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Sustainable production of melon seedlings (*Cucumis melo* L.) Zacapa with different substrates

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ABSTRACT
Objective: Different substrates were evaluated in polystyrene containers for the production of Harper-type melon (*Cucumis melo*) seedlings, focusing on growth performance and preliminary management prior to transplantation.
Design/Methodology/Approach: A completely randomized design was implemented, consisting of 15 treatments with 30 replicates each, using one plant per experimental unit. The treatments included four pure substrates: T1 peat moss (PM), T2 rice husk (RH), T3 vermicompost (V), T4 red clay (RC), and eleven combinations of these substrates in varying proportions. Plant height, leaf length and width, stem diameter, root length and diameter, among other variables, were recorded.
Results: Significant differences were observed across all treatments for all evaluated variables. The highest statistically significant plant heights were achieved with T10 (PM 10% + RH 70% + V 10% + RC 10%) and T11 (PM 33.33% + RH 33.33% + V 33.33%), reaching 4.74 cm and 4.78 cm, respectively. The greatest leaf length and width were recorded in T14 (PM 30% + V 70%), with values of 3.25 cm and 3.29 cm, respectively, corresponding to a leaf area of 10.69 cm^2. Study
Limitations/Implications: This study focused exclusively on the technological evaluation of melon seedling production. Future research should include an assessment of the economic profitability of the most promising treatments.
Findings/Conclusions: The PM-based substrate demonstrated a germination rate of 97.85%, indicating strong commercial potential for the production of melon seedlings.

Keywords: Cucurbitaceae, germination, growth, seedling management, containers.

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INTRODUCTION

Melon (*Cucumis melo*) is an annual, herbaceous, creeping or climbing plant belonging to the Cucurbitaceae family. It is a phanerogamous species that reproduces through seeds (Mármol, 2008). In Mexico, approximately 19,759 hectares are cultivated annually,

with a production value of USD $219.35 million. The leading melon-producing states, in order of importance, are Guerrero, Sonora, Michoacán, Coahuila, and Chihuahua, with 3,583, 3,573, 3,532, 3,375, and 1,522 hectares planted, respectively (SIAP, 2024). Melon cultivation can be established either directly in the field or through transplantation (Robles Trinidad *et al.*, 2005). Direct sowing involves placing seeds directly into the prepared soil, whereas transplantation depends on obtaining seedlings in optimal sanitary conditions and with strong vigor before being transferred to the field (Jasso Chaverría *et al.*, 2012). In this context, the substrate becomes an essential input for the production of high-quality seedlings (Cabrera, 1999). According to Barbaro and Karlanián (2020), the substrate must meet specific physical properties that ensure an appropriate balance between air and water content properties that are closely linked to plant development and root distribution within the container. Additionally, Crawford and Abarca (2017) emphasize the importance of optimal phytosanitary control and the use of containers with the ideal number of cavities for production, under temperatures ranging from 28 to 30 °C. However, several challenges arise during the seedling production process in containers, with one of the most common being the improper use of substrates (Robles-Trinidad *et al.*, 2005; Domínguez-Liévano and Espinosa-Zaragoza, 2021). Such misuse often results in low germination rates, compact root balls that are difficult to extract without damaging the roots, or fragile root balls that crumble easily. Despite the practical relevance of substrate management, this area has received relatively little attention from researchers (Barret *et al.*, 2016). Moreover, due to the high cost of imported substrates, there is a growing need to identify locally produced materials that are physically stable and of proven quality and safety (Quesada-Roldán and Méndez-Soto, 2005). This scenario led to the formulation of the following research question: Which type of substrate can be used in the production of melon seedlings in containers to achieve optimal growth, facilitate easy handling, ¿and utilize local resources at the time of transplantation? Currently, a variety of substrates are used for horticultural seedling production in containers. These substrates can be classified as organic of natural origin such as peat moss, coconut fiber, sugarcane bagasse, rice husk, cereal straw, and vermicompost (Cruz-Crespo *et al.*, 2013). Among these, compost and vermicompost are notable because they are produced through biological processes that transform organic waste into relatively stable materials (Claassen and Carey, 2004). There are also inorganic substrates of natural origin, including perlite, vermiculite, sand, volcanic soils, and expanded clay, among others (Baixauli Soria and Aguilar Olivert, 2002; Cruz-Crespo *et al.*, 2013). Importantly, the physical properties of a substrate are considered more critical than its chemical properties, as the latter can be adjusted through nutrient solution management, while the former are much harder to modify (Baixauli-Soria and Aguilar-Olivert, 2002). These physical properties are determined by the internal structure of the particles, their granulometric distribution, and structural stability (Pastor-Sáez, 1999). In this context, several studies have highlighted the impact of substrates on the production of horticultural seedlings across various crops. For instance, García López *et al.* (2022) reported that tomato seedlings exhibited the highest germination rate (96%) when grown in a mixture of 50% commercial peat substrate and 50% vermicompost, outperforming other mixtures such as 70% vermicompost with 30% vermiculite, 100% peat, and 100%

