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Article

Emergence and Structural Characteristic of the *Solanum pimpinellifolium* in Trays under Different Levels and Types of Substrates

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Abstract: The cultivated tomato is one of the most consumed vegetables in the world, and the preparation of seedlings plays a fundamental role in the success of the crop, which is often plagued by fungi and bacteria from its earliest stages. This study aimed to analyze the emergence speed index and morphological parameters of Wanda hybrid cherry tomato seedlings (Solanum lycopersicum var. pimpinellifolium) in trays with two different types and levels of substrates in a protected environment using certified seeds. The experiment was conducted in the greenhouse of the IFCE—Campus Crato during the months of August and September 2022. Two basic substrates were used to promote germination and emergence: one was the commercial Vivato Slim Plus®, and the other was based on worm humus produced in Minhobuckets kits. The experimental design was completely randomized, consisting of five doses of commercial substrate (SBC) and earthworm humus (HDM) in the following proportions: S1—HDM; S2—SBC; S3—HDM + SBC (1:1), S4—HDM + SBC (1:3), and S5—HDM + SBC (3:1). The ESI, morphological parameters (SD, PH, ROOTL, and NL), and the dry biomass of the seedlings (LDB, SDB, RDB, and TDB) were determined. Data were subjected to an analysis of variance, and Tukey's test (0.05) was used; dry biomass data were submitted to square root transformation. For the emergence speed index, SBC (S2) outperformed the others. Regarding the morphological parameters and dry biomass, all substrates yielded satisfactory results, despite not showing a statistical difference between the averages. The substrate S4 produced the best results in all evaluated parameters.

Keywords: emergence speed; earthworm humus; commercial substrates; protected environment; natural baits

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1. Introduction

The cultivated tomato (*Solanum lycopersicum* L.), a member of the Solanaceae family, has several groups, with mini-tomatoes, especially cherry tomatoes (*S. pimpinellifolium* [1–4] and *S. lycopersicum* var. *cerasiforme*), gaining popularity in Brazilian households and becoming one of the most cultivated vegetables globally [5–7]. This surge in popularity is attributed to the fruit's exceptional quality in terms of vitamins, antioxidants, delightful flavor, diverse sizes, and vibrant colors [8–12]. However, the journey of seedling preparation has been fraught with challenges, as seeds must not only exhibit excellent germination and emergence but also demonstrate resilience against viral and bacterial diseases, as they are pivotal for successful cultivation [13].

Brazilian law establishes quality standards for seeds, focusing mainly on germination and purity as criteria for physiological quality, but vigor remains unaddressed [13]. As a result, producers often rely on quality assurances printed on seed packaging from companies. Consequently, hybrid seeds and cultivation in protected environments have gained prominence, owing to their high productivity and fruit quality in the former case and pest protection in the latter [14]. According to the Isla company [15], Wanda seeds exhibit resistance to Fol:0-2 (Fusarium wilt race 1, 2, and 3), TMV (tobacco mosaic virus), TSWV (tomato spotted wilt virus), and Vd (Verticillium wilt dahliae) [16–22]. It is worth noting that Brazil has been a pioneer in organic production, but there are limited offerings of cultivars produced following agroecological principles. Even in organic practices, the use of subpar materials cannot be justified [23].

Another critical factor in seed germination and emergence, besides quality standards and resistance to pests and diseases, is the material used as a bed for seed placement during planting for seedling formation under optimal conditions for their development. Typically, commercial substrates are used, but these materials come at high prices, impacting higher production costs [24,25]. To mitigate these costs, various organic and inorganic materials are employed, either individually or in combination, such as green coconut fiber, peat, wood waste, pine bark, carbonized rice husk, rockwool, and phenolic foam, among others [26,27].

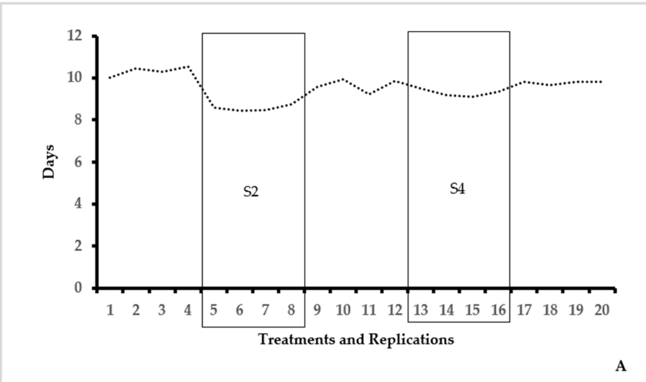
Compost and vermicompost (humus) products are also used for seed germination and seedling formation. Compost, composed of nitrogen- and carbon-rich materials, provides an ideal medium for earthworms, resulting in the production of humus. Guinea grass (*Panicum maximum* Jacq. cv. guinea grass), often considered a weed, thrives in rural areas due to its adaptability to tropical and subtropical climates [28]. A promising way to eliminate most contaminants is photocatalytic technology, capable of promoting the decomposition of organic compounds and the degradation of pollutants and microorganisms, in addition to the production of active species derived from the biological oxidation process (photodegradation process) [29]. A study by Cruz et al. [30] demonstrated that the presence of guinea grass negatively influenced the initial growth of eucalyptus clones. Another study by Presoto et al. [31] identified guinea grass as a prominent weed in sugarcane plantations and challenging to control. Nevertheless, the study by Moura et al. [32] revealed that using 10% guinea grass as a replacement for manure could be utilized as an organic enhancer in lettuce production. Furthermore, abiotic factors also influence seed germination and emergence, such as water and temperature, affecting performance and interfering with germination speed, water absorption, and biochemical reactions [33,34]. Therefore, to meet the germination requirements of cherry tomato seeds, ideal temperatures (16 to 29 °C) and sufficient water during the first six hours of imbibition are crucial factors [35]. The choice of the ideal substrate for cherry tomato seedling production depends on several factors, including local availability, cost-effectiveness, physical, chemical, and biological characteristics of the material, and crop requirements. Several studies have compared the performance of different organic substrates in seed germination and cherry tomato seedling development, with varied results.

