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Short Communication

Innovative Substrate Design for Sustainable Agriculture: Kitchen Compost and Organic Waste in Cucumber Seedling Cultivation

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Abstract

This study explores the effects of various seedling substrates on cucumber growth, focusing on their physical, chemical, and nutrient properties. Substrates were formulated with different ratios of kitchen compost, peat, rice husk, and straw. Key growth indicators, including germination rate, plant height, leaf area, root development, and biomass, were analyzed using a seedling index and fuzzy membership function. Results showed that moderate bulk density, high porosity, and optimal moisture content significantly enhanced seedling growth. Chemical properties, such as pH (5.5-7.5), low EC, and reduced chloride ion concentration, were crucial for healthy development. While alkali-hydrolyzed nitrogen, available phosphorus, and potassium were beneficial, excessive levels inhibited growth. The T2 treatment (15% kitchen compost, 45% peat, 40% rice husk) showed the best performance, offering balanced physical structure, nutrient availability, and salinity control. It promoted superior growth in leaf area, root length, and biomass while meeting local agricultural standards. This study demonstrates the potential of combining kitchen compost with agricultural waste for sustainable seedling substrates, providing insights for optimizing vegetable seedling production and enhancing the use of organic waste in agriculture. Future research should examine broader applications across various crops.

Keywords: cucumber seedlings, kitchen compost, seedling substrate, physicochemical properties, sustainable agriculture

Introduction

The resource utilization of kitchen waste has become a research hotspot in both the agricultural and environmental fields [1, 2]. With the acceleration of urbanization and population growth, the generation of kitchen waste continues to increase, posing a significant

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challenge for effective disposal and utilization [3]. Composting is an economically efficient method for processing kitchen waste, which can transform organic waste into nutrient-rich compost, making it suitable for agricultural use [4, 5]. However, kitchen waste typically contains high levels of salt, and traditional composting techniques often fail to adequately remove these salts [6]. This issue is especially problematic with high-salinity waste, as the resulting compost may contain salt concentrations that adversely affect agricultural production. Thus, the presence of salt in kitchen compost has become a major barrier to its widespread use, particularly in dryland farming, where excessive salt levels can lead to soil salinization and, subsequently, negatively impact crop growth.

To maximize the utilization of kitchen waste while mitigating the negative impact of salt on soil, researchers have proposed combining kitchen compost with other organic materials to prepare multi-component seedling substrates [7, 8]. This approach not only facilitates further resource utilization of kitchen waste but also effectively alleviates its high-salt content. Additionally, vegetable seedling substrates play a crucial role in agricultural production by providing essential nutrients for crops and supporting seed germination, seedling growth rates, and overall health [9]. Therefore, developing suitable and environmentally friendly vegetable seedling substrates that align with sustainable development principles while enhancing agricultural efficiency and sustainability has become a key research focus [10].

Traditional seedling substrates predominantly use peat as the primary component [11]. Peat provides abundant organic matter, which helps improve the physical and chemical properties of the substrate, particularly in terms of water retention and air permeability [12]. However, peat, as a non-renewable resource, is being depleted due to increasing extraction, making it less suitable for meeting the sustainable resource utilization requirements in current agricultural production [13]. In response, researchers have begun to explore the use of renewable resources and agricultural waste as substitutes for peat in seedling substrates [14]. Agricultural wastes, especially plant-based residues such as straw and rice husks, are rich in nutrients and easily accessible, making them ideal raw materials for new seedling substrates.

Previous studies have shown that agricultural waste, after composting or fermentation, can significantly improve the physical and chemical properties of seedling substrates and enhance their fertility [15]. While the application of straw-based agricultural waste in seedling substrates has gained recognition, there has been relatively little research on using animal manure, such as cow or chicken manure, in seedling substrates. However, studies on the use of cow manure compost in seedling substrates have shown promising results [16]. Despite this progress, how to effectively integrate various agricultural wastes for comprehensive utilization remains an important research question.

In comparison to agricultural waste, kitchen waste contains higher nutrient levels. When processed through appropriate techniques, the nutrient release characteristics of kitchen compost are more stable, providing a rich nutrient supply for plant growth [17]. Furthermore, the treatment of kitchen waste not only addresses waste disposal issues but also reduces reliance on peat, aligning with sustainable agricultural production needs. Existing research suggests that, in some seedling experiments, the moderate use of kitchen compost as a peat substitute can improve the growth of vegetables such as cucumbers and increase seedling survival rates [18, 19]. However, while using kitchen compost alone to replace peat improves some growth indicators, it still has certain shortcomings, particularly in terms of organic matter content and salt control, which do not fully meet industry standards for vegetable seedling substrates.

Therefore, this study focuses on the application of kitchen compost in cucumber seedling substrates. By mixing kitchen compost with other agricultural wastes, such as fermented rice husks and straw, and preparing seedling substrates with varying compositions, the study aims to enhance the physical and chemical properties and fertility of the substrate, promoting the growth and development of cucumbers. By comparing the effects of different substrate formulations on cucumber growth, the study seeks to identify the most suitable substrate composition, providing theoretical support for cucumber transplantation and offering new perspectives and technical references for the resource utilization of kitchen waste.

Materials and Methods

Experimental Materials

This study was conducted at the Organic Recycling Research Institute (Suzhou) of China Agricultural University, within the artificial climate and plant cultivation center. The experimental crop used was cucumber (*Cucumis sativus*), variety "Shenqing No. 1". This variety was chosen for its strong adaptability under various growth conditions and its ability to respond well to different substrate conditions, which makes it suitable for evaluating the effects of various growing media.

The kitchen compost used in the experiment was sourced from kitchen waste collected from the Taihu Lake area and fully composted through aerobic fermentation at the Taihu Organic Waste Utilization Demonstration Center [20]. This processing method effectively transforms the organic materials and nutrients in kitchen waste into compost, making it suitable for agricultural seedling production. The peat moss used in the study was provided by Lüyuan Meijia Agricultural Technology Co., Ltd., which is known for its good water

Table 1. Physical and chemical properties of the test material.

Indicator	Kitchen Compost	Peat	Fermented Straw	Fermented Rice Husk	Commercial Substrate
pH	7.76	6.07	8.46	7.32	5.64
EC/(mS·cm^{-1})	5.22	0.49	0.95	0.81	0.28
Bulk Density /(g·cm^{-3})	0.49	0.27	0.29	0.25	0.44
Water Content/%	19.00	34.35	12.87	5.32	32.33
AN/(mg·kg^{-1})	2020.47	591.05	1201.59	776.30	497.70
AP/(mg·kg^{-1})	996.27	357.83	612.81	929.96	97.20
AK/(mg·kg^{-1})	2984.31	1374.27	411.82	410.43	596.25
Humic Acid/%	24.40	0.29	0.12	0.06	1.54

retention and aeration properties, promoting healthy root growth. The rice straw and rice husks were collected from ecological farms in the Taihu Lake region and fermented naturally. This natural fermentation not only reduces harmful components but also enhances organic matter content, improving soil structure and increasing substrate aeration.

