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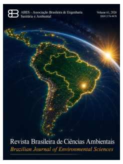

Sustainable use of bottle gourd residue combined with vermicompost and vermiculite in lettuce production

Uso sustentável do resíduo de porongo associado a vermicomposto e vermiculita na produção de alface

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ABSTRACT

The use of agro-industrial residues as agricultural inputs represents a sustainable alternative to reduce environmental impacts and promote circular economy. We evaluated the potential of bottle gourd (*Lagenaria siceraria* (Molina) Standl) residue at different proportions and particle sizes, combined with vermicompost and vermiculite, as a component of substrates for lettuce (*Lactuca sativa* L.) cv. Veneranda seedling and plant production. Two greenhouse experiments were conducted to compare the substrates containing bottle gourd residue, vermiculite, vermicompost, and a commercial substrate. One experiment evaluated seedling production and the other evaluated lettuce production. In both experiments, treatment T7 (20% bottle gourd residue, 0.5 cm particle size + 80% vermicompost) resulted in superior plant growth and better root ball stability. From an environmental perspective, considering the bulk density of bottle gourd residue (0.24 g cm^{-3}), incorporation reached 30–120 g per pot (2.5 L) and up to 48 kg m^{-3} of substrate, partially replacing conventional inputs with high energy demand such as vermiculite, perlite, and pine bark. These indicators highlight the potential of residue reuse to reduce waste, mitigate greenhouse gas emissions, and promote more resilient agricultural systems. Therefore, bottle gourd residue emerges as an environmentally sound and agronomically efficient alternative, aligned with the Sustainable Development Goals (SDGs 12 and 13).

Keywords: agricultural residue; environmental sustainability; *Lactuca sativa* L.; substrate; *Lagenaria siceraria* (Molina) Standl.

RESUMO

O uso de resíduos agroindustriais como insumo agrícola representa uma alternativa sustentável para reduzir impactos ambientais e promover a economia circular. Este trabalho avaliou o potencial do resíduo de porongo (*Lagenaria siceraria* [Molina] Standl), em diferentes proporções e granulometrias, associado ao vermicomposto e vermiculita, na composição de substratos para a produção de mudas e plantas de alface (*Lactuca sativa* L.) da cultivar Veneranda. Foram conduzidos dois experimentos em casa de vegetação: (I) produção de mudas e (II) produção de alface, comparando-se tratamentos contendo resíduo de porongo, vermiculita, vermicomposto e substrato comercial. Em ambos os experimentos, os resultados demonstraram que o tratamento T7 (20% porongo 0,5 cm + 80% vermicomposto) apresentou desempenho superior ao substrato comercial em crescimento vegetal e estabilidade do torrão. Do ponto de vista ambiental, considerando-se a densidade do resíduo de porongo (0,24 g cm^{-3}), a incorporação equivaleu a 30–120 g por vaso (2,5 L) e até 48 kg m^{-3} de substrato, substituindo parcialmente insumos convencionais de elevado custo energético, como vermiculita, perlita e casca de pinus. Esses indicadores reforçam o potencial do reaproveitamento de resíduos para reduzir descartes, mitigar emissões de gases de efeito estufa e promover sistemas agrícolas mais resilientes. Assim, o resíduo de porongo apresenta-se como alternativa ambientalmente viável e agronomicamente eficiente, alinhada aos Objetivos de Desenvolvimento Sustentável (ODS 12 e 13).

Palavras-chave: resíduo agrícola; sustentabilidade ambiental; *Lactuca sativa* L.; economia circular; *Lagenaria siceraria* (Molina) Standl.

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Introduction

Waste management is a global challenge that contributes to environmental contamination, greenhouse gas emissions, and inefficient resource use (Silva et al., 2021; Rashwan et al., 2023; Nascimento et al., 2024). Although global post-harvest agricultural waste production reaches billions of tons (Sileshi et al., 2025), most of it is underutilized, highlighting the need for strategies that integrate agricultural production and environmental management within the framework of a circular economy more urgently (Silva et al., 2021; Oliveira et al., 2023; Xu et al., 2023; Bhatia and Sindhu, 2024; Sileshi et al., 2025).

Reusing residues from established production chains is a promising approach. Bottle Gourd (*Lagenaria siceraria* (Molina) Standl.) stands out for generating solid waste with potential applications in the formulation of agricultural substrates, replacing high-cost and non-renewable materials (Steffen et al., 2023). Bottle gourd is a widely cultivated species with multiple traditional uses (Saeed et al., 2022; Zaatout et al., 2023; Brdar-Jokanović et al., 2024), especially in Rio Grande do Sul (Brazil), where it is used to manufacture chimarrão gourds (Bisognin et al., 1992; Cancelier and David, 2020). However, in this chain, only the upper portion of the fruit is used, resulting in the disposal of approximately 50–80% of its biomass, usually in the open air (Wacht et al., 2024), constituting a regional environmental liability.