vermicompost, which achieved germination rates of 93%, 92%, and 87%, respectively. Similarly, García-Velázquez *et al.* (2024) found that tomato plants (*Solanum lycopersicum* L.) grown in containers with a substrate mix of soil, humus, and rice husk (3:2:1) had superior stem diameter growth (3.87 mm) and total fresh biomass (5.302 g) compared to those grown with soil, peat, and rice husk (3:2:1), which exhibited 3.59 mm stem diameter and 4.995 g fresh biomass. In another study, Meneses Fernández and Quesada-Roldán (2018) reported that Dutch cucumber plants reached heights of 110 cm and 105 cm, 25 days after transplantation, when grown in mixtures of 40% coconut fiber + 40% palm fiber + 20% commercial organic fertilizer and 70% coconut fiber + 30% commercial organic fertilizer, respectively. These results were superior to other treatments, including mixtures of 50% coconut fiber + 50% palm fiber, 70% palm fiber + 30% melina sawdust, and a control using 100% commercial coconut fiber tablets, which only achieved heights between 45 and 78 cm. Additionally, Fernández-Zárate *et al.* (2022) found that *Cinchona pubescens* Vahl. (Rubiaceae) seedlings achieved an 88.3% germination rate using 100% forest soil, surpassing mixtures of 50% forest soil + 50% sand and 75% forest soil + 25% sand, which exceeded 50%, whereas the 25% forest soil + 75% sand mixture and 100% sand substrate resulted in germination rates below 50%. Furthermore, Cardoza-Viera *et al.* (2024) reported that maize seedlings exhibited the highest plant height values at all sampling times when grown in a 50% rice husk + 50% vermicompost mixture, reaching 32.47 cm at 18 days after emergence (DAE). This performance was significantly superior to substrates based on 100% sand, 75% sand + 25% rice husk, and 50% sand + 25% rice husk + 25% vermicompost, which achieved plant heights of 19.5 cm, 23.23 cm, and 29.37 cm, respectively. Therefore, the aim of this study was to evaluate the effect of different substrates in polystyrene containers on the growth and early management of Harper-type melon seedlings for transplantation purposes.

MATERIALS AND METHODS

Location and characterization of the experiment

The experiment was conducted in the municipality of Buenavista, Michoacán, Mexico, located at kilometer 2 on the highway from Crucero de la Ruana, Buenavista, Michoacán, to Tazumbos, Jilotlán de los Dolores, Jalisco, at coordinates 19° 13’ 52” N, 102° 40’ 13” W, and an elevation of 418 meters above sea level (Google Earth, 2024). The site features a BS1 (h’) W (W) dry climate, classified within the group of dry climates BS1 (García, 2004), with an average annual temperature of 33.5 °C and an average annual precipitation of 599.3 mm (SMN-CONAGUA, 2024).

Plant material

The study used Harper-type melon (*Cucumis melo*) ‘Zacapa’ seeds, provided by the seed company US Agriseeds® (US Agriseeds, 2024).

Seedling management

For seedling production, 45 polystyrene containers with 248 cavities each were used, with a volume capacity of 35 cc per cone. Direct sowing was performed at a depth of 1 to 2 cm under the roof of a metal structure, where the trays remained for 48 hours.

Subsequently, the containers were transferred to a black shade house with 20% shade netting, measuring 10×20 m, to complete the germination cycle. Once germinated, the seedlings were placed on an open-air metal structure for 10 days. To manage sucking insect pests, the commercial repellent Oleotech Garlic® (20% *Allium sativum* oil) from Biotech/México and the adherent Inex A® (20.2% ethoxylated fatty alcohol) from Cosmocel/México were applied at a dose of 1.0 mL L^{-1} each, twice throughout the cycle. Applications were carried out using a manual backpack sprayer with a 15-liter capacity, brand SWISSMEX, model COSMOS®, directing the spray toward the foliage. For fungal disease prevention, *Trichoderma harzianum* (6.1×10^7 CFU mL^{-1}) was applied at a dose of 5.0 mL L^{-1}, four times throughout the cycle, using a 5-liter capacity metal watering can during irrigation. Nutritional management involved the application of 16-16-16 (N-P_2O_5-K_2O) fertilizer, GRO GREEN by Campbell, at a dose of 1.0 g L^{-1}, diluted in irrigation water and applied seven days after germination. Irrigation was performed manually, daily, in the early morning hours, using 1.0 L of water per container.

Experimental design

A completely randomized experimental design was employed, with 15 treatments, 30 replicates, and one melon plant per experimental unit.

Treatments

Among the 15 treatments, four were pure substrates (controls), and eleven were mixtures of these substrates in varying volumetric proportions (Table 1). A total of 3,720 melon seedlings were distributed across 15 rows, with each row representing one treatment and containing 744 seedlings arranged in three containers. For data collection, 10 seedlings

Table 1. Treatments used for the evaluation of melon seedlings.