The seedling substrates in this study were prepared by mixing the above raw materials, using fresh materials to ensure that the nutrients and physicochemical properties of the substrates were maximized. Table 1 lists the key physicochemical properties of the raw materials used, which provides a foundation for the subsequent analysis of the substrate's characteristics.

Experimental Design and Treatment Methods

This experiment set up seven different treatments, including a commercial seedling substrate (CK) and 6 experimental treatments (T1-T6), with each treatment having three replications. The commercial seedling substrate was selected as a control treatment to provide a baseline for comparison. This substrate is a commercially available peat-based seedling mix that complies with NY/T 2118-2012, the Chinese agricultural industry standard for vegetable seedling substrates. The physicochemical properties of CK, including pH, EC, bulk density, and nutrient content, align with the standard's recommended range, ensuring comparability with experimental treatments. The volume ratios of the materials used in each treatment are shown in Table 2. To ensure the reliability of the experimental results, all treatments were prepared according to the respective mixing ratios, and the experimental conditions were strictly controlled.

The selection of these specific ratios was based on prior studies and industry practices. Previous research has demonstrated that certain proportions of kitchen compost and peat significantly affect seedling growth. For instance, a study by Liu et al. found that a 50% kitchen compost and 50% peat mixture produced the best cucumber seedling growth [21]. Building upon this finding, we selected various combinations of kitchen compost, peat, and other organic materials to explore their effects on cucumber seedling development. These selected ratios aim to balance the provision of essential nutrients, aeration, and moisture retention while optimizing growth conditions for cucumber seedlings.

Substrate Preparation

According to the mixing schemes outlined in Table 2, each type of raw material was mixed according to the specified ratios and placed into plastic trays (60 cm × 48 cm × 20 cm) to ensure uniform mixing. To ensure the representativeness of the samples and the accuracy

Table 2. Mixing ratio information of seedling substrate materials.

Treatment	Kitchen Compost	Peat	Fermented Straw	Fermented Rice Husk
T1	15	45	40	0
T2	15	45	0	40
T3	15	45	20	20
T4	30	30	40	0
T5	30	30	0	40
T6	30	30	20	20

of the data, 100 g samples were randomly taken from the mixed substrates for subsequent physicochemical analysis.

Seeding and Management

The seedling substrates for all treatments were placed into 50-cell seedling trays, with one cucumber seed sown per cell, at a depth of approximately 0.5 cm. Each seedling tray was watered evenly with 800 mL of water, and during the experimental period, 400 mL of water was added every two days to maintain optimal moisture levels. All seedling trays were placed in an artificial climate room, where a constant temperature of 25°C and a humidity level of 80% were maintained to simulate the ideal growing conditions for cucumbers. To minimize variations caused by uneven lighting or airflow, seedling trays were rotated every three days within the growth chamber.

Measurement of Substrate Physicochemical Properties

The physicochemical properties of the seedling substrates, including bulk density, relative water content, total porosity, aeration porosity, and water-holding porosity, were determined according to the agricultural industry standard NY/T2118-2012 [22]. To measure these properties, a 200 mL ring knife with a bottom cover was used. The mass of the empty ring knife was recorded as M_0, and the fresh substrate sample was packed evenly into the ring knife, with the total mass recorded as M_1. The ring knife with the substrate was then dried in an oven at 105°C for 4 hours, cooled naturally for 4 hours, and weighed again (M_2). All samples were dried at 105°C until they reached constant weight, which ensured that no fluctuations in moisture content were present. After this, the sample was packed in its compacted form, with the top cover fitted, and the mass recorded as M_3. The ring knife was then submerged in water for 24 hours, and the mass was recorded as M_4. After natural drainage for 3 hours on a filter paper-lined funnel, the final mass was recorded as M_5. These measurements were used to calculate water content (W), bulk density (Y), total porosity (TP), aeration porosity (AP), and water-holding porosity (WHP) using the following formulas:

$$W = (M_1 - M_2)/(M_1 - M_0)$$

$$Y = (M_1 - M_0) \times (1 - W)/200$$

$$TP = (M_4 - M_3)/200$$

$$AP = (M_4 - M_5)/200$$

$$WHP = TP - AP$$

For the determination of the chemical properties of the substrates, several standard methods were employed. pH was measured using a pH meter (Model PHS-3C) with a substrate-to-water ratio of 1:2.5 (w/v) following GB/T 12193-2009. Electrical conductivity (EC) was determined using a conductivity meter (Model DDS-307) at a substrate-to-water ratio of 1:5 (w/v), in accordance with NY/T 1121-2006. To ensure measurement accuracy, all instruments were calibrated before and after each measurement using certified standard solutions. The pH meter was calibrated using standard buffer solutions (pH 4.00, 7.00, 10.00) before each set of measurements. The EC meter was calibrated using a 1413 μS/cm conductivity standard solution. Measurements were conducted in triplicate to minimize deviations.

The alkali-hydrolyzed nitrogen content was measured using the Kjeldahl method described in NY/T 1121-2006. Available phosphorus was quantified through the molybdenum-antimony colorimetric method as outlined in GB/T 19489-2008, while available potassium was assessed using flame photometry as specified in NY/T 1121-2006. The humic acid content was determined by extracting the humic acid with sodium hydroxide and measuring its absorbance at 465 nm using a spectrophotometer, following the method described in NY/T 2118-2012. Finally, the chloride ion content was determined by the silver nitrate titration method, according to NY/T 1121-2006, to evaluate any potential impact on plant growth.

Measurement of Cucumber Seedling Growth Indicators

Ten days after sowing, the germination rate of cucumber seeds was calculated by counting the number of seedlings. Fifteen healthy cucumber seedlings were randomly selected from each treatment group 15 days after sowing. Seedling height was measured using a ruler, and stem diameter was measured with a caliper. Leaf area was determined using the length-to-width ratio method, while chlorophyll content was measured using a CCM-200plus chlorophyll content meter on fully expanded leaves, with the result expressed as the Chlorophyll Content Index (SPAD). The total root length, total root area, and total root volume of cucumber seedlings were measured using a root scanner. The fresh weight of the aboveground and underground parts of the seedlings was determined using an electronic balance. The samples were then subjected to enzymatic inactivation at 90°C, followed by drying at 60°C until constant weight was achieved to determine the dry weight. The seedling index was calculated using the formula [19]:

$$\text{Seedling Index} = \left(\frac{\text{Stem thickness}}{\text{Seedling Height}} + \frac{\text{Underground Dry Weight}}{\text{Aboveground Dry Weight}}\right) \times (\text{Aboveground Dry Weight} + \text{Underground Dry Weight})$$

Additionally, the degree of membership for each growth indicator under different treatments was calculated using the membership function method [23].