This residue may be suitable as a structural component in plant substrates. These substrates require materials that ensure water and nutrient availability, aeration, and root support. Examples include vermiculite, perlite, and pine bark, which are commonly used for their lightness, stability, and macroporosity (Mariotti et al., 2023; Dzięcioł and Szlachetka, 2024). However, vermiculite and perlite depend on energy-intensive processes that are costly and have a significant environmental impact, whereas pine bark and other wood fiber-based substrates can cause temporary nitrogen immobilization and require additional processing to ensure substrate uniformity (Mariotti et al., 2023; Dzięcioł and Szlachetka, 2024; Wu et al., 2025). Other lignocellulosic residues have also been investigated for aeration, although excess amounts can reduce water retention capacity (Agarwal et al., 2023). Therefore, the search for viable, sustainable, and technically suitable alternatives is essential.

Bottle gourd residue has important characteristics, as it is rich in lignocellulose, has low density, rigidity, durability, and porosity similar to pine bark, resists compaction even in high humidity, decomposes slowly, and ensures structural stability in substrates (Steffen et al., 2023; Wacht et al., 2024). The incorporation of this residue into the substrate composition is technically feasible, economically attractive, and environmentally sustainable, promoting the recycling of an agro-industrial liability and integrating agricultural production and waste management.

Some organic agro-industrial waste is reused through vermicomposting, a low-cost and sustainable process that transforms waste into agricultural inputs rich in macro- and micronutrients, improving soil fertility and structure (Sakthivel et al., 2022; Xu et al., 2023). In addition to reducing environmental impacts, this practice can generate new sources of income for family farmers, aligning with the principles of the circular economy and the UN Sustainable Development Goals (SDGs).

In this context, this study transcends the agronomic validation of a substrate, proposing an interdisciplinary approach that integrates agro-industrial waste management with the sustainability of production systems. Therefore, understanding the potential of using bottle gourd residue in substrate formulation, replacing pine bark, vermiculite, and perlite, especially when associated with vermicompost, represents a promising strategy for reconciling agricultural productivity and mitigating environmental impacts. This study aimed to evaluate, from an environmental and agronomic perspective, whether bottle gourd residue combined with vermicompost favors the production of seedlings and lettuce plants of the Veneranda cultivar.

Materials and Methods

This study consisted of two experiments conducted in a greenhouse. The bottle gourd residue used to compose the substrates was collected from a private rural property located in the district of Arroio do Só, Santa Maria (RS). These residues were spread on a plastic sheet and subsequently crushed by five passes of a tractor wheel (Massey Ferguson 297 Advanced). After this stage, the residues were crushed in a Forge Crusher (IBL Industrial Busse Ltda, model C1F-M), obtaining two distinct particle sizes, 0.5 (residues ranging from 0 to 0.5 cm) and 1.0 cm (residues from 0.5 to 1.0 cm) in diameter (Figure 1), suitable for substrate composition (Steffen et al., 2023). The shredded materials were then sieved and separated into the desired diameters for later use in the experiments.

Experiment 1 evaluated the use of the Veneranda cultivar in the production of lettuce seedlings. It was conducted over a period of 28 days using a randomized design (CRD), with repeated measurements performed on the same experimental units at 14, 21, and 28 days after emergence (DAE). The experiment consisted of 11 treatments with 10 replicates, evaluated three times (14, 21, and 28 days after emergence [DAE]), totaling 330 experimental units. The treatments were as follows:

- T1) 100% commercial substrate (CM);
- T2) 5% 1 cm bottle gourd residue + 95% vermicompost (Gr5G1V95);
- T3) 10% 1 cm bottle gourd residue + 90% vermicompost (Gr10G1V90); T4) 20% 1 cm bottle gourd residue + 80% vermicompost (Gr20G1V80);
- T5) 5% 0.5 cm bottle gourd residue + 95% vermicompost (Gr5G05V95);
- T6) 10% 0.5 cm bottle gourd residue + 90% vermicompost (Gr10G05V90);