Treatment	Substratum	Percentage
T1	PM	100%
T2	RH	100%
T3	WC	100%
T4	RC	100%
T5	PM+RH	50% + 50%
T6	RH+WC	50% + 50%
T7	RH+RC	50% + 50%
T8	PM+RH+WC	20% + 30% +50%
T9	RH+WC+RC	50% + 25% + 25%
T10	PM+RH+WC+RC	10% + 70% + 10% + 10%
T11	PM+RH+WC	33.33% + 33.33% +33.33%
T12	PM+RH+WC+RC	25% + 25% + 25% + 25%
T13	RH+WC	80% + 20%
T14	PM+L	80% + 20%
T15	PM+CA	10% + 90%

PM: peat moss; RH: rice husk; WC: wormcompost; RC: red clay were randomly selected from each container, resulting in 30 seedlings per treatment. The remaining 714 seedlings were used as buffer plants to ensure reliable data collection.

Study variables

The recorded variables were: (1) Plant height [cm], measured from the root collar to the point where the stem ends and the cotyledon leaves begin; (2) Leaf length [cm], measured from the base to the apex of the leaf along an imaginary vertical axis; (3) Main leaf width [cm], measured from the left lateral edge to the right edge of the leaf along an imaginary transverse axis; (4) Stem diameter [mm], measured at the basal starting point of the stem; (5) Root length [cm], measured from the root collar to the apex where the root terminates; (6) Root diameter [mm], measured at the thickest point of the main root collar. For measurements expressed in millimeters, a digital caliper (Hardened brand) with a graduated scale from 0.01 to 150 mm and an accuracy of 0.01 to 0.3 mm was used. For measurements expressed in centimeters, a 30 cm metal ruler was employed. Data collection was carried out 15 days after sowing. Additionally, (7) Germination percentage [%] was recorded five days after sowing, determined per container.

$$\% = \frac{NGP}{NC} \times 100\%$$

Where: *NGP*=Number of Germinated Plants, *NC*=Number of Cavities (248).

Root ball extraction, plant handling, and substrate consistency

To establish the parameters for root ball extraction, plant handling, and substrate consistency, and to mechanically characterize the substrate materials, representative numerical values were assigned as follows: 0=difficult and 1=easy. This coding system generated a binary scale. After the fieldwork, a coding matrix was developed for data interpretation. The quantitative data coding process involved assigning numerical values to represent each category or item, where each category was assigned a specific numerical value or symbol with defined meaning (Hernández-Sampierí, Fernández-Collado, and Baptista-Lucio, 2014). To confirm the internal validity of the instrument, the global value of Cronbach's alpha internal consistency index was used.

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum Vi}{Vt}\right]$$

Where: α=Alpha, *K*=number of variables, *Vi*=variance of each variable, *Vt*=total variance. This index is conceptualized as the average of the correlations among the variables that comprise an instrument (Streiner, 2003). It measures reliability in terms of internal consistency (Celina and Ocampo, 2005; Cervantes, 2005), with the final value being considered an ordinal variable (Supo, 2013).

Statistical analysis

Normality and homoscedasticity tests of the variance data were performed [Post-Hoc], followed by an analysis of variance (ANOVA) to evaluate the effects of each treatment, along with Tukey's mean separation test ($P \leq 0.05$). All analyses were conducted using the STATISTICA software package, Version 13.3 (TIBCO Inc., 2017).

RESULTS

The results of the normality and homoscedasticity tests of the variance data (Post-Hoc) indicated a satisfactory linear alignment of the data along the straight line. All variables exhibited a normal distribution, confirming the reliability of the experiment. The analysis of variance revealed significant differences among all treatments for all evaluated variables (Table 2).

Plant Height

Tukey's mean comparison test ($P \leq 0.05$) for this variable showed that treatments T7, T10, T11, and T13 were statistically similar, recording the highest values. Treatments T9 and T15 also demonstrated a significant growth effect, with 3.89 cm and 3.85 cm, respectively, both surpassing T1, which recorded 3.47 cm. However, the highest numerical value was observed in T9, reaching 5.00 cm (Table 3).

Leaf length

The best results with significant effects ($P \leq 0.05$) were observed in treatments T11 and T12, with values of 3.15 cm and 3.04 cm, respectively. These treatments exhibited greater longitudinal leaf growth compared to T8 and T9, which also showed significant effects with 2.79 cm and 2.43 cm, respectively, though belonging to a different statistical group (Table 3). However, T2 did not show statistical significance and recorded the lowest numerical value among all treatments, with 0.70 cm.

Leaf width

Treatments T12 and T13 were statistically similar ($P \leq 0.05$), with values of 3.21 cm and 2.96 cm, respectively, showing the greatest increase in leaf width, differentiating them

Table 2. Analysis of variance for the variables evaluated.

Variable	Degrees of Freedom	Mean Square Effect	Mean Square Error	Calculated F	P-value	CV
PH	14.35	0.43738	0.18631	2.3476	0.0039*	29.44
LL	14.35	0.16271	0.07066	2.3028	0.0047*	44.73
LW	14.35	0.25727	0.07992	3.2191	0.0001*	49.62
SD	14.35	60.66080	23.14329	2.6211	0.0012*	28.75
RL	14.35	0.96921	0.42632	2.2734	0.0053*	15.76
RD	14.35	21.75461	4.80519	4.5273	0.0000*	31.05
GP	14.35	3.519766	1.077517	3.2665	0.0031*	9.17

PH: plant height; LL: leaf length; LW: leaf width; SD: stem diameter; RL: root length; RD: root diameter; GP: germination percentage; CV: coefficient of variation (%); Significant ($P \leq 0.05$).

