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ORIGINAL PAPER

Biodegradation of Some Lignocellulosic Wastes during Composting and Their Valorization as Plant Growth Media

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Abstract

Purpose The purpose of this study was characterization of lignocellulosic agricultural wastes biodegradation during composting process and evaluating composts as alternative growth media.

Methods In this study, agricultural wastes such as spent mushroom (reishi) substrate (SMS), hazelnut pruning waste (HPW), and spent coffee grounds (SCG) were used for composting. K1, K2, and K3 composts were obtained from mainly SMS, HPW, and SCG, respectively. Chemical content and FTIR and TGA evaluation of final composts were compared to initial mixtures or agricultural wastes as controls. Height and dry biomass of tomato seedlings and fresh weight of shoots, fresh yield, and dry biomass of microgreens cultivated in growth media with different proportions of compost fertilizers were compared to those cultivated in peat moss (control).

Results Holocellulose/lignin of all initial mixtures decreased in final compost fertilizers. Absorption bands belonging to carbohydrates, aliphatic and nitrogen compounds that changed were evaluated between agricultural wastes and final composts. Dry biomass of tomato seedlings in growth media of SMS1 (90% K1 + 10% sand), SCG1 (90% K3 + 10% sand), SCG2 (45% K3 + 45% peat + 10% sand) and 15 + 15 + 15 (compound fertilizer) was higher than the control. Fresh yield of *Lepidium sativum* microgreens was higher in growth media of SCG1, SCG2, and SCG3 (20% K3 + 70% peat + 10% sand) at 1.890, 1.908, and 1.799 kg m^{-2} compared to control.

Conclusions Biodegradation of lignocellulosic agricultural wastes could be characterized by chemical and analytical methods. As peat moss is not a sustainable source, all compost fertilizers in this study could be used sustainably as growth media for soilless cultivation.

Keywords Compost fertilizers · Soilless agriculture · Alternative plant growth media · Fourier-transform infrared (FTIR) spectroscopy · Thermogravimetric analysis (TGA) · Holocellulose/lignin ratio

1 Introduction

Soilless vegetable production in greenhouses is essential to avoid soil degradation and extensive land use (Pradhan and Deo 2019). Peat moss is commonly used as plant growth media (PGM) in soilless systems due to its optimal physicochemical properties. However, its excessive use as a PGM causes carbon (C) emissions due to the large C storage capacity of peatlands. Although they cover about 4 times less land area, they can store about 2 times more C than forest areas around the globe (Beaulne et al. 2021). Therefore, peatlands should be protected from anthropogenic disturbance and degradation to mitigate climate change (Loisel and Gallego-Sala 2022). Coco peat is commonly used as an alternative organic growth medium. However, the cost and importation of coco peat limit its reach and use in many countries (Gavilanes-Teran et al. 2017). Some other inorganic (perlite, rockwool, vermiculite, sand, zeolite, etc.) and organic (pine bark, sawdust, wood chips, sugarcane fiber, etc.) substrates could be used as PGM (Maluin et al. 2021). In recent years, compost fertilizers obtained from organic wastes have gained high attention for use as PGM due to their sustainability, recycling of organic wastes, and also

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supporting the improvement of vegetable yield and quality (Giménez et al. 2020). We focused in this study on compost fertilizers obtained from some lignocellulosic agricultural wastes derived from *Corylus sp.* and *Coffea sp.* as PGM.

Microgreens have become very popular in recent years due to their high nutritional value, such as phenolics, vitamins, antioxidants, and aromatic flavors, compared to mature plants. They could be grown indoors and in greenhouses, and their cultivation time is only 7–21 days (Bhaswant et al. 2023; Yeargin et al. 2023). There are different varieties of vegetables, herbs, and grains cultivated as microgreens (*Beta vulgaris* L. var. *italica*, *Lactuca sativa* L., *Brassica rapa* L., *Lepidium sativum* L., *Brassica oleracea* L., etc.) (Maluin et al. 2021). For the cultivation of microgreens, peat-based PGM are generally used, but it is revealed that alternative PGM, such as spent mushroom substrates and organic composts, etc., could be used (Poudel et al. 2023).

Lignocellulose constitutes 50% of the total plant biomass on earth (Hemati et al. 2023). Approximately 200 billion tons of lignocellulosic wastes are generated annually (Diaz and Blandino 2022). One of the lignocellulosic wastes is spent coffee grounds, which are produced at a rate of 7 million tons per year (FAO 2022). About 1.7 million tons of hazelnut pruning waste, which is another lignocellulosic waste, is released annually in Türkiye (Ceylan 2024). In addition, mushroom cultivation on lignocellulosic materials produces spent mushroom substrates (Ma et al. 2023). These wastes can be composted, but they have a very rigid structure, mainly due to the lignin content. These materials take longer to compost than vegetables. The carbon/nitrogen (C/N) ratio is one of the critical components for the success of producing optimized composts with lignocellulosic wastes (Xie et al. 2022). The biodegradation of lignocellulosic materials in the composting process converts the lignin, holocellulose (cellulose, hemicellulose), protein, and pectin contents of the feedstocks into the final compost. This conversion influences the amount of humic substances, which is closely related to the compost maturity index, fertility, and stability of the soil (Wu et al. 2022). There are some methods, such as measurement of pH, electrical conductivity (EC), C/N ratio, humic/fulvic acid ratio, determination of seed germination index, holocellulose/lignin ratio, etc., to evaluate the maturity of composts. Fourier transform infrared (FTIR) spectroscopy, which is a non-destructive method for evaluating compost fertilizers and their raw materials, shows the degree of degradation of lignocellulosic materials and the maturity of composts (Grube et al. 2006; Tandy et al. 2010). Thermogravimetric analysis (TGA) is another rapid and inexpensive method for testing the maturity and stability of composts (Díaz et al. 2021).