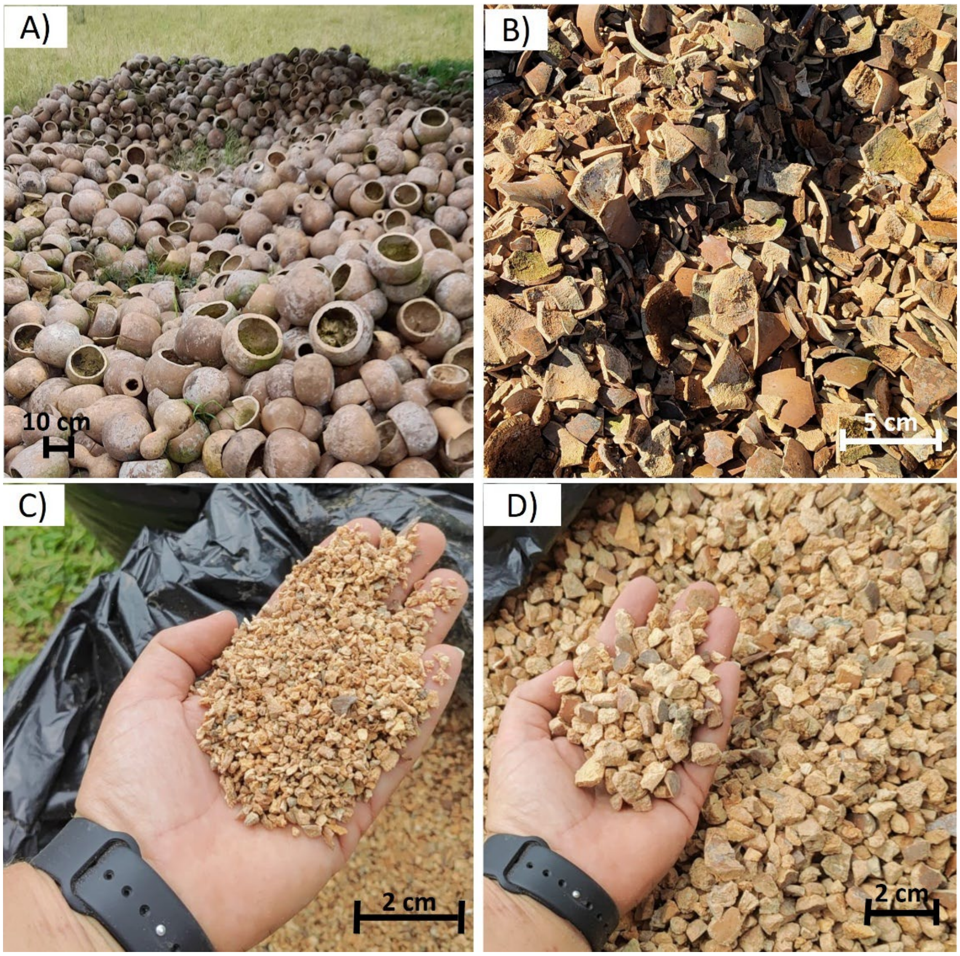

Figure 1 – Characterization of bottle gourd residue: (A) bottle gourd residue generated by the manufacture of bottle gourds; (B) bottle gourd residue broken by tractor; (C) bottle gourd residue with a particle size of 0.5 cm; (D) bottle gourd residue with a particle size of 1.0 cm.

- T7) 20% 0.5 cm bottle gourd residue + 80% vermicompost (Gr20G05V80);
- T8) 5% vermiculite + 95% vermicompost (Ve5V95);
- T9) 10% vermiculite + 90% vermicompost (Ve10V90);
- T10) 20% vermiculite + 80% vermicompost (Ve20V80);
- T11) 100% vermicompost (V).

Three seeds were used per experimental unit, planted at a depth of 0.5 cm in plastic trays with 128 cells containing the treatments. Seven days after emergence, thinning was performed to maintain a single seedling per cell. During the experiment, the cells were manually and periodically irrigated with water, as required to maintain substrate moisture. The average temperature was 25.37°C, and the relative humidity was 70%. These parameters were monitored daily using a thermo-hygrometer.

Fresh mass production of the shoots (SFM) and roots (RFM), number of leaves (NL), seedling height (SH), root length (RL), root adhesion to the substrate (RAS), and chlorophyll content (SPAD) were evaluated 14, 21 and 28 days after emergence (DAE). At the beginning and end of the experiment, physical and chemical parameters were determined for the substrates, according to the methodology recommended by César et al. (2017). The chemical analysis of the vermicompost indicated the following composition: water pH (1:1) 6.5; Ca (cmol_c dm^{-3}) 7.3; Mg (cmol_c dm^{-3}) 5.5; Al (cmol_c dm^{-3}) 0.0; H+Al (cmol_c dm^{-3}) 1.7; CTC eff. (cmol_c dm^{-3}) 18.6; CTC pH 7.0 (cmol_c dm^{-3}) 20.3; V% 91.5; SMP index 6.8; OM % (m m^{-1}) 12.5; Clay % (m m^{-1}) 5.0; Texture 4.0; S (mg dm^{-3}) 56.3; P (Mehlich-1) (mg dm^{-3}) 299.3; K (mg dm^{-3}) 2248.0; Cu (mg dm^{-3}) 1.74; Zn (mg dm^{-3}) 24.32; B (mg dm^{-3}) 1.27.