For instance, Borges and Mendonça [36] evaluated four substrates in cherry tomato seedling production: 1—commercial substrate Plantmax®; 2—grass straw; 3—vermiculite; 4—bovine manure. They found no significant differences among the substrates for parameters such as shoot height, fresh phytomass, and seedling quality index. Costa et al. [37] studied the effect of four substrates on the seedling formation and fruit production of three cherry tomato cultivars in two protected environments: an agricultural greenhouse and a 50% shaded structure. The tested substrates included: 1—commercial substrate Plantmax®; 2—cassava stems; 3—vermiculite; 4—bovine manure. The authors discovered that the best substrates for seedling production were those containing cassava stems mixed with bovine manure or vermiculite and bovine manure, resulting in higher productivity and fruit quantity per plant. In a study by Santos et al. [38] the performance of three commercial substrates on cherry tomato seed germination and seedling development was compared: 1—Top Garden®; 2—Bioplant; 3—Top Strato®. While no significant differences were observed in seed germination and emergence among the substrates, the Bioplant substrate promoted better seedling development. Pilla et al. [39] suggested that compost tea positively affects horticultural crops, including phytopathogen control and bioactive molecule content, in addition to providing nutrients. They proposed that the emergence of horticultural seedlings in vermicomposting benefits from irrigation, as nutrients are carried for seedling growth.

Given the limited information on the use of vermicompost in seed emergence analysis and the hypothesis that substrates based on earthworm humus and/or commercial substrates could create favorable conditions for cherry tomato seed germination and emergence, thereby reducing production costs, this study aims to analyze the effects of individual and mixed substrates (SBC and HDM) on the emergence and growth of cherry tomato Wanda seeds in a protected environment, as well as their morphological structure.

2. Results

The cherry tomato seeds employed in this experiment exhibited 100% germination within 12 days of sowing, affirming their quality, vigor, and efficiency. The average emergence time (AET) was 10 days for substrates with a higher volume of earthworm humus (HDM) and 9 days for the commercial substrate (SBC), as depicted in Figure 1A. This result confirms that S2 (SBC-commercial substrate) and S4 (HDM + SBC) outperformed others in terms of this parameter.



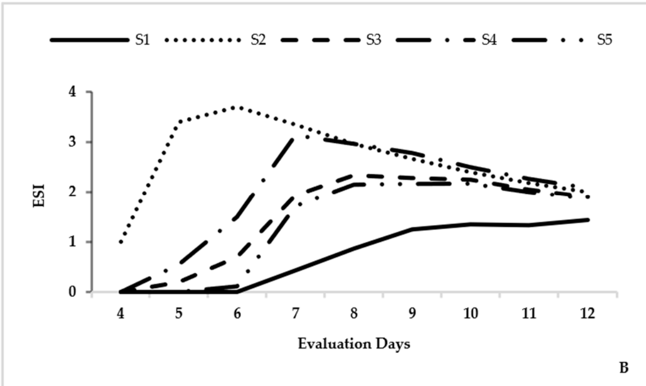


Figure 1. (**A**) AET of Wanda cherry tomato seeds in different substrates. AET: average emergence time. (**B**) ESI: emergence speed index.

Seed emergence commenced on the fourth day after sowing, marked by radicle protrusion (visible germination), with 100% emergence observed in SBC. The commercial substrate (SBC) facilitated seed emergence between Days 5 and 6 (Figure 1B).

The air temperatures and relative humidities were recorded using a thermo-hygrometer within the nursery (Figure 2) and outside the protected environment using an agrometeorological station (Figure 3). These measurements revealed fluctuations over time and between internal and external nursery readings.

At 9:00 am, a significant temperature difference was observed between the internal and external environments, with an increase of 6.3 °C inside compared to outside. This means that while the external temperature measured 18.5 °C, the internal temperature reached 25.5 °C. To understand this morning temperature rise, we must analyze the late afternoon temperature at 5:00 p.m., where the opposite trend occurred. At that time, the internal temperature was 2.13 °C lower than the external temperature. This trend is logically explained by the higher internal temperature in the morning, resulting from greater temperature accumulation during the day compared to external temperatures, both at noon (12:00 p.m.) and in the early afternoon (2:00 p.m.).

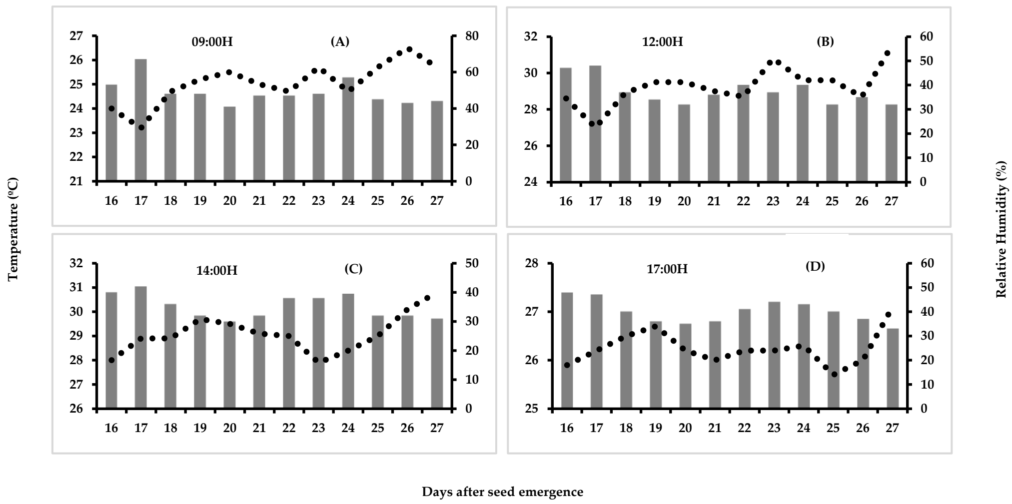


Figure 2. Temperature and relative humidity inside the seedling nursery at different time points. The dotted line represents the temperature, and the bars show the relative humidity. In subfigure (**A**) temperature and humidity measurement at 9:00 am, (**B**) at 12:00 pm, (**C**) at 2:00 pm and (**D**) at 5:00 pm. Source: Compiled by the authors. Measurement using a digital thermo-hygrometer.