Table 3. Mean values of the treatments for all variables evaluated in melon seedlings.

Treatment	PH	LL	LW	SD	RL	RD	GP
T1	3.47 cd	1.63 d	1.55 c	1.94 ab	6.81 bc	1.74 ab	97.85 g
T2	2.87 bc	0.70 a	0.60 a	2.16 a	6.63 abc	1.51 a	79.97 bcd
T3	2.16 a	0.78 ab	0.70 ab	2.00 ab	5.48 a	1.55 ab	80.11 bcd
T4	2.84 bc	1.18 d	1.03 c	2.17 bc	6.23 ab	1.79 ab	74.46 ab
T5	2.73 ab	1.13 bc	0.98 ab	2.02 ab	7.11 c	1.68 ab	82.26 cd
T6	3.29 bcd	1.72 d	1.67 c	2.60 de	6.62 abc	2.15 cd	70.16 a
T7	4.62 fg	2.36 e	2.36 d	2.79 ef	6.91 bc	2.27 de	90.32 ef
T8	5.00 g	2.79 fg	2.89 ef	3.09 g	7.02 bc	2.70 fg	90.05 ef
T9	3.89 de	2.43 fg	2.47 d	3.15 g	7.3 cd	2.92 h	94.09 efg
T10	4.74 fg	2.42 e	2.54 de	3.03 fg	6.99 bc	2.58 ef	95.30 fg
T11	4.78 fg	3.15 gh	3.32 g	3.17 g	6.51 abc	2.81 fg	90.05 ef
T12	4.37 efg	3.04 gh	3.21 fg	3.15 g	7.3 cd	2.81 fg	87.10 de
T13	4.66 fg	2.47 ef	2.96 fg	2.41 cd	8.13 d	1.85 bc	77.15 abc
T14	4.23 ef	3.25 h	3.29 g	3.59 h	6.98 bc	3.58 h	90.05 ef
T15	3.85 de	1.75 d	1.82 c	2.47 d	6.98 bc	1.75 ab	94.09 efg
HSD=	0.04	0.03	0.03	0.52	0.07	0.31	0.40

PH: plant height (cm); LL: leaf length (cm); LW: leaf width (cm); SD: stem diameter (mm); RL: root length (cm); RD: root diameter (mm); GP: germination percentage (%); T1: peat moss (PM); T2: rice husk (RH); T3: wormcompost (WC); T4: red clay (RC); T5: PM 50% + RH 50%; T6: RH 50% + WC 50%; T7: RH 50% + RC 50%; T8: PM 20% + RH 30% + WC 50%; T9: RH 50% + WC 25% + Topure 25%; T10: PM 10% + RH 70% + WC 10% + RC 10%; T11: PM 33.33% + RH 33.33% + WC 33.33%; T12: PM 25% + RH 25% + WC 25% + RC 25%; T13: RH 80% + WC 20%; T14: PM 30% + WC 70%; T15: PM 10% + RH 90%; HSD: honestly significant difference; different letters within the same column indicate significant differences according to Tukey's test ($P \leq 0.05$).

from the other treatments. Treatment T8 also showed a statistically significant difference ($P \leq 0.05$), with a value of 2.89 cm, which was 9.96% and 2.36% lower than T12 and T13, respectively. As in the case of leaf length, T2 recorded the lowest numerical value for leaf width, with 0.60 cm (Table 3).

Stem diameter

Treatments T1, T3, T4, T5, T6, T7, T10, and T13 showed statistically significant differences ($P \leq 0.05$) and were distinct from one another (Table 3). The highest value was observed in T10, with 30.30 mm, while the lowest was recorded in T1, with 19.40 mm, which is considered the commercial control. However, treatments T11, T12, and T14 showed only numerical values of 31.77 mm, 30.50 mm, and 35.97 mm, respectively, without statistical significance.

Root length

Twelve treatments presented statistically significant differences ($P \leq 0.05$), ranging from 6.23 cm to 7.02 cm. Among these, T1, T7, T8, T10, T4, and T15 stood out for showing statistical similarity and forming the largest group, with intermediate average values of 6.81 cm, 6.91 cm, 7.02 cm, 6.99 cm, 6.98 cm, and 6.98 cm, respectively. However, T13 exhibited the highest numerical value of 8.13 cm without statistical significance.

Root diameter

This variable was characterized by six statistical groups (P≤0.05). The group formed by T8, T11, and T12 reached the highest average values of 27.03 mm, 28.17 mm, and 28.13 mm, respectively, showing statistical similarity. In contrast, the group consisting of T1, T3, T4, T5, and T15 exhibited the lowest average values, with 17.40 mm, 15.50 mm, 17.93 mm, 16.87 mm, and 17.53 mm, respectively, also showing statistical equality.