The bottle gourd residues were analyzed for mineral composition at the Laboratório de Química da Madeira (LAQUIM - UFSM), with the following composition: P (g kg^{-1}) 1.43; K (g kg^{-1}) 10.95; Ca (g kg^{-1}) 2.73; Mg (g kg^{-1}) 1.46; S (g kg^{-1}) 0.56; Cu (mg kg^{-1}) 7.77; Fe (mg kg^{-1}) 706.59; Mn (mg kg^{-1}) 35.17; and Zn (mg kg^{-1}) 25.74.

To assess the stability of the root ball, a scoring scale was adapted from Jiang et al. (2017), based on visual observation of the cohesion of the root ball when removing the seedling from the container. Scores were assigned according to the following criteria:

- 1: when 50% or more of the root ball remained in the container during seedling removal;
- 3: when 30% - 50% of the root ball remained retained;
- 5: when the root ball detached from the container but did not maintain its cohesion;
- 7: when the root ball was completely removed from the container, maintaining more than 90% of its cohesive structure (Figure 2).

Experiment II aimed to evaluate lettuce production and was conducted for 34 days after transplanting. The experiment followed a completely randomized design (CRD) with 11 treatments, as described in Experiment I, and seven replicates, totaling 77 experimental units. A lower number of replicates was used in comparison to Experiment I as the objective of this experiment was lettuce production. Lettuce seeds of the curly-leaf cultivar Veneranda were sown in plastic trays containing commercial substrate. Seedlings were transplanted 23 days after emergence into 2.8-L pots, each filled with 2.5 L of substrate according to the respective treatment, with one seedling per pot. During the experiment, irrigation was performed manually and periodically to maintain adequate substrate moisture. The average temperature was 18.5°C and the relative air humidity was 77%, both monitored daily. At the end of the crop cycle, the following variables were evaluated: number of leaves (NL), plant height (PH), chlorophyll content (SPAD), root length (RL), shoot fresh and dry mass (SFM and SDM), and root fresh and dry mass (RFM and RDM).

Data obtained from Experiments I and II were subjected to analysis of variance (ANOVA), and means were compared using the Scott–Knott test at the 5% probability level, using SISVAR statistical software (Ferreira, 2019).

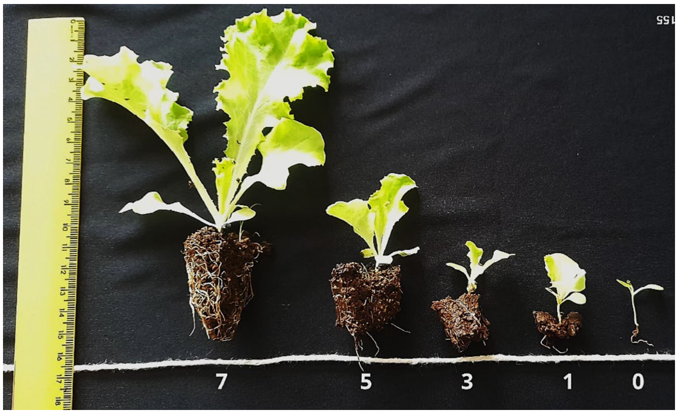

Figure 2 – Visual scale used to assess root ball stability in lettuce seedlings. 0: Bare root, with no adhering substrate; 1: when 50% or more of the root ball remained in the container during removal; 3: when 30–50% of the root ball remained in the container; 5: The root ball was detached from the container but did not maintain its cohesion; 7: The root ball was completely removed from the container, maintaining more than 90% of its cohesive structure.

Results and Discussion

Production of lettuce seedlings: Experiment I

Substrate composition influenced the initial growth dynamics of the lettuce seedlings throughout the evaluation period. Fourteen days after sowing, treatment T7 (Gr20G05V80) did not differ from the commercial control T1 (CM) in terms of number of leaves (NL), SPAD index, SFM, RFM, and root ball stability (Table 1). At 21 days, T7 (Gr20G05V80) remained statistically equivalent to the control in terms of the number of leaves and root length but stood out with higher means for fresh root mass. This behavior is consistent with the physiological pattern of the crop, characterized by slower initial growth, focusing on structural stabilization, hormonal regulation, and root formation, preceding the development phase from that period onwards (Piro et al., 2023).