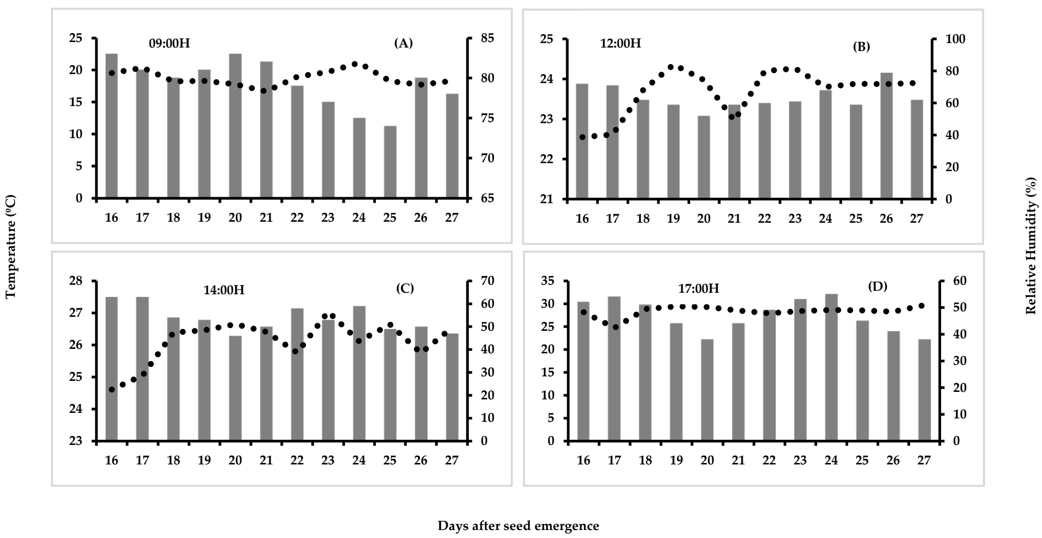


Figure 3. Temperature and relative humidity outside the seedling nursery at different time points. The dotted line represents the temperature, and the bars show the relative humidity. In subfigure (**A**) temperature and humidity measurement at 9:00 am, (**B**) at 12:00 pm, (**C**) at 2:00 pm and (**D**) at 5:00 pm. Source: Adapted from the Agrometeorological Station of FUNCEME, 2022 [29].

An examination of daily temperature trends during the experiment period revealed that internal temperatures at 9:00 am, 12:00 p.m., and 2:00 p.m. were consistently higher than external temperatures. Only at 5:00 p.m. were external temperatures higher than internal temperatures.

Analyzing the average parameters presented in Table 1, we observed significant effects only for the emergence speed index (ESI) and plant height (PH). However, there were no statistical differences in stem diameter (SD), root length (ROOTL), and the number of leaves (NL) according to Tukey's test.

Regarding the ESI displayed in Table 1, S1 significantly differed from the averages of the other substrate types, exhibiting the lowest index. S2 and S4 did not significantly differ but yielded the best results, with no significant deviation from S3 and S5. However, the mixtures containing 50% and 75% humus content did not meet the initial ESI requirements in the tests, indicating an impact on the nutritional reserve quality of the plants and, consequently, on seedling quality. The analysis of dry biomass for the leaves, stem, root system, and total seedlings is detailed in Table 2.

Table 1. Morphological parameters for quality assessment of Wanda hybrid cherry tomato seedlings: emergence speed index (ESI), stem diameter (SD) in mm, plant height (PH) in cm, root length (ROOTL) in mm, and number of leaves (NL), subjected to different substrate types. Crato, Ceara, Brazil, 2023.

Substrates	ESI	SD (mm)	PH (cm)	ROOTL (mm)	NL
S1	1.43 ± 0.46 c	2.80 ± 0.46 a	13.06 ± 3.37 c	9.25 ± 1.95 a	4.00 ± 0.00 a
S2	1.99 ± 0.12 a	2.52 ± 0.19 a	13.56 ± 0.88 c	9.13 ± 2.43 a	4.00 ± 0.41 a
S3	1.89 ± 0.18 b	2.73 ± 0.11 a	15.06 ± 1.86 b	9.25 ± 1.66 a	4.00 ± 0.29 a
S4	2.08 ± 0.00 a	2.73 ± 0.40 a	19.19 ±2.79 a	8.94 ± 2.73 a	4.00 ± 0.25 a
S5	1.87 ± 0.08 b	2.78 ± 0.27 a	16.75 ± 0.98 b	7.63 ± 2.01 a	4.00 ± 0.00 a
CV (%)	11.92	12.40	15.61	25.02	6.64
MSD (5%)	0.49	0.75	5.46	4.98	0.61

S1: earthworm humus (HDM), S2: commercial substrate (SBC), S3: HDM + SBC (1:1), S4: HDM + SBC (1:3), S5: HDM + SBC (3:1); CV: coefficient of variation; MSD: minimal significant difference. The averages and standard deviations followed by the same lowercase letters in the column do not significantly differ from each other, as determined by Tukey's test (p < 0.05). The data presented represent means from four biological replicates (±standard deviation).

