhance mitotic activity (Hes *et al.*, 2019). This concentration-dependent behavior characterizes a hormetic response, where moderate doses promote growth while high doses induce inhibition, a pattern documented in other Solanaceae (Sousa *et al.*, 2024).

Biologically, the radicle is the most sensitive organ to allelochemicals due to direct contact and high metabolic rates (Haida *et al.*, 2010). Agronomically, root inhibition is critical; a compromised root system limits water/nutrient uptake and anchorage, reducing resilience to



abiotic stress (Taiz *et al.*, 2017). Thus, while *A. vera* shows potential as a biostimulant, dose optimization is mandatory to avoid anthraquinone-mediated phytotoxicity.

The Pearson correlation coefficients (r) among the evaluated parameters for *C. annuum* seeds are presented in Table 3. A positive correlation was observed between the Germination Speed Index (GSI) and all other traits, including Germination Percentage (GP), Root Length (RL), Shoot Height (SH), and Stem Diameter (SD). However, the correlation between GSI and GP ($r = 0.22$) was not statistically significant, indicating that while faster germination tended to accompany higher germination rates, this trend was not strong enough to establish a direct functional relationship. Thus, GSI appears to influence only the initial emergence rate, with limited predictive power for subsequent seedling growth performance.

Table 3

*Pearson correlation coefficients (r) among germination and growth parameters of sweet pepper (*C. annuum*) seeds treated with *A. vera* leaf extract. Lower Tocantins region, Pará, Brazil, 2025.*

Variables	GVI	GP	RL	SH	SD
IVG	0				
PG	0.22 ^{ns}	0			
CR	-0.14 ^{ns}	-0.04 ^{ns}	0		
AP	-0.17 ^{ns}	-0.12 ^{ns}	0.007 ^{ns}	0	
DC	-0.08 ^{ns}	0.003 ^{ns}	-0.29 ^{ns}	0.68 **	0

ns = not significant; ** = significant at the 1% probability level (Scott-Knott test). **Note:** germination speed index (GSI), germination percentage (GP), root length (RL), shoot height (SH), stem diameter (SD) ($n = 100$). Source: Authors, 2025.

Correlation analysis revealed a positive association between GSI and GP, consistent with the vigor-viability relationship described by Wylot *et al.* (2019). Nevertheless, the lack of statistical significance is attributable to the low coefficient of variation in germination rates (>98%), which masked potential linear dependencies.

A significant allometric correlation ($r = 0.68$, $p \leq 0.01$) was observed between SH and SD. This demonstrates a functional coupling between axis elongation and secondary thickening, a crucial morphogenetic strategy for hydraulic conductivity and structural support (Moraes Campos *et al.*, 2021). In contrast, the decoupling of Root Length (RL) from aerial traits suggests that below-ground and above-ground tissues responded differentially to the extract, operating under independent physiological controls.



Beyond biometric data, the study revealed a significant phytosanitary advantage. Fungal proliferation was restricted to the control treatment, with zero incidence in *A. vera* exposed seeds. This fungistatic or fungicidal activity is likely driven by the synergistic action of glycoproteins and anthraquinones found in the whole-leaf extract. As noted by Habeeb *et al.* (2007), these metabolites compromise fungal membrane integrity. Consequently, *A. vera* extract emerges not only as a potential growth modulator but as a sustainable alternative for seed health management.

5 CONCLUSION

The *A. vera* leaf extract did not produce statistically significant effects on germination or early seedling growth of sweet pepper (*C. annuum* L.). However, a slight increase in shoot height and stem diameter was observed at intermediate concentrations, while higher concentrations reduced root elongation, indicating a dose-dependent (hormetic) response.

The results suggest that *A. vera* may act as a mild biostimulant at low concentrations and as an inhibitor at higher doses, likely due to the presence of anthraquinones and phenolic compounds. Moreover, the absence of fungal growth in treated seeds points to a potential antifungal effect.

A. vera extract shows promise as a natural seed treatment, but its optimal concentration must be defined to ensure beneficial effects without compromising seedling development.



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