Table 3. Physical Properties of Seedling Substrates under Different Treatments.

Treatment	Bulk Density/ ($g·cm^{-3}$)	Moisture Content/%	TP/%	AP/%	WHP/%
CK	0.44±0.04a	32.33±1.06d	0.83±0.04b	0.23±0.03ab	0.59±0.04a
T1	0.41±0.02a	31.21±1.75e	0.85±0.01a	0.19±0.04cd	0.66±0.06b
T2	0.42±0.04a	34.36±1.91c	0.78±0.02d	0.18±0.02d	0.59±0.08b
T3	0.36±0.02b	36.04±3.37ab	0.81±0.03b	0.21±0.01abc	0.60±0.04b
T4	0.41±0.01a	37.08±1.51a	0.80±0.03c	0.21±0.01bcd	0.59±0.01b
T5	0.42±0.02a	35.36±2.42bc	0.70±0.02f	0.24±0.02a	0.46±0.02c
T6	0.43±0.03a	31.26±3.01e	0.75±0.03e	0.22±0.01abc	0.53±0.01d

Note: Different lowercase letters in the same column represent significant differences ($P<0.05$).

The membership function method was used to evaluate seedling growth by integrating multiple indicators (e.g., plant height, stem diameter, leaf area, chlorophyll content, root length). Unlike traditional ANOVA, which analyzes each indicator separately, the fuzzy membership function synthesizes multiple factors into a single ranking score. For example, while ANOVA might show that T2 has a higher plant height but lower root length, the membership function provides a holistic performance ranking. This approach better reflects the overall suitability of each treatment for seedling growth. A higher membership value indicates better seedling growth under the corresponding substrate composition, allowing for a comprehensive evaluation of the seedling growth indicators. The formula for calculating the membership value is:

$$U(X_i) = \frac{X_{ij} - X_{jmin}}{X_{jmax} - X_{jmin}}$$

Where i represents the treatment, j represents the seedling growth indicator, X_{ij} is the measured value for indicator j under treatment i, X_{jmax} is the maximum value of indicator j across all treatments, and X_{jmin} is the minimum value of indicator j across all treatments.

Data Processing

Raw data were recorded using Excel 2019. One-way analysis of variance (ANOVA) was performed using Duncan's multiple range test in DPS 18.1 software [24]. Correlation analysis and graphical representations were conducted using Origin 2021 Pro software.

Results

Physical Properties of Seedling Substrates under Different Treatments

The agricultural industry standard NY/T 2118-2012 provides clear recommendations for the physical properties of vegetable seedling substrates: bulk density should be between 0.20 and 0.60 $g·cm^{-3}$, total porosity should exceed 60%, aeration porosity should exceed 15%, water-holding porosity should exceed 45%, and moisture content should be less than 35%. As shown in Table 3, the CK, T1, T2, and T6 treatments meet the requirements of the industry standard for seedling substrate physical properties, providing relatively good growth conditions for crops. Among these treatments, there were no significant differences in bulk density. For moisture content, the treatments followed the order: T2 > CK > T6 > T1. Specifically, T2 treatment showed an increase of 6.27%, 9.91%, and 2.60% compared to CK, T6, and T1, respectively, and the differences between them were significant ($P<0.05$). Regarding total porosity, significant differences were observed ($P<0.05$), with T1 having the highest value, showing increases of 2.41%, 8.97%, and 13.33% compared to CK, T2, and T6, respectively. The aeration porosity was highest in the CK treatment, which was 4.55%, 21.05%, and 27.78% higher than T6, T1, and T2, respectively. Significant differences were found between CK and T1, T2 treatments ($P<0.05$), but no significant difference between CK and T6, and no significant difference between T1 and T2. T1 treatment had the highest water-holding porosity, with increases of 11.86%, 11.86%, and 24.53% compared to CK, T2, and T6, respectively. No significant difference was found between T1 and T2 treatments.

Chemical Properties of Seedling Substrates under Different Treatments

Previous studies have indicated that a pH range of 5.5 to 7.5 and an EC of less than 2.5 $mS·cm^{-1}$ are optimal for seedling growth. As shown in Table 4, the pH and EC values of the CK and T2 treatments fall within the ideal range for seedling growth. The pH and EC of the CK treatment were both lower than those of the T2 treatment, with significant differences ($P<0.05$). Specifically, the pH of CK decreased by 20.31% compared to T2, and the EC decreased by 73.08%. Regarding chloride ion content, previous

Table 4. Chemical Properties of Seedling Substrates under Different Treatments.

Treatment	pH	EC/(mS·cm^{-1})	Chloride Ion/%	Humic Acid/%
CK	5.73±0.14e	0.28±0.02e	0.02±0.00e	1.54±0.23a
T1	7.62±0.32c	1.41±0.09b	0.15±0.01b	3.79±0.21b
T2	7.19±0.24d	1.04±0.11d	0.06±0.01d	3.19±0.18b
T3	7.56±0.19c	1.03±0.97d	0.12±0.02a	3.80±0.75b
T4	8.01±0.18b	1.47±0.13b	0.18±0.01b	7.19±0.32c
T5	8.04±0.31b	2.11±0.21a	0.11±0.02a	7.50±0.88c
T6	8.18±0.27a	1.13±0.87c	0.16±0.01c	7.60±0.64c

Note: Different lowercase letters in the same column represent significant differences (P<0.05).

research has shown that when the chloride ion content in soil exceeds 0.06%, cucumber seedling growth is significantly inhibited. In this experiment, the chloride ion content in the CK and T2 treatments was relatively low, with T2 showing significantly higher chloride ion content than CK (P<0.05). This can be attributed to the higher salt content in kitchen waste compost, which increased the chloride ion content when added to the seedling substrate. Humic acid plays a significant role in promoting seed germination and nutrient absorption in cucumber plants. Its content is also an important indicator for evaluating seedling substrate quality. In this study, the CK treatment had the lowest humic acid content, while no significant differences were observed among the T1-T3 treatments. The T4-T6 treatments had the highest humic acid content, likely due to the higher addition of kitchen waste compost, which contains relatively high levels of humic acid.