Table 2. Dry biomass of the leaves, stem, root system, and total of Wanda hybrid cherry tomato seedlings subjected to various substrates. Crato, Ceara, Brazil, 2023.

Substrates	Dry Biomass (mg)			
	LDB	SDB	RDB	TDB
S1	6.81 ± 1.27 a	5.19 ± 1.72 a	5.11 ± 1.91 a	10.01 ± 2.65 a
S2	7.51 ± 1.60 a	5.80 ± 0.84 a	6.44 ± 1.13 a	11.48 ± 2.01 a
S3	7.57 ± 1.09 a	5.97 ± 1.08 a	5.37 ± 1.25 a	11.04 ± 1.90 a
S4	9.01 ± 0.68 a	7.59 ± 1.09 a	5.94 ± 0.75 a	13.20 ± 1.38 a
S5	6.88 ± 0.90 a	5.68 ± 0,95 a	4.51 ± 1.49 a	10.03 ± 1.78 a
CV (%)	16.01	21.33	26.04	19.10
MSD (5%)	2.72	2.90	3.21	4.80

The raw data for DB underwent square root transformation [SQRT(X)]. Averages followed by the same lowercase letters in the column do not significantly differ from each other according to Tukey's test (p < 0.05). Abbreviations: LDB → leaf dry biomass, SDB → stem dry biomass, RDB → root dry biomass, TDB → total dry biomass. The data represent means from four biological replicates (±standard deviation).

No significant differences were identified in terms of dry biomass values for the various parts of the seedlings or their sum (Table 2).

3. Discussion

In a vigor test on Mulungu (*Erythrina velutina*), Guedes et al. [40] argued that high germination percentages achieved under highly favorable conditions allow tested seeds to express their maximum potential for producing normal seedlings. In this study, the vigor level was notably achieved, especially in the substrate based on commercial material (SBC) at 100%, thereby demonstrating its efficacy in the field germination process of hybrid cherry tomatoes, without the controlled conditions established in the laboratory, such as temperature, light, substrate, and humidity maintenance. It is crucial to emphasize that this study conducted an emergence test rather than a germination test. Field conditions, as noted by Silveira et al. [41], provide a better context for interpreting obtained data, as they subject seeds to the climate conditions of the natural environment.

Regarding the data presented in Figure 3A concerning the average germination time, the utilization of a 1/3 mixture of HDM (earthworm humus) with SBC (commercial substrate) did not exhibit any significant difference compared to using SBC alone concerning the average germination time. This suggests that using a 1/3 HDM + SBC mixture may potentially reduce the costs of producing hybrid cherry tomato seedlings while maintaining the efficiency of pure SBC.

In a study conducted by Lima et al. [42], which examined substrates including S1 (soil), S2 (soil + bovine manure (BM) 1:1), S3 (soil + organic compost (OC) 1:1), S4 (soil + humus (HM) 1:1), and S5 (soil + BM + OC + HM, 1:1:1:1), all substrates demonstrated favorable average emergence, indicating their suitability for cherry tomato seed emergence, particularly due to attributes such as porosity and sterility. Porosity facilitates water and air movement, aiding seed emergence, while sterility inhibits the action of microorganisms that may induce plant abnormalities. Ultrasound is a promising green physical treatment technology in the food industry and can be an effective tool to improve seed germination such as: increasing germination speed, improving vigor, increasing germination percentage, facilitating dormancy breaking, and acting positively on the development of seedlings [43]. According to the authors, the best emergence speed indices were observed in S2, S4, and S5, highlighting the organic matter's presence in these substrates, akin to the results in our study, where S2 (SBC) and S4 (HDM + SBC at a 1:3 ratio) displayed favorable emergence speed performances. It is noteworthy that seedlings in the substrates S2 and S4 exhibited superior morphological quality until Day 27 of transplantation, indicating their capacity to withstand extended periods, up to Day 35, while maintaining vigor.

Miranda et al. [44] analyzed the effects of different substrates on the germination of *Mimosa caesalpiniifolia Benth*, commonly known as "sabiá" or "sanção-do-campo", and found that substrates based on subsoil and bovine manure yielded the highest germination percentages. Additionally, substrates based on subsoil with caprine/ovine manure (T2) and subsoil with bovine manure (T3) demonstrated the best rates of emergence velocity. These findings align with our study, as the substrates used here contained a high organic matter content, with humus produced from the composting of bovine manure + guinea grass (3:1), subsequently used as earthworm food in Minhobuckets kits, eventually transforming into worm humus.

In vigor tests with tomato seeds, specifically seedling emergence, carried out by Barros et al. [45], in which they used a mixture of earth and sand in a 1:1 ratio, of the many studied, none exceeded the average of 100 seedlings (50% germination per lot) on the fourteenth day. In contrast, in this study, seedling emergence reached nearly 100% in 12 days, indicating the quality of the substrate used and confirming a germination percentage higher than that stated on the label (97%) and a purity percentage of 100%. It is worth noting that the seed importer Isla [15] of Wanda hybrid cherry tomato seeds states that germination begins on the fifth day; but, in the SBC, germination started on the fourth day and finished on the twelfth day, two days earlier than the estimation of the company. This indicates that the materials used were effective in this research, as Teixeira et al. [46] state that seed vigor is often evaluated with the first count, confirming the high vigor of the seeds used. They also affirm that efficient seedling establishment requires rapid and uniform germination, especially under adverse environmental conditions.

The formation of seedlings from seeds involves successive ordered metabolic and physiological events, influenced by intrinsic and extrinsic factors, such as temperature and light [46,47].

Regarding temperature, according to the Isla company [15], the seeds can tolerate temperature variations between 16 °C and 41 °C, with an optimal range of 21–35 °C, and the considered optimal temperature is 35 °C. The temperatures recorded during the experiment in the nursery aligned with the optimal recommendation, ranging from 23.2 °C at 9:00 a.m. to 31.5 °C at 12:00 p.m. These conditions are consistent with the ideal temperature range for the vegetative growth of tomato plants, which, according to Melo et al. [48] is between 21 and 24 °C. These findings suggest that the temperature conditions during the experiment were conducive to cherry tomato seedling growth.