Germination percentage

Treatments T9 and T15 recorded the best statistically significant results (P≤0.05), both achieving an average value of 94.09%. Treatments T7, T8, T11, and T14 also showed statistical similarity, with average values of 90.32% and 90.05% for the last three. Meanwhile, T4 recorded a statistically significant value of 74.46%, although this was lower compared to the aforementioned treatments. T1 achieved a numerical value of 97.85%, which, while not statistically different, represented the highest value among all evaluated treatments (Table 3).

Root ball extraction, plant handling, and substrate consistency

The calculated value of α=0.71 indicated that the measurement instrument demonstrated high internal consistency and stability (Table 4). According to Celina and Ocampo (2005), the minimum acceptable value for Cronbach's alpha coefficient is 0.70;

Table 4. Cronbach's alpha calculation matrix.

Treatment	Substratum	Percentage	Item or variable			∑ Vt
			EP (VNR)	MP (VNR)	CS (VNR)	
T1	PM	100%	1	1	1	3
T2	RH	100%	1	0	1	2
T3	WC	100%	0	0	0	0
T4	RC	100%	0	0	0	0
T5	PM+RH	50% + 50%	1	0	1	2
T6	RH+WC	50% + 50%	0	0	1	1
T7	RH+RC	50% + 50%	1	0	1	2
T8	PM+RH+WC	20% + 30% + 50%	1	1	1	3
T9	RH+WC+RC	50% + 25% + 25%	0	0	1	1
T10	PM+RH+WC+RC	10% + 70% + 10% + 10%	1	0	1	2
T11	PM+RH+WC	33.33% + 33.33% +33.33%	1	1	1	3
T12	PM+RH+WC+RC	25% +25% +25% + 25%	0	0	0	0
T13	RH+WC	80% + 20%	1	0	1	2
T14	PM+WC	30% + 70%	0	0	0	0
T15	PM+RH	10% + 90%	1	0	1	2
		∑ Vi	0.24	0.16	0.22	1.26

EC: root ball extraction; PH: plant handling; SC: substrate consistency; NRV: numerical representative values [EC and PH: 0=difficult, 1=easy; SC: 0=crumbles, 1=does not crumble]; α: 0.71 (Cronbach's alpha); ∑ Vi: variance of each variable; ∑ Vt: total variance; PM: peat moss; RH: rice husk; WC: wormcompost; RC: red clay.

values below this threshold reflect low internal consistency, while values above 0.90 may suggest redundancy or duplication.

DISCUSSION

Plant height

The best growth effects in melon seedlings for plant height were observed with substrate mixtures T7 (RH+RC [50% + 50%]), T10 (PM+RH+WC+RC [10% + 70% + 10% + 10%]), T11 (PM+RH+WC [33.33% + 33.33% + 33.33%]), and T13 (RH+WC [80% + 20%]), with values of 4.62 cm, 4.74 cm, 4.78 cm, and 4.66 cm, respectively. These results were superior when compared to the pure substrates T1 (PM [100%]), T2 (RH [100%]), T3 (WC [100%]), and T4 (RC [100%]), which recorded 3.47 cm, 2.87 cm, 2.16 cm, and 2.84 cm, respectively, and were considered the controls. The evaluated mixtures were also characterized by the presence of wormcompost and whole, raw rice husk. These findings align with those reported by David-Santoya *et al.* (2018) for habanero pepper seedlings, where greater plant height was achieved with substrate mixtures of bocashi + *Gliricidia sepium* (cacahuananche) + plant residues [50% + 25% + 25%], cocoa husk + *G. sepium* + plant residues [50% + 25% + 25%], and cocoa husk + *G. sepium* + sheep manure [50% + 25% + 25%], with values of 7.1 cm, 7.3 cm, and 8.1 cm, respectively. All these mixtures were combined with vermicompost and soil at a 1:1 ratio and produced through a primary wormcomposting process using plant residues, outperforming the control soil treatment (100%) which recorded 5.0 cm.

Leaf length and width

Treatment T14 (PM 30% + WC 70%) achieved the highest growth rates in both leaf length and width among all evaluated substrates, with values of 3.25 cm and 3.29 cm, respectively, corresponding to a leaf area of 10.69 cm^2. In contrast, the control treatments T1 (PM 100%) and T2 (RH 100%) showed the lowest leaf area growth rates, recording 2.52 cm^2 and 0.42 cm^2, respectively. Similarly, Chirinos *et al.* (1997) used leaf length and width as reliable indicators for estimating leaf area growth in melon under field conditions, with measurements that are easily obtained. According to Bidwell (1993), such growth whether measured by length, thickness, or area results in an increase in volume or mass, occurring in different directions and at varying rates. The observed differences in leaf area growth rates of 8.17 cm^2 and 10.27 cm^2, respectively, are attributed to the mineral concentrations present in these three substrates. In this regard, Durán-Umaña and Henríquez-Henríquez (2010) reported nutrient contents in peat moss of 18, 130, 128, 76, and 252 mg kg^{-1} for N, P, K, Ca, and Mg, respectively. For wormcompost, they reported contents of 23.5, 18.8, 33.4, 7.8, 3, and 4.6 g kg^{-1} for N, P, Ca, Mg, K, and S, respectively, as well as levels of 5, 149, 181, 813, 633, and 25 mg kg^{-1} for Fe, Cu, Zn, Mn, B, and other trace elements. Additionally, Sanchez-Hernández and Domínguez (2019) emphasized that wormcompost contains a well-established microbial community that enhances substrate fertility through nutrient supply. In comparison, Cruz-Crespo *et al.* (2023) reported that rice husk-based substrates contain lower levels of N, P, K, Ca, and Mg, with respective concentrations of 13, 782, 2,195, 86, and 939 mg kg^{-1}.