Nutrient Content in Seedling Substrates under Different Treatments

The nutrient content in seedling substrates plays a crucial role in cucumber seed germination and seedling growth. The experimental results (Table 5) show that the alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), and available potassium (AK) contents in the CK treatment were significantly lower than those in the other treatments (P<0.05). The AN, AP, and AK contents in the T1-T3 treatments were significantly lower than those in the T4-T6 treatments (P<0.05). This can be attributed to the lower addition of kitchen waste compost in the T1-T3 treatments compared to the T4-T6 treatments, as kitchen waste compost contains higher nutrient levels than peat. In terms of organic matter content, the T1-T3 treatments also had significantly lower organic matter content than the T4-T6 treatments (P<0.05). According to the agricultural industry standard NY/T2118-2012, the organic matter content in vegetable seedling substrates should exceed 35%. Among the treatments, only the CK and T4 treatments met this standard. The organic matter content in the T5 and T6 treatments was closest to the requirement set in NY/T2118-2012.

Seedling Growth Indicators under Different Treatments

According to the agricultural industry standard NY/T 2118-2012, the seedling emergence rate of vegetable seedling substrates should not be lower than 90%, and all treatments in this experiment met this standard. When the same proportion of rice husk and straw was added, except for chlorophyll content, the seedling growth indicators for the substrate with 25%

Table 5. Nutrient Content in Seedling Substrates Under Different Treatments.

Treatment	AN/(mg·kg^{-1})	AP/(mg·kg^{-1})	AK/(mg·kg^{-1})	Organic Matter/%
CK	497.70±17.23e	97.20±3.85a	596.25±41.83a	35.21±1.02a
T1	1222.50±16.71d	129.10±7.31b	1560.37±107.06b	25.49±1.64b
T2	1217.70±25.37d	141.10±11.56c	1907.37±167.54c	22.73±1.32c
T3	1339.70±21.33c	147.00±18.73d	1783.72±133.80d	23.91±1.23c
T4	1507.37±22.81b	204.30±11.51e	2799.45±181.97e	38.34±3.19d
T5	1705.37±12.10a	268.00±13.87f	3186.14±206.13f	34.55±3.08a
T6	1499.03±29.79b	214.50±15.32g	3125.18±283.01f	34.79±2.87a

Note: Different lowercase letters in the same column represent significant differences (P<0.05).

Table 6. Aboveground Growth Performance of Cucumber Seedlings.

Treatment	Germination Rate (%)	Plant Height (cm)	Stem Diameter (mm)	Leaf Area (cm²)	Chlorophyll Content (SPAD)	Fresh Weight of Aboveground (g)	Dry Weight of Aboveground (g)
CK	94.00±0.00ab	5.63±0.52abc	0.37±0.11ab	43.64±11.19a	41.67±1.43c	2.46±0.86a	1.76±0.18 ab
T1	92.67±2.87ab	6.23±0.34a	0.38±0.05ab	34.59±5.52b	43.90±0.49b	2.00±0.45ab	1.54±0.04c
T2	92.00±0.00b	5.69±0.87a	0.36±0.09abc	42.15±11.53a	41.93±3.00bc	2.44±0.87a	1.79±0.02a
T3	92.67±2.87ab	5.85±1.33ab	0.40±0.05a	39.68±4.96a	43.43±2.23bc	2.40±0.96a	1.72±0.11b
T4	94.67±2.87a	5.05±0.56c	0.32±0.04c	19.99±4.03d	47.10±3.05a	1.51±0.35c	1.17±0.01e
T5	94.00±0.00ab	5.39±1.01bc	0.35±0.12bc	26.14±3.61c	42.00±6.15c	1.72±0.29bc	1.25±0.13d
T6	94.67±5.74a	5.39±0.47bc	0.35±0.05bc	28.76±2.84c	42.63±1.37bc	1.63±0.86bc	1.19±0.14e

Note: Different lowercase letters in the same row represent significant differences ($P<0.05$).

kitchen waste compost were significantly higher than those with 50% kitchen waste compost. Specifically, leaf area, total root length, total root area, fresh weight of the aerial part, dry weight of the aerial part, and seedling vigor index all showed significant differences ($P<0.05$). This suggests that the substrate with 25% kitchen waste compost addition promotes cucumber seedling growth, while the addition ratio of rice husk and straw still has a significant impact (Table 6, Table 7).

For the T1 treatment, plant height and chlorophyll content were higher than those in the T2 and T3 treatments, but no significant difference was observed. In the T2 treatment, leaf area, total root length, total root area, fresh weight of the aerial part, dry weight of the aerial part, fresh weight of the underground part, and dry weight of the underground part were higher than those in T1 and T3 treatments, with total root length, total root area, dry weight of the aerial part, fresh weight of the underground part, and dry weight of the underground part showing significant differences ($P<0.05$). The T3 treatment exhibited a higher stem diameter than the T1 and T2 treatments, though no significant difference was found.

In conclusion, the T2 treatment resulted in the optimal growth conditions for cucumber seedlings. When comparing T2 with the CK treatment, it was found that, except for plant height, chlorophyll content, and dry weight of the aerial part, the CK treatment showed higher values in all other growth indicators and seedling vigor index, though none of these differences reached statistical significance.

Comprehensive Evaluation of Cucumber Seedling Growth

In this study, both the seedling index (Fig. 1a)) and fuzzy membership function method (Fig. 1b)) were used for a comprehensive evaluation of cucumber seedling growth. The results showed that the seedling index of the CK treatment was 1.00, the highest, indicating that this treatment effectively promoted cucumber seedling growth and resulted in the most robust overall development. The T2 treatment had a seedling index of 0.88, ranking second among all treatments, showing good growth performance. In contrast, the seedling indices of the T1, T3, T5, and T6 treatments were significantly lower than those of CK and T2, with

Table 7. Underground Growth Performance of Cucumber Seedlings.

Treatment	Root Length (cm)	Root Area (cm²)	Fresh Weight of Underground (g)	Dry Weight of Underground (g)
CK	75.30±5.25a	77.93±0.57a	1.06±0.37a	0.35±0.09a
T1	41.72±6.74bc	45.33±10.56bc	0.75±0.23b	0.25±0.08b
T2	73.99±6.13a	74.47±5.70a	1.05±0.39a	0.33±0.06a
T3	46.25±15.53b	48.94±17.77b	0.79±0.18b	0.24±0.06b
T4	25.74±9.87d	30.69±9.25d	0.57±0.15b	0.19±0.06b
T5	36.80±17.65bc	40.55±23.51bcd	0.68±0.33b	0.21±0.11b
T6	34.85±12.40cd	37.27±17.66cd	0.68±0.28b	0.21±0.18b

Note: Different lowercase letters in the same row represent significant differences ($P<0.05$).

values of 0.36, 0.40, 0.47, and 0.15, respectively, and T6 showed the poorest performance. The T4 treatment had a seedling index of 0.00, indicating almost no promotion of cucumber seedling growth, which was significantly lower than that of other treatments, suggesting that this treatment had a strong inhibitory effect on seedling growth (Fig. 1a)).