This acceleration became evident at 28 days, when T7 (Gr20G05V80) surpassed the commercial substrate in most variables, including biomass and SPAD index (Table 1). This behavior indicates that the commercial substrate could not sustain an increasing nutrient demand for nutrients after the second assessment, unlike T7 (Gr20G05V80), in which the vermicompost contributed to a continuous supply of nutrients. However, this result also indicates that higher proportions of vermicompost do not always result in greater plant growth, as nutrient absorption in physiologically limited and excess conditions can compromise seedling development (Manzoor et al., 2024). The higher SPAD index observed in this treatment reflects the availability of nutrients, mainly nitrogen, which correlates directly with biomass production and vegetative vigor (Veazie et al., 2022; Wang et al., 2024).

In addition to nutritional input, vermicompost can act through bioactive compounds formed during vermicomposting, such as humic substances and growth regulators, which stimulate physiological processes associated with the initial vigor of seedlings (Manzoor et al., 2024). Correlation analysis (Figure 3) confirmed that T7 was superior to the other alternative substrates in terms of the number of leaves, height, and root ball structure in the three seasons evaluated (Figure 4A).

Production of lettuce plants: Experiment II

In Experiment II, most treatments resulted in satisfactory development (Figure 4B). Treatment T10 (Ve20V80) had the highest mean values for height and biomass (Table 2). However, treatment T7 (Gr20G05V80) proved to be a competitive alternative, with robust agronomic performance. Regarding the SPAD index, the treatments containing bottle gourd (T2, T5, and T6) presented higher values (>11.33), consistent with the adequate range of foliar nitrogen reported in the literature for the crop (Andrade, 2019). Although vermiculite (present in T10) favored total biomass, the bottle gourd-based substrates ensured adequate nutrition and plant health until harvest (Table 2).

Table 1 – Average values at 14, 21, and 28 days after transplanting of seedlings height (SH), number of leaves (NL), root length (RL), chlorophyll index (SPAD), shoot fresh mass (SFM), and root fresh mass (RFM) of lettuce seedlings of the Veneranda cultivar under greenhouse conditions.

14 DAYS							
Treatment*	**SH (cm)**	**Nº L**	**RL (cm)**	**SPAD**	**SFM (mg)**	**RFM (mg)**	**Root Ball stability**
T1 (CM)	5.25 a	4.40 a	9.91 a	10.16 a	167.86 b	28.11 a	7 a
T2 (Gr5G1V95)	1.76 d	4.00 a	3.52 c	6.90 b	63.75 c	15.89 b	1 b
T3 (Gr10G1V90)	0.68 d	1.90 b	1.85 c	5.44 b	22.72 d	16.46 b	1 b
T4 (Gr20G1V80)	1.47 d	2.70 b	3.14 c	6.37 b	24.97 d	17.74 b	1 b
T5 (Gr5G05V95)	2.25 c	4.00 a	2.97 c	7.79 b	44.26 d	8.934 c	1 b
T6 (Gr10G05V90)	2.98 c	4.20 a	5.50 b	9.11 a	110.43 c	20.27 b	3 a
T7 (Gr20G05V80)	4.21 b	4.90 a	6.00 b	9.57 a	229.24 a	24.08 a	3 a
T8 (Ve5V95)	1.69 d	3.50 b	5.39 b	9.74 a	32.20 d	3.00 c	5 a
T9 (Ve10V90)	1.69 d	2.90 b	4.51 c	7.42 b	23.01 d	3.89 c	5 a
T10 (Ve20V80)	1.86 d	3.10 b	4.88 b	8.02 b	32.69 d	16.69 b	5 a
T11 (V)	3.01 c	4.40 a	6.11 b	10.78 a	88.3 c	13.69 b	5 a
21 DAYS							
T1 (CM)	4.65 c	5.00 a	9.28 a	8.26 a	194.51 c	52.58 b	7 a
T2 (Gr5G1V95)	1.67 d	1.70 c	3.22 c	2.71 b	114.37 d	37.36 b	3 b
T3 (Gr10G1V90)	0.00 d	0.00 d	0.00 d	0.00 b	0.00 d	0.00 c	0 c
T4 (Gr20G1V80)	0.82 d	3.10 b	1.82 c	5.70 a	14.93 d	2.60 c	0 c
T5 (Gr5G05V95)	0.28 d	0.80 d	0.00 d	3.32 b	5.91 d	0.68 c	0 c
T6 (Gr10G05V90)	1.44 d	3.70 b	1.00 d	8.77 a	59.47 d	3.35 c	0 c
T7 (Gr20G05V80)	8.62 a	5.90 a	8.72 a	11.47 a	858.63 a	127.28 a	7 a
T8 (Ve5V95)	0.52 d	3.60 b	0.00 d	7.20 a	44.25 d	3.85 c	1 b
T9 (Ve10V90)	3.81 c	5.00 a	7.02 b	9.60 a	162.17 c	48.20 b	5 a
T10 (Ve20V80)	5.94 b	5.00 a	0.00 d	8.62 a	300.73 b	107.66 a	7 a
T11 (V)	3.35 c	3.90 b	4.85 b	6.62 a	171.32 c	39.76 b	3 b
28 DAYS							
T1 (CM)	4.48 b	5.10 a	9.10 a	6.95 b	219.28 b	78.89 b	5 a
T2 (Gr5G1V95)	1.87 c	1.90 c	1.70 b	2.95 c	57.36 b	5.99 c	3 b
T3 (Gr10G1V90)	0.16 d	0.30 c	0.05 c	0.31 c	2.29 b	1.41 c	0 c
T4 (Gr20G1V80)	0.95 d	1.60 c	1.91 b	2.05 c	49.50 b	3.05 c	3 b
T5 (Gr5G05V95)	0.20 d	0.90 c	0.30 c	1.62 c	2.69 b	0.25 c	0 c
T6 (Gr10G05V90)	2.06 c	3.30 b	1.20 c	3.07 c	110.51 b	7.46 c	3 b
T7 (Gr20G05V80)	9.07 a	5.80 a	8.33 a	9.28 a	966.44 a	195.78 a	7 a
T8 (Ve5V95)	1.94 c	4.10 b	3.43 b	6.51 b	76.46 b	5.41 c	3 b
T9 (Ve10V90)	1.72 c	2.20 c	2.12 b	3.50 c	93.59 b	12.34 c	1 b
T10 (Ve20V80)	1.71 c	4.40 b	2.65 b	6.59 b	62.20 b	8.29 c	3 b
T11 (V)	0.29 d	0.70 c	0.18 c	1.24 c	4.09 b	1.47 c	0 c