Stem diameter

Melon seedlings grown in the T14 mixture (PM 30% + WC 70%) again exhibited the greatest stem diameter growth, with an average value of 3.60 mm. In contrast, the lowest significant growth was observed in the control substrate T1 (PM 100%), with 1.94 mm. This difference of 1.66 mm between both treatments represents a 46.11% higher growth in T14. Such a sudden increase is likely attributed to the effect of the microorganism Trichoderma harzianum, applied during substrate preparation, which promotes rhizosphere development enriched with organic matter from peat moss and wormcompost. Alfiky and Weisskopf (2021) noted that *T. harzianum* enhances plant growth as a plant growth promoter. Additionally, it can decompose organic matter, a process closely linked to its high enzymatic capacity for substrate degradation (Infante *et al.*, 2009).

Root length

The best significant results for root length growth were observed in the substrates of treatments T1 (PM 100%), T7 (RH 50% + RC 50%), T8 (PM 20% + RH 30% + WC 50%), T10 (PM 10% + RH 70% + WC 10% + RC 10%), T14 (PM 70% + WC 30%), and T15 (PM 10% + RH 90%), with values of 6.81 cm, 6.91 cm, 7.02 cm, 6.99 cm, 6.98 cm, and 6.98 cm, respectively. This growth effect is primarily due to the arrangement of substrate particles within the container cavities, optimizing pore space for oxygenation and water availability to the melon seedling roots. This interpretation aligns with the observations of Valenzuela *et al.* (2012), who highlighted the critical importance of oxygen availability in the root zone for water absorption. However, the highest root length growth was recorded in treatment T13 (RH 80% + WC 20%) with a value of 8.13 cm. Similarly, Medina Saavedra *et al.* (2023) reported root length values of 6.95 cm in cucumber seedlings grown in T5 (PM 100%), a result comparable to that of T1 in the present study. According to Valenzuela *et al.* (2012), peat moss features a porosity of 85.86%, water retention capacity of 59.91%, and air-filled pore space of 25.95%. These physical properties make peat moss a highly versatile substrate for vegetable seedling production.

Root diameter

The substrate mixtures of T8 (PM 20% + RH 30% + WC 50%), T11 (PM 33.33% + RH 33.33% + WC 33.33%), and T12 (PM 25% + RH 25% + WC 25% + RC 25%) achieved the highest growth rates in root diameter when compared to the commercial control T1 (PM 100%), with increases of 28.14%, 38.29%, and 38.07%, respectively, in root volume. From a physical perspective, these results can be attributed to two key characteristics: high water retention capacity at low tension (0 to 100 cm water column) and high aeration capacity, as described by Burés (1997). These conditions facilitated efficient water absorption by the seedling roots, leading to rapid root diameter growth. These same mixtures also exhibited superior growth in stem diameter compared to the commercial control, confirming the physical continuity of growth between the root system and the stem (Table 3). The T14 mixture (PM 30% + WC 70%) recorded the highest numerical value for root diameter among all evaluated substrates, with an average of 3.58 mm. In contrast, the lowest value was observed in T2 (RH 100%), with 1.59 mm. This represents an increase of 1.99 mm, equivalent to a 57.82% higher root volume growth. According to Barret (2016), the container environment provides a very shallow layer of growing medium, which quickly becomes saturated during irrigation and has limited water storage capacity. In this context, rice husk demonstrated a physical structure unable to retain water effectively when compared to the peat moss + wormcompost mixture, thereby limiting root diameter growth. On the other hand, the combination of textures in the mixture confirmed greater water retention capacity. Additionally, Bidwell (1993) noted that the organic matter present in a substrate significantly influences water retention, nutrient holding capacity, and provides substrates for microbial metabolism. Water and nutrient absorption occur primarily in the younger regions of the root, which are structurally heterogeneous and continuously changing in their anatomical and physiological characteristics. As Esau (1985) pointed out, water absorption rates along the root vary according to its length, age, and the internal conditions of the seedlings. Consequently, this leads to longitudinal growth as well as an increase in the vascular cylinder diameter of the root.