From the fuzzy membership function analysis, the average membership value for the CK treatment was 10.61, the highest among all treatments, confirming its optimal seedling growth effect. The T2 treatment had an average membership value of 9.33, ranking second and demonstrating relatively good growth performance. The T3 treatment had a membership value of 7.54, which was at a moderate level, indicating its performance was average. The T1 treatment had an average membership value of 6.29, which was higher than T3, T5, and T6, but still significantly lower than CK and T2, indicating poorer growth promotion. The T5 and T6 treatments had membership values of 3.53 and 3.46, respectively, both of which were quite low, indicating that these treatments did not significantly promote cucumber seedling growth. The T4 treatment had a membership value of 2.00, which was much lower than the other treatments, showing that it barely supported cucumber seedling growth (Fig. 1b)).

Overall, considering both the seedling index and fuzzy membership function analysis, it can be concluded that the CK treatment performed the best and is suitable for cucumber seedling cultivation. The T2 treatment also showed good performance, especially in the fuzzy membership function evaluation, where it ranked second, suggesting it also promoted healthy seedling growth. The T1 and T3 treatments had poorer overall performance, although some growth indicators showed positive results, but they were still inferior to CK and T2. The T5 and T6 treatments performed poorly, particularly in terms of the seedling index, which may be due to the excessive amount of kitchen waste compost that hindered seedling growth. The T4 treatment performed the worst and requires further optimization of its substrate composition. In cucumber seedling cultivation, the proper substrate composition is crucial for promoting seedling growth, particularly the appropriate balance of kitchen waste compost with rice husks and straw.

Correlation Analysis

The growth of cucumber seedlings is closely related to the physical properties and nutrient content of the substrate, and correlation analysis reveals significant connections between these factors. First, in terms of physical properties, moderate bulk density, high porosity, and optimal moisture levels are critical for the coordinated development of both aboveground and underground plant parts. Bulk density showed a negative correlation with plant height, stem diameter, and leaf area but was positively correlated with root length, suggesting that higher bulk density may restrict aboveground growth while providing support for root development. Total porosity and water-holding porosity exhibited significant positive correlations with plant height, stem diameter, and leaf area, indicating that a well-structured porous substrate promotes aboveground growth, particularly plant height. Moisture content was positively correlated with chlorophyll accumulation but negatively correlated with the fresh weight of the aboveground part, suggesting that excessive moisture could hinder aboveground biomass accumulation, whereas moderate moisture supports photosynthetic activity.

Regarding nutrient content, indices such as alkali-hydrolyzed nitrogen, available phosphorus, and available potassium demonstrated inhibitory effects on seedling growth at high concentrations. Alkali-hydrolyzed nitrogen showed negative correlations with plant height, leaf area, and root length, indicating that excessive nitrogen could lead to nutrient imbalances, thereby suppressing both aboveground and underground growth. Similarly, available phosphorus and potassium were negatively correlated with root length and leaf area, suggesting that elevated phosphorus and potassium levels might impede root and leaf development. Humic acid, on the other hand, positively influenced chlorophyll content and photosynthesis under moderate conditions, but excessive levels appeared to negatively affect root development.

Additionally, the coordination between aboveground and underground growth plays a vital role in seedling development. Leaf area exhibited significant positive correlations with plant height, stem diameter, and root metrics, highlighting its importance in supporting photosynthesis and biomass accumulation. Root length was strongly positively correlated with the fresh weight of the aboveground part and the dry weight of the underground part, further emphasizing the essential role of healthy root systems in sustaining overall plant growth. Overall, moderate bulk density, an appropriate porosity structure, and balanced nutrient levels are key to optimizing seedling substrates. By carefully regulating the physical and chemical properties of the substrate, the healthy growth of cucumber seedlings can be effectively promoted, providing a solid foundation for subsequent transplantation and production (Fig. 2).

Discussion

This study comprehensively analyzed the effects of different seedling substrate treatments on cucumber seedling growth, focusing on how physical properties, chemical characteristics, and nutrient content collectively influence plant development. The findings highlight the critical role of optimizing substrate properties to achieve efficient seedling cultivation while

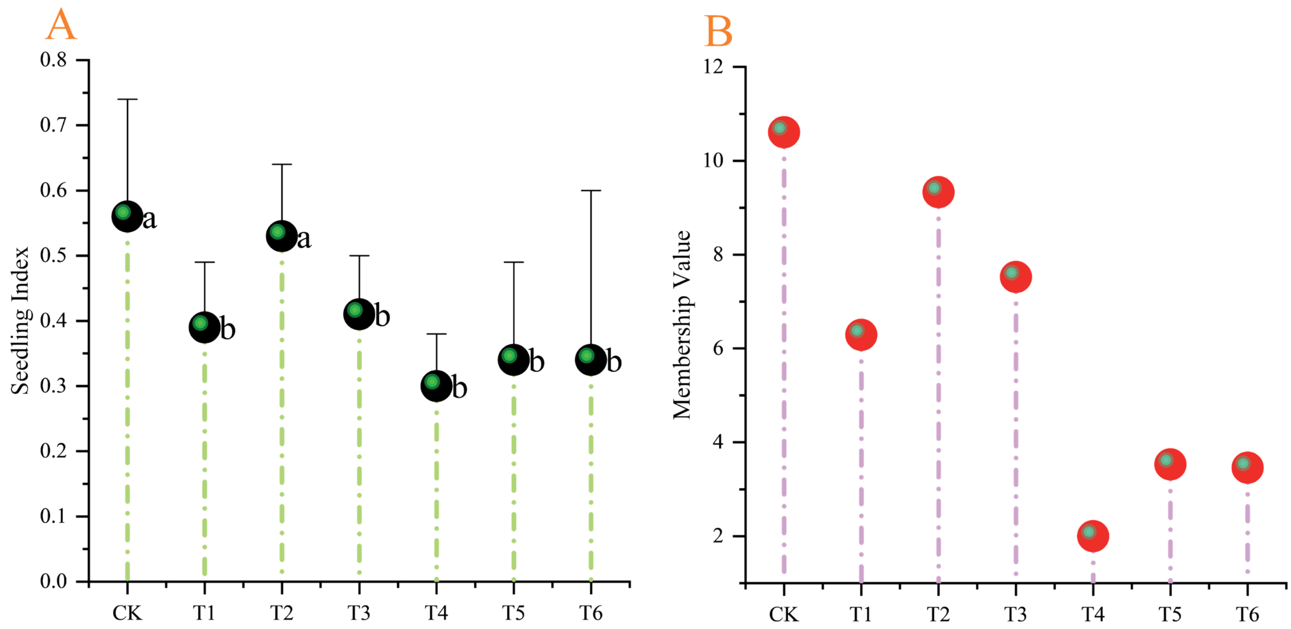

Fig. 1. Comprehensive Evaluation of Cucumber Seedling Growth.
Note: Different lowercase letters in the same column represent significant differences (*P*<0.05).