Inadequate temperatures can adversely affect various physiological functions. For instance, they can damage cell membranes, leading to a slowdown in seed germination. Therefore, temperature can become a limiting factor for plant productivity [49,50].

Hubert and Minuzzi [51] expound that there is a temporal lag for soil to heat up or cool down under conditions of coverage, such as those in greenhouse plantations. This mitigates direct solar radiation and delays temperature fluctuations. Consequently, the internal temperatures, i.e., those within the seedling greenhouse, consistently lag behind in cooling down, as evidenced by the significant temperature increases recorded at 9 a.m., 12 p.m., and 2 p.m. during the day, corroborating the accumulation of this temporal lag. The greenhouse structure retains internal temperatures, making temperature reduction challenging.

Concerning stem diameter or collar diameter, despite the lack of significant differences in the variance analysis, the substrate predominantly composed of pure humus exhibited seedlings with larger diameters. This may be attributed to the possibility that, over the 27-day observation period, the pure humus substrate potentially offered superior quality in terms of the effects observed throughout the entire analysis period. Nonetheless, it is imperative to underscore that the substrates S2 and S4 yielded seedlings with a superior visual morphological quality. These findings surpass those reported by Lima et al. [42], as the stem diameter in trays with 200 cells did not exceed 2 mm in their study, while in our research, the smallest diameter measured 2.51 mm. Miranda et al. [44], highlight that the evaluation timing for the stem diameter variable exerts a predominant influence, as the measurement may not have reached its peak, resulting in lower diameter measurements in their research.

According to Melo et al. [52], in forest seedlings, quality assessment is based on morphological parameters such as stem diameter and height. Ritchie et al. [53] also assert that stem diameter is the primary indicator of seedling survival, and this argument is also applicable to forest seedlings. Consequently, for the successful establishment of cherry tomato plantings, data pertaining to stem diameter during seedling development can substantially influence seedling establishment during final planting, both in containers and in the soil.

Other parameters are important in assessing seedling quality, as a single parameter is insufficient [52]. Concerning plant height, a parameter displaying significant differences in the mean according to the variance analysis in the substrate comprised of HDM + SBC (1:3) (Table 1), the greatest height demonstrated was 19.19 cm. The results of our research indicate that, in all studied substrates, plant heights exceeded those reported by Lima et al. [42], where the height did not surpass 8.1 cm in trays with 200 cells, even with a substrate composed of soil + BM + OC + HM (1:1; 1:1). Our findings suggest that the substrate S4—HDM + SBC (1:1) facilitated superior seedling growth. Miranda et al. [44], concerning Sabiá tree height, reported that the substrates that contained some degree of animal manure led to better seedling development, although there were no significant differences between the studied averages.

In a study by Borges and Mendonça [36], the substrate predominantly composed of vermiculite resulted in a greater plant height compared to other substrates tested, including Plantmax®, grass straw, and bovine manure. However, the average values of these substrates did not differ significantly from each other, contrasting with our research findings.

Medeiros et al. [54], in a study using substrates comprising Plantmax®, organic compost, and washed sand, noted that cherry tomato seedlings cv. *Samambaia* exhibited a greater height in the substrate based on organic compost. This substrate yielded similar results to washed sand, while the commercial substrate resulted in significantly smaller tomato seedling heights compared to the former two substrates. Nevertheless, the results presented by these authors did not surpass those observed in this study. Notably, the study utilizing organic compost even outperformed the results achieved with the substrate consisting of 50% HDM and 50% SBC.

Santos et al. [38] presented data on the cherry tomato aerial part length lower than the measurements in our study, even when employing commercial substrates such as Top Garden®, Bioplant®, and Top Strato®. The best results in their study were obtained with Bioplant®, with an average aerial part length of 6.57 cm, falling short of the results in our study with SBC Vivatto Slim Plus®, where the aerial part length or plant height reached 13.56 cm. The substrates employed in our research consistently surpassed the results presented by Santos et al. [55], who, despite using commercial substrates combined with carbonized rice husk, achieved superior outcomes only with T1—PlantHort® I + 50% CAC, which yielded an average plant height of 9.0 cm. All of the previously mentioned results remained below those reported in our study. Despite their data collection occurring after 24 days, the plant height data in our study still exceeded their findings.

Root length and the number of leaves were variables that displayed no significant differences among the mean values. However, the substrate configured as S5—HDM + SBC (3:1) exhibited the shortest root size, while the substrates S1, S2, and S3 yielded the highest performance, all at approximately 9.2 mm. In a study by Carballo-Méndez et al. [56], evaluating the electrical conductivity of the nutrient solution and its effects on the survival and growth of pepper and tomato cuttings, tomato root length was reported at 5.62 cm with an electrical conductivity of 0.92 dSm^{-1}. No differences in rooting were observed under conditions of higher electrical conductivity compared to lower electrical conductivities. This may suggest that the substrate primarily composed of pure humus facilitated comprehensive rooting. Nevertheless, further investigation into the electrical conductivity of worm humus is required for a more precise inference.

The number of definitive leaves in our study averaged four per seedling, exceeding the findings of Carballo-Méndez et al. [56], who reported an average of 2.49 leaves at high electrical conductivity levels. This also surpassed the data presented by Lima et al. [42], where, using trays with 200 cells, the number of leaves for the substrates S3 (soil + OC) and S5 (soil + BM + OC + HM) reached a maximum average of three leaves per unit. Hence, the substrates employed in our research collectively contributed to a greater number of leaves per cherry tomato plant.