Identical letters in the column correspond to averages that did not show statistical differences according to the Scott-Knott test at 5% significance; T1: 100% commercial substrate (CM); T2: 5% 1 cm bottle gourd residue + 95% vermicompost (Gr5G1V95); T3: 10% 1 cm bottle gourd residue + 90% vermicompost (Gr10G1V90); T4: 20% 1 cm bottle gourd residue + 80% vermicompost (Gr20G1V80); T5: 5% 0.5 cm bottle gourd residue + 95% vermicompost (Gr5G05V95); T6: 10% 0.5 cm bottle gourd residue + 90% vermicompost (Gr10G05V90); T7: 20% 0.5 cm bottle gourd residue + 80% vermicompost (Gr20G05V80); T8: 5% vermiculite + 95% vermicompost (Ve5V95); T9: 10% vermiculite + 90% vermicompost (Ve10V90); T10: 20% vermiculite + 80% vermicompost (Ve20V80); T11: 100% vermicompost (V).

	NL	SH	T	RL	SPAD	SFM	RFM	SDM
SH	0.77							
T	0.69	0.73						
RL	0.67	0.70	0.75					
SPAD	0.78	0.60	0.62	0.62				
SFM	0.53	0.79	0.52	0.51	0.42			
RFM	0.43	0.66	0.46	0.43	0.35	0.82		
SDM	0.37	0.17	0.15	0.16	0.35	0.10	0.10	
RDM	0.37	0.22	0.23	0.16	0.33	0.14	0.12	0.58

Figure 3 – Correlation between the traits evaluated in Experiment I.
NL: Number of leaves; SH: Seedling height; T: Root ball stability; RL: Root length; SPAD; SFM: Shoot fresh mass; RFM: Root fresh mass; SDM: shoot dry mass RDM: Root dry mass.

Figure 4 – (A) Lettuce seedlings of the Veneranda cultivar, Experiment I; (B) lettuce plants, Experiment II, in a greenhouse.
T1: 100% commercial substrate (CM); T2: 5% 1 cm bottle gourd residue + 95% vermicompost (Gr5G1V95); T3: 10% 1 cm bottle gourd residue + 90% vermicompost (Gr10G1V90); T4: 20% 1 cm bottle gourd residue + 80% vermicompost (Gr20G1V80); T5: 5% 0.5 cm bottle gourd residue + 95% vermicompost (Gr5G05V95); T6: 10% 0.5 cm bottle gourd residue + 90% vermicompost (Gr10G05V90); T7: 20% 0.5 cm bottle gourd residue + 80% vermicompost (Gr20G05V80); T8: 5% vermiculite + 95% vermicompost (Ve5V95); T9: 10% vermiculite + 90% vermicompost (Ve10V90); T10: 20% vermiculite + 80% vermicompost (Ve20V80); T11: 100% vermicompost (V).