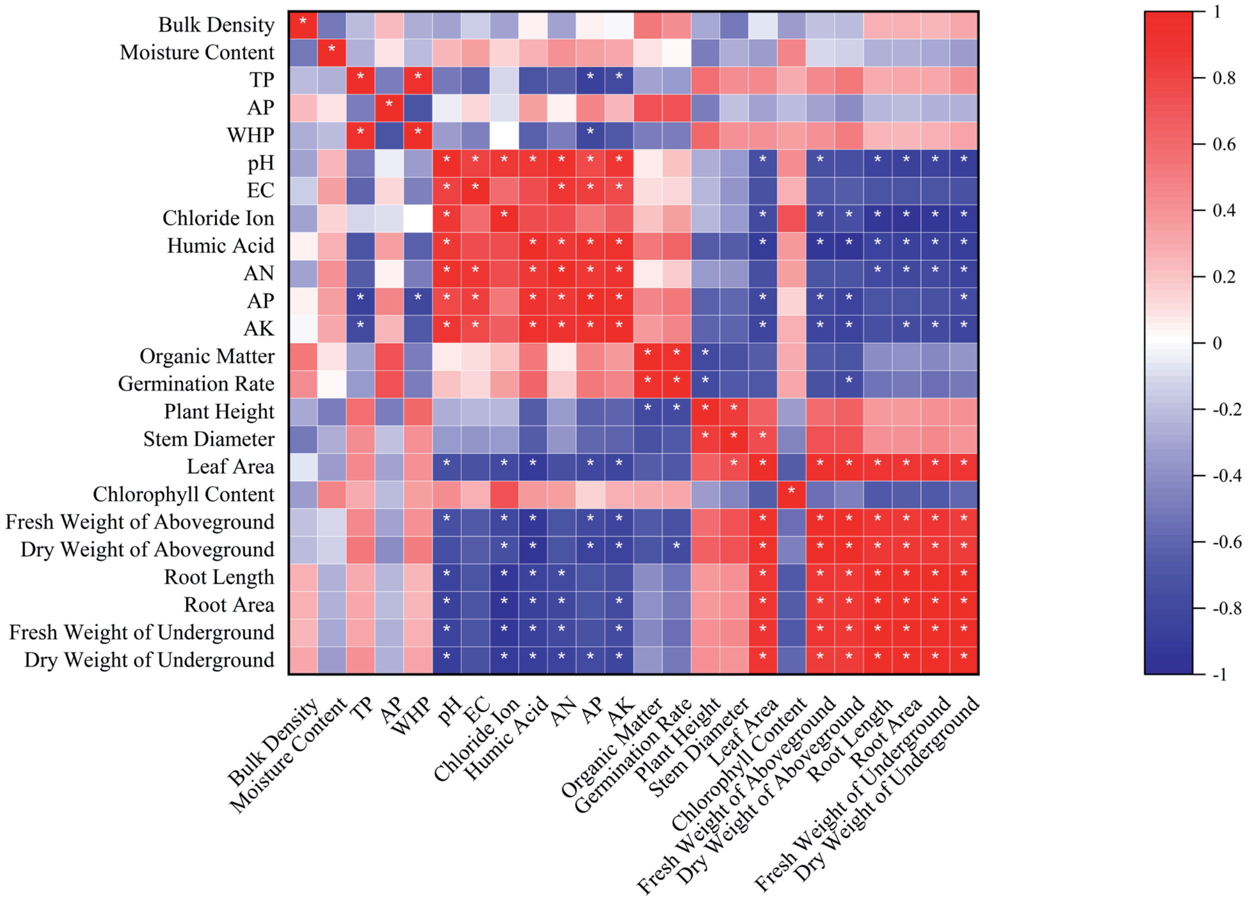

Fig. 2. Correlation Analysis.
Note: * represents significant difference *P*<0.05.

providing practical insights into the resource utilization of kitchen waste.

The physical properties of the substrate significantly impacted both aboveground and underground seedling growth. Substrates with moderate bulk density (0.36-0.44 $g\cdot cm^{-3}$), such as the T1 and T2 treatments, demonstrated superior performance across all growth indicators. T3, with its lower bulk density, facilitated root extension but exhibited reduced aboveground biomass, likely due to insufficient water retention. Conversely, higher bulk density restricted gaseous exchange and hindered root respiration under high moisture conditions. This highlights the importance of balancing structural stability with aeration, aligning with findings from previous studies on substrate optimization [25].

Porosity was another critical factor influencing seedling growth. Treatments with higher total porosity (e.g., T1 and T2) provided favorable root development and aboveground growth. However, T1's inadequate air porosity may have limited oxygen supply, reducing underground biomass accumulation. T2 achieved an optimal balance of porosity, supporting the balanced growth of both aboveground and underground parts. This demonstrates the significance of optimizing pore structure to enhance both aeration and water retention in substrate design, which could be applied to large-scale agricultural settings.

Moisture content further influenced seedling performance, with treatments like T4 and T5 supporting chlorophyll accumulation but likely causing oxygen deficiency in the root zone, limiting root growth. T2, with moderate moisture content, effectively supported both aboveground and underground growth, highlighting the importance of precise water management. In large-scale farming, irrigation practices should be adjusted to prevent over-saturation and promote root health, ensuring the sustainable use of water resources.

Chemical properties, including pH, EC, and chloride ion concentration, were critical for seedling growth. T2 exhibited an optimal pH of 7.19, within the neutral range conducive to nutrient absorption and metabolic activity. In contrast, treatments such as T4 and T5, with alkaline pH levels exceeding 8.0, likely inhibited the availability of essential micronutrients like iron and zinc, adversely affecting plant photosynthesis and growth [26]. These findings align with the recommendation that substrate pH be maintained between 5.5 and 7.5 [27].

EC and chloride ion concentrations, key indicators of salinity, were critical in influencing seedling performance [16]. High EC values (e.g., 2.11 $mS\cdot cm^{-1}$ in T5) significantly suppressed root length and fresh weight, while T2, with an EC of 1.04 $mS\cdot cm^{-1}$, demonstrated optimal growth across all indicators. Chloride ion concentrations exceeding the threshold of 0.06% (e.g., in T4 and T5) showed notable inhibition of root systems and leaf area. T2 successfully controlled salinity levels, creating a favorable environment for seedling development. These results highlight the importance of balancing nutrient provision and salt control when incorporating kitchen compost into substrates [6].