Regarding dry biomass variables, none of the responses exhibited significant effects. Nevertheless, it can be inferred that the dry mass of leaves was higher in S4 and lower in S1 (Figure 4). This trend was also observed for stem dry mass and total dry mass. Concerning root dry mass, S2 displayed the highest value, while S5 exhibited the lowest value. It is essential to highlight that the data underwent square root transformation, and the actual values of the total dry mass in S4 were 175.6375 mg, considerably lower than those reported by Lima et al. [42].

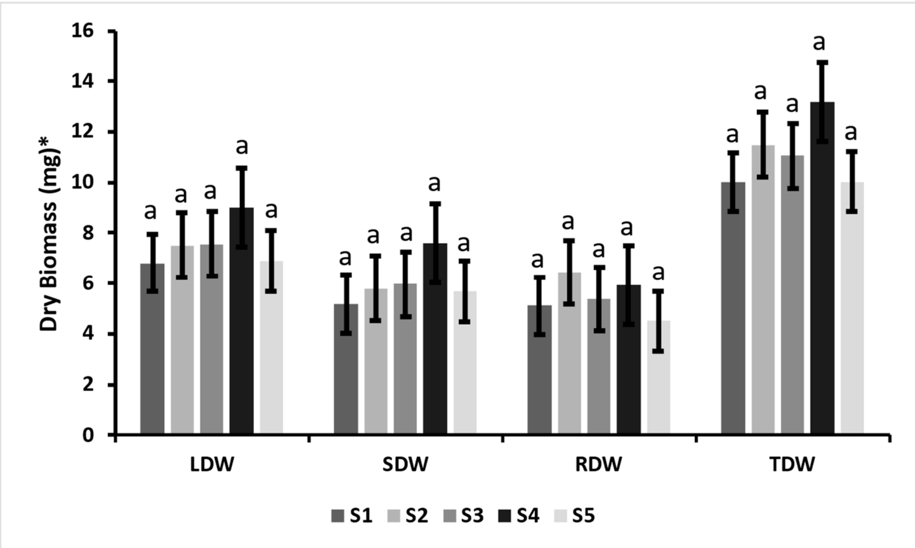


Figure 4. Biomass accumulation of tomato seedlings propagated from seeds with different substrates. LDW: leaf dry weight, SDW: stem dry weight, RDW: root dry weight, TDW: total dry weight. Each bar represents the mean ± standard error. In the same column, bars labeled with identical letters indicate no significant difference according to Tukey's test at a 5% significance level. The data underwent square root transformation. * Material subjected to a temperature of 65 °C to obtain dry mass and measured on a precision scale.

4. Materials and Methods

4.1. Experimental Location

The experiment transpired within a screened agricultural nursery boasting a wooden structure measuring 6.17 × 13.45 × 3.05 m. This nursery features half masonry walls and is enveloped by a black monofilament mesh set at a 45° angle, providing 50% shade. It is strategically situated at the Department of Research, Extension, and Production (DREP) of the Federal Institute of Education, Science, and Technology of Ceará (IFCE)—Campus Crato. This institution is located in the municipality of Crato (CE), positioned in the southern region of Ceará, nestled within the Cariri microregion.

The geographical coordinates of the municipality of Crato, Ceara, Brazil, are as follows: an altitude of 442 m, a south latitude of 7°14′03″, and a Greenwich west longitude of 39°24′34″. In accordance with Koeppen's classification [57], the climate in this region is characterized as hot tropical semi-arid and hot tropical sub-humid (BSh). The average annual temperature ranges from 24 °C to 26 °C, with an annual rainfall of 1091.0 mm, primarily concentrated between January and May (IPECE, 2023). In 2022, the annual precipitation reached 1327.0 mm (FUNCEME, 2023). The experimental period spanned from 9 August to 8 September 2022, encompassing a duration of 30 days. Meteorological data recorded at the Official Agrometeorological Station during the experiment are detailed in Table 3.

Table 3. Average monthly values of temperature, relative humidity (RH %), atmospheric pressure (Pa), and monthly precipitation during the experiment.

Months 2022	Temperature (°C)			Relative Humidity (%)			Atmospheric Pressure (atm)			Precipitation
	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	(mm)
August	23.3	33.1	15.9	66	96	27	953.64	958.06	949.87	10.6
September	24.8	34.6	16.7	30	96	24	952.48	958.04	946.78	6.4

Avg: average temperature, humidity, atmospheric pressure. Max: maximum temperature, humidity, atmospheric pressure. Min: minimum temperature. humidity, atmospheric pressure Source: Agrometeorological Station of FUNCEME/IFCE [58] ID: 35853 Location: Longitude: −39.4436, Latitude: −7.2122.

4.2. Experimental Design and Procedures

The experiment was executed utilizing a completely randomized design, encompassing five fertilizer doses based on SBC (commercial substrate), earthworm humus (HDM), and their blends, each with four replicates. Each experimental unit comprised a single seed, resulting in 25 seeds per replication (see Table 4) [59].

Table 4. Description of the composition of treatments and materials used.

	Composition	Proportions	Repetitions
T1	Earthworm Humus—HDM Analysis		4
T2	Commercial Substrate—SBC Control		4
T3	Earthworm Humus—HDM + Commercial Substrate—SBC	1:1	4
T4	Earthworm Humus—HDM + Commercial Substrate—SBC	1:3	4
T5	Earthworm Humus—HDM + Commercial Substrate—SBC	3:1	4
		Total	20

T1—S1, T2—S2, T3—S3, T4—S4, and T5—S5.

The seeds employed in the study were sourced from the Wanda hybrid indeterminate cherry tomato (mini-tomato) cultivar, Lot Number 152,040, Import 267, with a total of 500 seeds. These seeds were acquired from the e-commerce platform of the Isla company. They possess the following characteristics: perennial nature, a 90-day summer growth cycle, round-flattened shape, red skin and flesh color, and resistance to Fol:0-2 (Fusarium wilt races 1, 2, and 3), TMV (tobacco mosaic virus), TSWV (tomato spotted wilt virus), and Vd (Verticillium wilt dahliae).