Influence of particle size and physical properties of materials

The combined analysis of the experiment showed that the particle size of the residue and the physical interaction of the components were decisive for agronomic performance. The success of treatments T7 (particle size 0.5 cm) and T10 (vermiculite) occurred due to the balance between water retention and aeration. Vermiculite is recognized for its physical and high water retention capacity, which favored growth in Experiment II (Li et al., 2017). Similarly, bottle gourd residue with a particle size of 0.5 cm promoted efficient aeration and drainage without compromising moisture, mimicking the functions of commercial structuring agents with the added advantage of lightness and porosity, which are beneficial for root development (Ingelmo et al., 2012). Similar results have been reported for other agricultural residues used as substrate structuring agents, such as sugarcane bagasse and coconut husks, which also promote improvements in aeration, drainage, and root development (Ingelmo et al., 2012).

In contrast, treatments composed of bottle gourd residue with a particle size of 1 cm (T3 and T4) consistently performed the worst in both phases of the study (Tables 1 and 2). The presence of larger particles reduced the homogeneity of the mixture, creating excessive macropores that hindered water and nutrient retention and formed physical barriers at the root-substrate interface. This physical imbalance limited root growth and, consequently, the development of the aerial part of the plant, corroborating studies that indicate particle size as a critical factor in the efficiency of alternative substrates (Agarwal et al., 2023; Steffen et al., 2023). Therefore, the viability of using porongo requires grinding it into smaller particles (<0.5 cm).

Environmental indicators and sustainability

The agronomic validation of T7 (Gr20G05V80) reinforces the feasibility of replacing high-energy and environmentally costly inputs, such as vermiculite and perlite, whose production involves thermal expansion above 800°C (Mariotti et al., 2023; Dzięcioł and Szlachetka, 2024), with locally sourced waste that has undergone only mechanical processing. Considering the density of bottle gourd residue (0.24 g cm^{-3}; Wacht et al., 2024), the use of 20% of this material in the substrate allows the reuse of approximately 48 kg of waste per cubic meter of substrate produced (Table 3).

Considering the high calorific value of bottle gourd residue (3902.9 kcal kg^{-1}), its agricultural application reinforces a strategy of multiple uses for biomass, adding environmental and economic value to the residue, and expanding its possibilities for sustainable use (Wacht et al., 2024). This practice contributes directly to the mitigation of environmental impacts and the circular economy (SDG 12), preventing the improper disposal of biomass with high energy and agricultural potential. Furthermore, by reducing dependence on commercial substrates and mineral exploitation (pine bark, peat, and vermiculite), the use of bottle gourd residue aligns with global efforts to reduce the carbon footprint and sustainably manage resources (SDG 13) (Rashwan et al., 2023; Bhatia and Sindhu, 2024).

This substitution not only represents cost savings but also an effective cleaner production (CP) strategy, reducing the carbon footprint associated with vermiculite mining, thermal expansion as well as mitigating the environmental liability of bottle gourd disposal.

In this sense, initiatives to reuse agro-industrial waste, when supported by public policies, can generate multiple benefits, such as strengthening family farming, reducing dependence on external inputs, and encouraging more resilient and sustainable production chains (Bhatia and Sindhu, 2024).

Table 2 – Average Plant Height (PH), number of leaves (NL), root length (RL), shoot fresh mass (SFM), root fresh mass (RFM), shoot dry mass (SDM), root dry mass (RDM), and chlorophyll content index (SPAD) of Veneranda lettuce cultivar, with 57 days, under greenhouse.