Nutrient content analysis revealed that adequate levels of alkali-hydrolyzed nitrogen, available phosphorus, and potassium were vital for promoting growth, but excessive concentrations caused nutrient imbalances that inhibited both aboveground and underground development [28, 29]. High nitrogen levels, for example, led to excessive vegetative growth at the expense of root system development. Over-concentrated phosphorus and potassium disrupted nutrient synergy, reducing overall uptake efficiency. Despite exceeding industry standards, T2 did not cause seedling damage, demonstrating the potential for fine-tuned nutrient optimization in substrate formulation.

The comprehensive evaluation showed that T2 (15% kitchen compost + 45% peat + 40% rice husk) performed best among all treatments, significantly enhancing cucumber seedling quality. T2 outperformed other treatments in terms of leaf area, root length, and fresh weight, highlighting the effectiveness of controlled kitchen compost addition and proper integration of organic materials. However, chloride ion stress remains a challenge, suggesting further research on mitigating salinity stress through exogenous substances such as brassinolide or organosilicon [30, 31].

While the study focused on cucumber seedlings, the results can be generalized to other crops, particularly those requiring similar growth conditions. Future research should explore the applicability of these substrates across a broader range of crops, including tomatoes, peppers, eggplants, and lettuce, as these vegetables also benefit from similar substrate conditions—well-drained yet capable of retaining sufficient moisture for optimal growth. These crops, like cucumbers, are sensitive to nutrient imbalances and salinity, so the fine-tuned nutrient balance demonstrated by T2 could improve seedling production efficiency across a variety of crop types.

Additionally, leafy greens (e.g., spinach, kale) and herbs (e.g., basil, cilantro) may also benefit from similar substrates, as these plants have high water requirements and benefit from the ability to manage moisture levels effectively. However, these crops may require slight adjustments in the nutrient profile – such as a higher ratio of nitrogen or potassium – to promote rapid leaf growth and meet the demands of high-yield production systems. Root crops, such as carrots and beets, may require a slightly different substrate composition, with modifications in bulk density and porosity to support root expansion and prevent compaction. For instance, root crops may benefit from substrates with lower bulk density to encourage root elongation while still ensuring adequate water retention for nutrient uptake.

Scalability is an important factor, as large-scale agricultural systems may require modifications in substrate formulation to address site-specific challenges, such as local soil characteristics, climate conditions, or crop types. For instance, hot and dry climates may require substrates with higher moisture retention capacity, while humid regions may prioritize substrates that improve drainage and prevent waterlogging.

In conclusion, the findings of this study not only contribute to the development of sustainable substrates for cucumber seedlings but also have broader applications across various crops. The principles of substrate optimization, such as balancing moisture retention, aeration, and nutrient availability, can be applied to improve seedling growth in a variety of crops, thereby advancing sustainable agriculture and promoting the efficient use of organic waste. Future research should focus on adapting these findings to other crop species and expanding the research to multi-crop systems that can maximize organic waste recycling and support global agricultural sustainability.

Conclusions

This study demonstrated that the moderate addition of kitchen compost, combined with rice husks and straw in a balanced ratio, significantly optimized the physical structure and nutrient supply of seedling substrates, thereby promoting healthy cucumber seedling growth. The T2 treatment (15% kitchen compost + 45% peat + 40% rice husk) showed the best performance, combining ideal physical and chemical properties with nutrient balance. This study provides valuable insights into the resource utilization of kitchen waste and offers important guidance for optimizing vegetable seedling substrates. The findings contribute to the efficient recycling of agricultural waste and support sustainable development in modern agriculture. Future research should explore the application of this substrate in other crops and investigate its scalability and implementation in large-scale agricultural systems.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. MUHAMMAD T., JIANG C., LI Y., MANAN I., MA C., GENG H., FATIMA I., ADNAN M. Impacts and mechanism of coal fly ash on kitchen waste composting performance: The perspective of microbial community. Chemosphere. **350**, 141068, **2024**.
2. LIU Z., GE L., LI S., PAN R., LIU X. Kitchen Waste Compost’s Impact on Rice Quality, Yield, and Soil Environment. Polish Journal of Environmental Studies. **32** (4), 3225, **2023**.
3. HU T., LIN Y., LIU Y., ZHAO Q., YU H., YANG Z., MENG F. Microbial electrochemical enhanced composting of sludge and kitchen waste: Electricity generation, composting efficiency and health risk assessment for land use. Heliyon. **10** (15), e35678, **2024**.
4. ZHANG X., KHALID M., WANG R., CHI Y., ZHANG D., CHU S., YANG X., ZHOU P. Enhancing lettuce growth and rhizosphere microbial community with Bacillus safensis YM1 compost in soilless cultivation: An agricultural approach for kitchen waste utilization. Scientia Horticulturae. **321**, 112345, **2023**.
5. PENG X.-Y., WANG S.-P., CHU X.-L., SUN Z.-Y., XIA Z.-Y., XIE C.-Y., GOU M., TANG Y.-Q. Valorizing kitchen waste to produce value-added fertilizer by thermophilic semi-continuous composting followed by static stacking: Performance and bacterial community succession analysis. Bioresource Technology. **373**, 128732, **2023**.
6. DU S., DING S., WEN X., YU M., ZOU X., WU D. Investigating inhibiting factors affecting seed germination index in kitchen waste compost products: Soluble carbon, nitrogen, and salt insights. Bioresource Technology. **406**, 130995, **2024**.
7. SHEN C., SHANGGUAN H., FU T., MI H., LIN H., HUANG L., TANG J. Electric field-assisted aerobic co-composting of chicken manure and kitchen waste: Ammonia mitigation and maturation enhancement. Bioresource Technology. **391**, 129931, **2024**.
8. MA R., WANG J., LIU Y., WANG G., YANG Y., LIU Y., KONG Y., LIN J., LI Q., LI G., YUAN J. Dynamics of antibiotic resistance genes and bacterial community during pig manure, kitchen waste, and sewage sludge composting. Journal of Environmental Management. **345**, 118651, **2023**.
9. CHANG R., GUO Q., PANDEY P., LI Y., CHEN Q., SUN Y. Pretreatment by composting increased the utilization proportion of pig manure biogas digestate and improved the seedling substrate quality. Waste Management. **129**, 47, **2021**.
10. XU S.-Y., WEI J.-K., XUE F.-Y., LI W.-C., GUAN T.-K., HU B.-Y., CHEN Q.-J., HAN Y.-Y., LIU C.-J., ZHANG G.-Q. Microbial inoculation influences microbial communities and physicochemical properties during lettuce seedling using composted spent mushroom substrate. Applied Soil Ecology. **174**, 104418, **2022**.
11. FAN X., WEI Y., SONG D., ZHOU T., LI R., SU X., ZHANG T., CHENG S., XIAO R. Biochar enhanced co-composting for peat-free seedling substrate: A win-win solution for sustainable development of modern vegetable industry. Process Safety and Environmental Protection. **2024**.
12. CONIGLIO R., SCHÜTT F., APPELT J. Challenges for the utilization of ammoxidized lignins and wood fibres as a peat substitute in horticultural substrates. Journal of Cleaner Production. **475**, 143737, **2024**.
13. DU M., XIAO Z., LUO Y. Advances and emerging trends in cultivation substrates for growing sprouts and microgreens toward safe and sustainable agriculture. Current Opinion in Food Science. **46**, 100863, **2022**.
14. LIN L., QIN J., ZHANG Y., YIN J., GUO G., KHAN M.A., LIU Y., LIU Q., WANG Q., CHANG K., MAŠEK