The tomato plant exhibits indeterminate growth, and its fruits weigh between 15 and 20 g. These seeds are certified in accordance with Law 10,711/03, which established the National System of Seeds and Seedlings, and regulated by Decree 5153/04.

The commercial substrate (SBC) employed was Vivatto Slim Plus®, manufactured by Technes Agricola Limited Liability Company (LLC) and procured from a local store in the city of Crato, CE. It comprises the following components: bio-stabilized pine bark, vermiculite, charcoal mill, water, phenolic foam, and additives, as delineated in Table 5.

Table 5. Minimum commercial substrate guarantees (SBC).

VIVATO SLIM Substrate	Registration Number at MAPA	Dilution 1:5 (*v/v*)		(m/m)		Basic Density	Additives (Mass/Mass)	
		pH	E.C.	W.H.C.	Hmd.		Fertilizer	Corrector
PLUS	SP-003662-5.000004	6.0	1.2	200%	48%	260.0 $Kg \cdot m^{-3}$	1.50%	0.20%

MAPA: Brazilian Ministry of Agriculture, Livestock, and Food Supply. E.C.: electric conductivity in $mS \cdot cm^{-1}$. W.H.C.: water holding capacity. Source: product label, Technes® 2022.

The earthworm humus (HDM) used was produced at the Vermicomposting Section of the Department of Research, Extension, and Production (DPEP) at IFCE Campus Crato. The production process involved 40 Minhobuckets kits, each containing approximately 0.6 dm^3 of *Eisenia andrei* earthworms and with a capacity of 6 L of substrate for the transformation period. The substrate employed for humus production consisted of composting a mixture of 3 parts of *P. maximum* grass (guinea grass) and 1 part of bovine manure, arranged in a trapezoidal form. Regular turning and irrigation were executed throughout the process. The characteristics of the humus are detailed in Table 6.

Table 6. Result of the physical–chemical analysis of earthworm humus (HDM).

Parameter	Method Used	R	U	Unt	Q.L.
Organic matter	IN-SDA Nº 003/2017 MAPA—Cap III—13	51.7	4.2	%	3.1
CEC	IN-SDA Nº 003/2017 MAPA—Cap III—13	1000	50	mmol/Kg	5
Fulvic acids (Organic C)	Embrapa (2017)	1	-	%	0.1
Humic acids (Organic C)	Embrapa (2017)	1.04	-	%	0.1

Source: Adapted from Campo—Center for Agricultural and Environmental Technology, 2022. CEC: cation exchange capacity. R: result. U: uncertainty. Unt: unit. Q.L.: quantitative limit (a limit that the equipment reads).

For the experiment, disposable thermoformed plastic trays (polypropylene) with 200 cells and a capacity of 18 cm^3 (31.0 mm length × 31.0 mm width, external dimensions h = 43 mm × L = 335 mm × W = 664 mm; distance between seedlings of 33.0 mm) were employed. These trays were non-toxic and recyclable, having undergone sterilization by washing with a 10% bleach solution, followed by complete drying in the shade for two days.

Subsequent to a two-day resting period in the shade, the trays were placed on a workbench to be filled with the respective substrates, as outlined in Table 4 on the preceding page. The substrates were arranged in a completely randomized design, as depicted in Figure 5, and the seeds were subsequently sown. Seedbeds were fashioned for the seed-sowing process, ensuring uniform depth and width in each cell to promote even germination and emergence. An atomic brush bottom was employed to achieve this uniformity.

Following seed sowing, the trays were stored in a closed environment and covered with plastic sheets to maintain total darkness. This two-day protection phase marked the transition from seed dormancy to the initiation of plant growth, following the model defined by Bewley [60] and Antonio and Almeida [35]. It facilitated the complete emergence of the radicle and encompassed distinct phases characterized by rapid water absorption by the seeds (Phase I—first 6 h), the activation of metabolic processes required for embryo growth (Phase II—between 6 and 49 h), and finally, the onset of embryo growth (Phase III—after 48 h) [60].

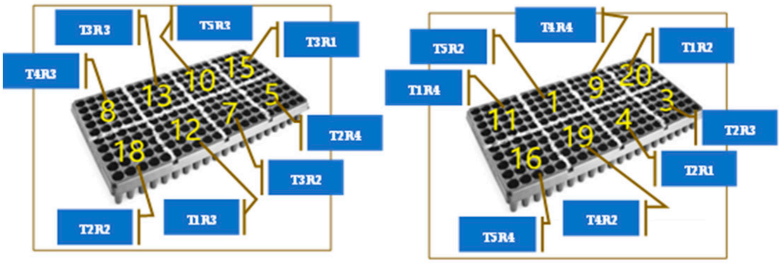


Figure 5. Detail of the draw on the trays.

Water was provided to the trays after sowing at a conductivity of 0.82 dS/m, as it is a critical factor for germination and emergence. Care was taken to avoid excessive watering, which could lead to the formation of a water film around the seeds, impeding aeration and germination [61]. After 48 h, the trays were transferred to the local nursery and placed on a support structure 60 cm above ground level to facilitate handling and encourage natural root pruning by the wind. Manual watering was conducted daily (300 to 500 mL/watering), 3 to 4 times per day. The volume of water increased by 200 mL every 8 days, ultimately reaching over 1 L of water in the final 8 days, close to transplanting.

Sowing took place on 11 August 2022. The assessment of the number of emerged seedlings commenced four days after sowing (DAS) and concluded at 15 DAS when the counts stabilized. The counting phase ended when one of the treatments reached stabilization, which occurred at 15 DAS. At this stage, the emergence rate index (ERI), percentage of emergence (PE), and mean emergence time (MET) were evaluated. Only seedlings with open cotyledons were considered emerged seedlings for counting purposes [61].