Treatment	PH (cm)	NL	SPAD	RL (cm)	SFM (mg)	SDM (mg)	RFM (mg)	RDM (mg)
T1 (CM)	21.21 b	8.57 a	10.65 b	10.17 a	10,437.14 c	376.33 c	534.70 a	21.30 b
T2 (Gr5G1V95)	17.38 c	9.28 a	11.92 a	8.67 a	12,324.29 b	563.40 b	361.40 b	42.63 a
T3 (Gr10G1V90)	10.41 e	5.14 b	9.95 b	9.22 a	1,632.89 d	85.44 d	314.83 b	20.74 b
T4 (Gr20G1V80)	8.21 f	4.71 b	9.08 b	9.64 a	770.00 d	39.27 d	190.31 b	13.30 b
T5 (Gr5G05V95)	15.72 d	8.85 a	11.33 a	9.27 a	9,207.14 c	435.56 c	504.43 a	36.83 a
T6 (Gr10G05V90)	15.50 d	8.42 a	11.67 a	10.50 a	9,288.57 c	442.99 c	571.90 a	40.36 a
T7 (Gr20G05V80)	17.94 c	8.71 a	11.20 b	10.07 a	10,502.86 c	498.96 c	577.67 a	39.24 a
T8 (Ve5V95)	17.28 c	8.42 a	10.41 b	8.78 a	12,408.57 b	491.13 c	640.86 a	49.69 a
T9 (Ve10V90)	20.77 b	9.00 a	10.20 b	10.52 a	13,954.29 b	599.36 b	613.74 a	40.97 a
T10 (Ve20V80)	23.31 a	9.71 a	9.89 b	9.47 a	20,242.86 a	798.77 a	577.67 a	38.33 a
T11 (V)	20.27 b	8.85 a	10.32 b	10.40 a	14,437.14 b	598.76 b	623.99 a	39.40 a

Identical letters in the column correspond to averages that do not present statistical differences, according to the Scott-Knott Test at 5% significance; T1: 100% commercial substrate (CM); T2: 5% 1 cm bottle gourd residue + 95% vermicompost (Gr5G1V95); T3: 10% 1 cm bottle gourd residue + 90% vermicompost (Gr10G1V90); T4: 20% 1 cm bottle gourd residue + 80% vermicompost (Gr20G1V80); T5: 5% 0.5 cm bottle gourd residue + 95% vermicompost (Gr5G05V95); T6: 10% 0.5 cm bottle gourd residue + 90% vermicompost (Gr10G05V90); T7: 20% 0.5 cm bottle gourd residue + 80% vermicompost (Gr20G05V80); T8: 5% vermiculite + 95% vermicompost (Ve5V95); T9: 10% vermiculite + 90% vermicompost (Ve10V90); T10: 20% vermiculite + 80% vermicompost (Ve20V80); T11: 100% vermicompost (V).

Table 3 – Amount of bottle gourd residue used in the substrate and reused per pot (2.5L) and per substrate.

Residue in substrate (%)	Reuse per pot (g)*	Reuse per m^3 (kg)*
5%	30 g	12 kg
10%	60 g	24 kg
20%	120 g	48 kg

*Values obtained from the density of the bottle gourd residue (0.24 g cm^{-3}).
Source: Wacht et al. (2024).

Conclusions

A substrate containing 20% bottle gourd residue (particle size 0.5 cm) combined with 80% vermicompost produced Veneranda lettuce seedlings with performance comparable to the commercial substrate under greenhouse conditions. Although vermiculite provides greater biomass accumulation in the adult phase, bottle gourd residue (0.5 cm) is a sustainable technical alternative, enabling the production of commercial plants with a lower environmental impact than mineral inputs.

The particle size of the bottle gourd residue is a critical limiting factor, with a technical feasibility restricted to fine grinding (≤0.5 cm), since larger particles make lettuce cultivation unfeasible.

The use of bottle gourd residue promoted quantifiable environmental benefits, allowing the reuse of up to 120 g of agro-industrial waste per pot, which is equivalent to 48 kg per cubic meter of substrate produced.

It is worth noting the manual irrigation management and the single source of waste, suggesting that the results should be validated in automated systems and with biomass from different sources to ensure the standardization on an industrial scale.

This study contributes to environmental science by demonstrating that the circularity of regional waste is a viable tool for promoting the resilience of agroecosystems, aligning agricultural practices with Sustainable Development Goals (SDGs 12 and 13).

It is necessary to develop public policies for the monitoring and management of waste from the bottle gourd chain (field and agro-industry), to prevent socio-environmental liabilities in the producing regions.

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Authors' Contributions

Onhinam, S. F.: conceptualization; writing – original draft; writing – review & editing; **Piazer**, A. M.: investigation; methodology; **Kessler**, N. C. H.: investigation; methodology; writing – original draft; **Santiago**, P. H.: investigation; methodology; **Rodrigues**, M. A: writing – review & editing; **Eckhardt**, D. P.: conceptualization; resources; **Magalhães**, J. B.: data curation; formal analysis; writing – review & editing; **Antoniolli**, Z. I.: conceptualization; data curation; supervision; validation; visualization; resources; funding; writing – original draft; writing – review & editing.

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