O., WANG J., HU S., MA W., LI X., GOUDA S.G., HUANG Q. Assessing the suitability of municipal sewage sludge and coconut bran as breeding medium for Oryza sativa L. seedlings and developing a standardized substrate. Journal of Environmental Management. **344**, 118644, **2023**.

15. ANTUNES L.F.D.S., VAZ A.F.D.S., MARTELLETO L.A.P., LEAL M.A.D.A., ALVES R.D.S., FERREIRA T.D.S., RUMJANEK N.G., CORREIA M.E.F., ROSA R.C.C., GUERRA J.G.M. Sustainable organic substrate production using millicompost in combination with different plant residues for the cultivation of Passiflora edulis seedlings. Environmental Technology & Innovation. **28**, 102612, **2022**.
16. MENG X., WANG Q., LV Z., CAI Y., ZHU M., LI J., MA X., CUI Z., REN L. Novel seedling substrate made by different types of biogas residues: Feasibility, carbon emission reduction and economic benefit potential. Industrial Crops and Products. **184**, 115028, **2022**.
17. LIU C., LI H., NI J.-Q., ZHUO G., ZHANG Q., ZHENG Y., ZHEN G. Synergistic effects of heterogeneous mature compost and aeration rate on humification and nitrogen fixing during kitchen waste composting. Journal of Environmental Management. **373**, 123743, **2025**.
18. LIU Z., GE L., LI S., PAN R., LIU X. Study on the Effect of Kitchen Waste Compost Substrate on the Cultivation of Brassica chinensis L. Polish Journal of Environmental Studies. **32** (5), 4139, **2023**.
19. WANG C., CHEN R., LU J., CHI H., TANG Y., ZHU X., LIU X. Impact of Exogenous Addition of Sulphur Powder on the Effectiveness of Kitchen Waste Compost Seedling Substrates. Polish Journal of Environmental Studies. **33** (6), 6389, **2024**.
20. ZHANG R., LI Y., QI C., LIU B., ZHOU K., YANG Y., DAI H., ZHAO Z., BIAN B. A novel strategy for urban and rural organic waste utilization with outstanding integrated benefits: based on study in China's Taihu Lake region. Journal of Cleaner Production. **450**, 142076, **2024**.
21. LIU X., SONG P., LIN Y., WANG Q., WANG L., TIAN G. Study on the ratio of food waste compost and peat to cucumber seedling substrate. Journal of Shanxi Agricultural University (Natural Science Edition). **42** (1), 35, **2022**.
22. YANG J., DING D., ZHANG X., GU H. A comparative analysis of soil physicochemical properties and microbial community structure among four shelterbelt species in the northeast China plain. Microbiology Spectrum. **12** (4), **2024**.
23. SINGH A., KUMAR A., KUMAR R., PRAKASH J., KUMAR N., VERMA A.K. Evaluation of salt tolerance in jamun (Syzygium cumini L. Skeels) using morpho-physiological traits and membership function analysis. Scientia Horticulturae. **326**, 112742, **2024**.
24. TANG Q.-Y., ZHANG C.-X. Data Processing System (DPS) software with experimental design, statistical analysis and data mining developed for use in entomological research. Insect Science. **20** (2), 254, **2013**.
25. GALLEGOS-CEDILLO V.M., NÁJERA C., GRUDA N. S., SIGNORE A., GALLEGOS J., RODRíGUEZ R., OCHOA J., EGEA-GILABERT C., FERNÁNDEZ J.A. An in-depth analysis of sustainable practices in vegetable seedlings nurseries: A review. Scientia Horticulturae. **334**, 113342, **2024**.
26. SHAKEEL S., MAHMOOD R., FATIMA A., NADEEM F., ALI S., ALI N., HAIDER M.S., MA Q. Iron (Fe) and zinc (Zn) coated urea application enhances nitrogen (N) status and bulb yield of onion (A. cepa) through prolonged urea-N stay in alkaline calcareous soil. Scientia Horticulturae. **336**, 113421, **2024**.
27. PENG T., QU F., WANG Z., LI Q., WANG X., ZHANG Y., XIONG X., LI G., HU S., HU X. Bacillus velezensis enhances tomato seedling productivity by coordinating functional traits and substrate properties systematically. Scientia Horticulturae. **339**, 113905, **2025**.
28. RAIMAM M.P., DE CASTRO G.L.S., RODRIGUES G.R., DE MORAES A.J.G., DA SILVA G.B. Inoculation of Bacillus sp. improves root architecture, gas exchange and efficiency of nutrient use in Corymbia seedlings. Scientia Horticulturae. **338**, 113756, **2024**.
29. CHEN W., HE L., TIAN S., YUAN D., MASABNI J., XIONG H., ZOU F. The role of ectomycorrhization with Scleroderma sp. in promoting substrate nutrients mobilization under phosphorus-enriched compost amendment: A case study with Castanea henryi seedlings. Forest Ecology and Management. **532**, 120823, **2023**.
30. HUALPA-RAMIREZ E., CARRASCO-LOZANO E.C., MADRID-ESPINOZA J., TEJOS R., RUIZ-LARA S., STANGE C., NORAMBUENA L. Stress salinity in plants: New strategies to cope with in the foreseeable scenario. Plant Physiology and Biochemistry. **208**, 108507, **2024**.
31. AHMAD B., MUKARRAM M., CHOUDHARY S., PETRÍK P., DAR T.A., KHAN M.M.A. Adaptive responses of nitric oxide (NO) and its intricate dialogue with phytohormones during salinity stress. Plant Physiology and Biochemistry. **208**, 108504, **2024**.