At 27 DAS, the seedlings were harvested intact, and the following measurements were recorded: plant height in centimeters (PH), stem diameter in millimeters (SD), root length in millimeters (ROOTL), number of leaves, dry biomass of the leaves (DBL), stems (DBS), and root system (DBR), as well as the total dry mass (TDM = DBL + DBS + DBR). Plant material was dried in a forced-air oven at 65 °C until reaching a constant mass. An analytical digital balance with a precision of one-thousandth of a gram was employed for weighing, while lengths were measured using a digital caliper with a precision of one-hundredth of a millimeter and a millimeter ruler.

Throughout the evaluation period, temperatures (°C) and relative humidity (%) were measured daily at 9 a.m., 12 p.m., 2 p.m., and 5 p.m., internally near the trays, using a Model BT-2 thermometer. Additionally, external measurements were obtained from the Agrometeorological Station of Funceme (Cearense Foundation of Meteorology and Water Resources), as illustrated in Figure 6A,B.

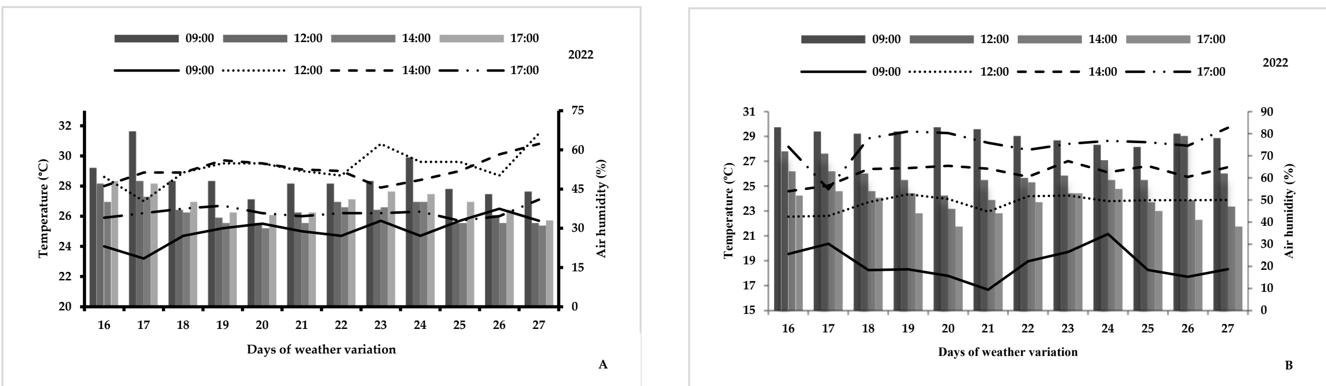


Figure 6. (**A**) Climate variation in a greenhouse. Source: Compiled by the authors (2023). (**B**) Climatic variation outside the greenhouse. Adapted from the Agrometeorological Station of Funceme, 2022.

The global solar radiation during the period, according to LABREN [62], was 22.0 MJm^{-2}/day (ID 44866 from the National Institute of Meteorology—INMET).

The assessment of emergence was performed daily after sowing. The percentage of emergence (E) for each replication was calculated using the formula:

$E = (N/4) \times 100$, where N = the number of germinated seeds in the plot.

The seed emergence speed index (ESI) was calculated using the formula:

$$ESI = \frac{E_1}{N_1} + \frac{E_2}{N_2} + \ldots + \frac{E_n}{N_n}$$

where:

ESI = emergence speed index;

N = number of normal seedlings verified on the day of counting;

D = number of days after sowing in which the count was performed.

The average seedling emergence time (AET) was computed based on the number of germinated seeds in each evaluation, multiplied by the respective time, and then divided by the total number of germinated seeds at the end of the test.

Seeds presenting radicle protrusion (visible germination) were regarded as germinated [63,64], and daily counts were conducted from the onset of germination to calculate the percentage of emergence, germination speed index, and average time of seedling emergence [65].

The data were subjected to individual analyses of variance for the substrates using Sisvar 5.8 software [66–68]. A comparison of means was performed using Tukey's test ($p <$ 0.05). Data that did not meet the normality test (Shapiro–Wilk) and the homogeneity test (Bartlett's, Levene's, or Fligner–Killenn) underwent square root transformation [sqrt(x)] for variance analysis. To carry out the normality and homogeneity tests, the functions shapiro.test, fligner.test, leveneTest, and the library (dplyr) packages were utilized, along with the library (RVAideMemoire), library (car), library (psych), library (rstatix), and library (DescTools) in RStudio Software: Version 2023.06.1 [69].

5. Conclusions

The commercial substrate (SBC) exhibited a remarkable performance, particularly in the emergence speed index, emphasizing its effectiveness in promoting prompt seed germination, regardless of seed quality.

Regarding morphological parameters and dry biomass, all substrates delivered satisfactory results, with no statistically significant differences observed among the averages.

Notably, the substrate S4 [HDM + SBC (1:3)] produced the most favorable outcomes across all assessed parameters. This suggests that a potential blend of substrates can enhance seedling emergence and quality while potentially reducing costs compared to commercially available substrates.

Seedlings originating from the substrates S2 and S4 displayed a superior morphological quality up to the 27th day post-transplant, with indications of continued support for up to 35 days with similar efficacy.

Further research, involving seeds of lower quality and in larger quantities, is needed to assess the efficiency of these substrates.

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Abbreviations

HDM	earthworm humus (EH)
SBC	commercial substrate (CS)
H	height
W	width
L	length
DAS	days after sowing
ESI	emergence speed index
PE	percentage of emergence
AET	average emergence time
PH	plant height
SD	stem diameter
ROOTL	root system
GSI	Germination Speed Index

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