Germination percentage

According to Mármol (2008), melon seeds should achieve a germination rate above 90%. However, seven of the evaluated substrates in this study did not meet this threshold. In contrast, the substrate T1 (PM 100%) and the mixtures T7 (RH 50% + RC 50%), T8 (PM 20% + RH 30% + WC 50%), T9 (RH 50% + WC 25% + RC 25%), T10 (PM 10% + RH 70% + WC 10% + RC 10%), T11 (PM 33.33% + RH 33.33% + WC 33.33%), T14 (PM 30% + WC 70%), and T15 (PM 10% + RH 90%) recorded values exceeding the established parameter, with 97.85%, 90.32%, 90.05%, 94.09%, 95.30%, 90.05%, 90.05%, and 94.09%, respectively. These results are mainly attributed to particle size, pore capacity for water retention, and overall water availability, which directly influenced melon seed germination. These germination percentages are comparable to those reported by Vera-Velázquez *et al.* (2020) in papaya, where substrates based on T1 (100% black soil, control), T2 (50% black soil + 25% worm humus + 25% sand), T3 (50% black soil + 25% compost + 25% sand), T4 (50% black soil + 30% worm humus + 20% sand), and T5 (50% black soil + 25% compost + 25% sand) achieved germination rates of 79%, 92%, 94%, 90%, and 92%, respectively.

Root ball extraction, plant handling, and substrate consistency

Regarding seedling management in containers, the substrates based on T1 (PM 100%), T8 (PM 20% + RH 30% + WC 50%), and T11 (PM 33.33% + RH 33.33% + WC 33.33%) exhibited easy root ball extraction and plant handling, with substrate consistency classified as non-crumbly (root balls remained intact, porous, and soft without root breakage during extraction). These substrates demonstrated stable physical properties for melon seedling production, and the fibrous nature of peat moss contributed to strong root adherence and homogeneous root distribution. One of the main criteria for substrate selection is ease of handling or compatibility, particularly when mixing different materials (Cruz-Crespo *et al.*, 2013). In contrast, the pure substrate T2 (RH 100%) exhibited easy root ball extraction but difficult plant handling, with a crumbly substrate consistency characterized by very loose root balls lacking mechanical root anchorage (Figure 1). These conditions confirmed the absence of fibrous structure in the substrate. Additionally, this mixture presented an overly open pore space, typical of lightweight materials with large, loose particles, which resulted in poor root adherence. Martínez and Roca (2011) emphasized that substrate materials must maintain structural stability to support the plant throughout its growth cycle. Once roots occupy the substrate within the containers, modifying its physical properties is no longer feasible.

Substrates based on T3 (WC 100%) and T4 (RC 100%), as well as mixtures T12 (PM+RH+WC+RC [25% + 25% + 25% + 25%]) and T14 (PM+WC [30% + 70%]), exhibited difficult root ball extraction and plant handling, with a substrate consistency classified as easily crumbling. These treatments presented sandy, loose root balls with root breakage during extraction and handling (Figure 1). Therefore, it is concluded that these three physical characteristics are inadequate for melon seedling management in containers. These findings are supported by Barret *et al.* (2016), who state that a substrate must meet the practical requirements of the production system in which it is used and must promote healthy root growth in the challenging environment of a container. The T5 mixture (PM+RH [50% + 50%]) was characterized by easy root ball extraction but

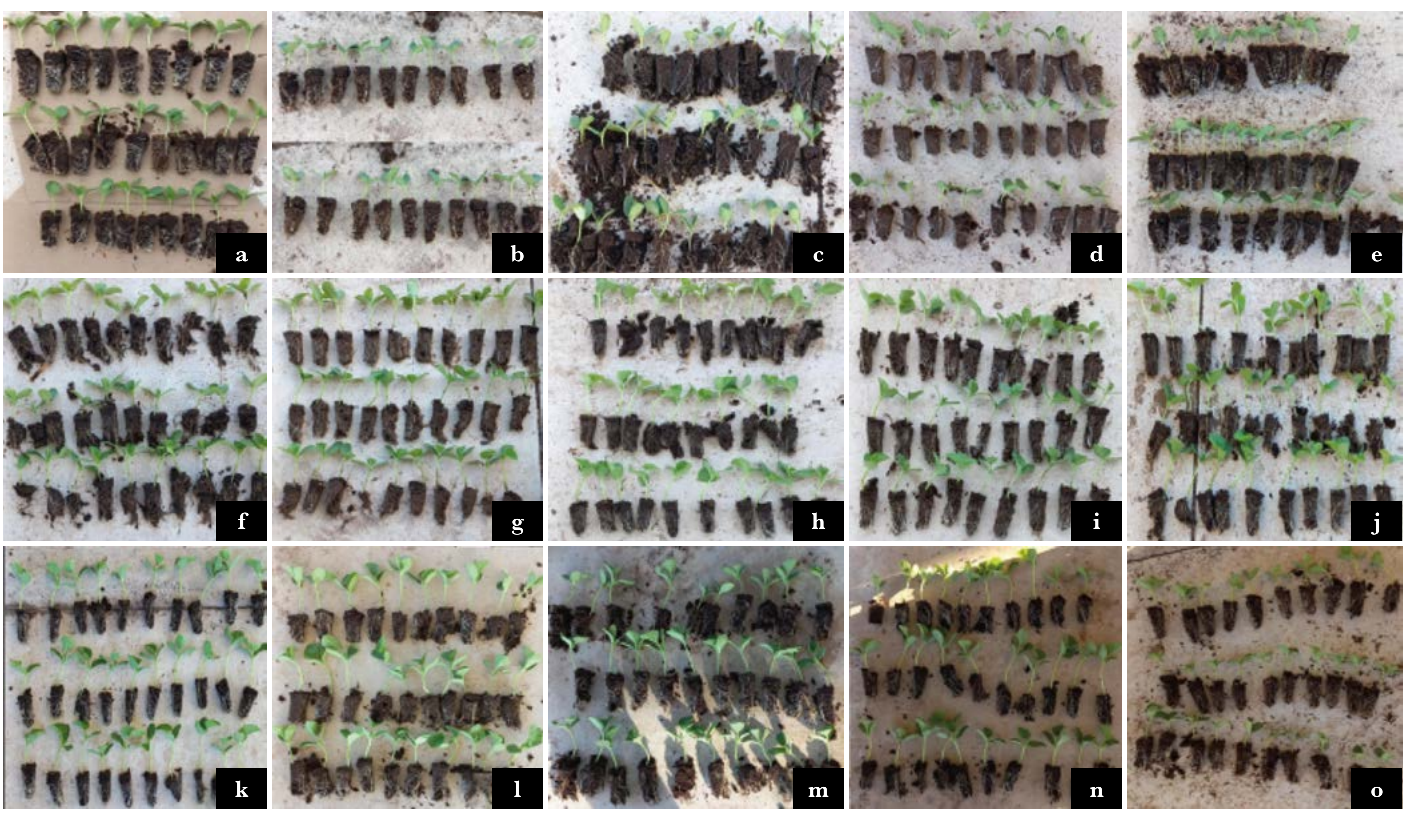

Figure 1. Harper-type melon (*Cucumis melo*) seedlings of the Zacapa hybrid after extraction from polystyrene containers with 248 cavities using the evaluated substrates: peat moss (PM), rice husk (RH), wormcompost (WC), red clay (RC), PM 50% + RH 50%, RH 50% + WC 50%, RH 50% + RC 50%, PM 20% + RH 30% + WC 50%, RH 50% + WC 25% + Topure 25%, PM 10% + RH 70% + WC 10% + RC 10%, PM 33.33% + RH 33.33% + WC 33.33%, PM 25% + RH 25% + WC 25% + RC 25%, RH 80% + WC 20%, PM 30% + WC 70%, PM 10% + RH 90%. El Crucero de La Ruana, municipality of Buenavista, Michoacán, Mexico.

difficult plant handling, with a soft, non-crumbly substrate consistency (intact root balls without root breakage). However, this mixture demonstrated instability in the second physical characteristic required for successful transplantation, as handling led to root ball disintegration. A noted issue in substrate characterization is the lack of standardized methodologies, which complicates result comparison (Cruz-Crespo *et al.*, 2013). The substrate mixtures T7 (RH+RC [50% + 50%]), T10 (PM+RH+WC+RC [10% + 70% + 10% + 10%]), T13 (RH+WC [80% + 20%]), and T15 (PM+RH [10% + 90%]) showed easy root ball extraction (very soft) but difficult plant handling due to the easily crumbling substrate consistency when removing plants from the containers (Figure 1). These findings confirmed that these evaluated mixtures are unstable regarding the second physical characteristic assessed. Zanin *et al.* (2011) also noted that when RH is used in substrates, its proportion should not exceed 50% by volume, due to its slow decomposition rate compared to the higher bio-stability of other organic materials. Therefore, further research is needed on other plant species to better characterize these mixtures physically. The physical mixtures of T6 (RH+WC [50% + 50%]) and T9 (RH+WC+RC [50% + 25% + 25%]) were characterized by combining a lightweight, porous material (RH) with denser, compact materials (WC and RC), resulting in difficult root ball extraction and plant handling, with a soft, easily crumbling substrate consistency. Regarding plant handling, Luna *et al.* (2012) emphasized that containers must often be moved, making transportation to the planting site a key issue in terms of logistics and safety. Consequently, these mixtures proved to be unviable for melon seedling production in containers due to the high porosity of the raw, whole RH, which negatively affected the last two evaluated conditions.

CONCLUSIONS

Among all evaluated treatments, the greatest growth effects in leaf length and width, stem diameter, root length, and root diameter were obtained with the mixture based on peat moss (PM) 30% + wormcompost (WC) 70%. In contrast, the lowest growth effects in leaf length and width, as well as root diameter, were observed in the substrate based on rice husk (RH) 100%.

The substrate consisting of peat moss (PM) 100% achieved a germination rate of 97.85%, thus maintaining its commercial potential for melon seedling production. Additionally, substrates based on PM 100%, PM 20% + RH 30% + WC 50%, and PM 33% + RH 33% + WC 33% demonstrated the best results in terms of root ball extraction, plant handling, and substrate consistency, thereby confirming their usability potential. However, mixtures based on RH 50% + WC 50% and RH 50% + WC 25% + red clay (RC) 25% proved to be inefficient for seedling production due to difficult root ball extraction and plant handling, combined with a substrate consistency that was prone to crumbling.

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