We hypothesized that: (i) biodegradation of lignocellulosic agricultural wastes can be determined during the composting process using analytical and chemical methods, and (ii) compost fertilizers obtained from these wastes can substitute peat partially or wholly as plant growth media for the cultivation of vegetables and microgreens. The aim of the study was the determination of the degradation characteristics of lignocellulosic agricultural wastes such as spent mushroom (reishi) substrates, hazelnut pruning waste, and spent coffee grounds during the composting process using FTIR, TGA, and the measurement of holocellulose and lignin contents. Degradations were compared between lignocellulosic agricultural wastes or initial compost mixtures and the final composts. Besides this, compost fertilizers obtained from these lignocellulosic agricultural wastes were evaluated for their phytotoxicity and viability as plant growth media in the cultivation of tomato seedlings (*Lycopersicon lycopersicum*) and two microgreens (*Lepidium sativum* and *Lactuca sativa*).

2 Materials and methods

2.1 Collection of Waste Materials, Composting, and Monitoring Processes

Fresh chicken manure was collected from animal farms, and hazelnut pruning waste (HPW) was collected from agricultural fields in Düzce province, Türkiye. Spent coffee grounds (SCG) were collected from a local coffee shop (Lazpresso Coffee) in Düzce. Spent mushroom substrate (SMS) was obtained after reishi (*Ganoderma lucidum*) mushroom cultivation with hazelnut pruning waste at Duzce University, Recycling of Agricultural Wastes to Industry Application and Research Center (DUTAGAM). HPW and SMS were shredded in app. 2 cm in diameter. SCG was air-dried before using composting material to avoid any fungal contamination. Chemical properties of these initial components, which were the most abundant lignocellulosic materials in the compost piles, were analyzed and listed in Table S1. Vegetable waste was collected from Duzce University's dining hall, and dry leaves and fresh grass clippings were collected from the campus.

The amount of initial mixture components was calculated according to their C/N ratios. They were composted in 1 m^3 outdoor compost units at Duzce University, Recycling of Agricultural Wastes to Industry Application and Research Center for 180 days from September 2023 to March 2024 in three replicates. All initial compost mixtures contained vegetable waste, dry leaves, and fresh grass clippings (Table 1). K1 compost was obtained from spent mushroom (reishi) substrates and chicken manure; K2 compost from hazelnut pruning waste and chicken manure; and K3 compost from hazelnut pruning waste and spent coffee grounds.

Table 1 Ratios of initial mixture components for composting

Compost Components (% w w^{-1})	K1	K2	K3
Fresh chicken manure	36.33	36.33	-
Spent coffee grounds	-	-	54.75
Spent mushroom (reishi) substrates	34.42	-	-
Hazelnut pruning waste	-	34.42	33.18
Vegetable waste	17.20	17.20	4.38
Dry leaves	7.27	7.27	3.31
Fresh grass clippings	4.78	4.78	4.38

w: weight, K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste

Ingredients of initial mixtures were chosen for the composting process because they were all waste materials. Besides this, spent mushroom (reishi) substrates and hazelnut pruning waste were used as the main carbon sources of K1 and K2, respectively. Fresh chicken manure in K1 and K2 and spent coffee grounds in K3 were used as the main nitrogen source. Dry leaves were used as a bulking agent. Fresh grass clippings and vegetable waste were used for the regulation of the C/N ratio of initial mixtures.

Temperature, pH, electrical conductivity (EC), and moisture content of composts were monitored according to (Ceylan 2024). Temperature was measured from three parts of the piles and ambient for every day at the bio-oxidative stage, and a graph of averaged temperatures was created. pH, EC, and moisture of piles were measured for every month during the whole composting process. Aeration was provided approximately every 5 days in the first month and every 10–20 days in the remaining two months of the bio-oxidative stage for cooling down the piles by turning. All compost piles were allowed to mature for 90 days after three months of composting.

2.2 Chemical Analysis of Initial Mixtures and Composts

Initial mixtures and final composts were air-dried, milled, and sieved to 40-mesh. Five g sample of initial mixtures and final composts were extracted for 6 h with acetone solvent for determination of extractive content according to TAPPI T 204 cm-17 (TAPPI 2017). Extractive content was calculated as weight loss at the end of the Soxhlet extraction process. Holocellulose content of extractive-free samples was determined by the chloride method according to (Wise and Jahn 1952). After chloritization of samples, removing residue was calculated as lignin content. Holocellulose/lignin ratio was calculated by dividing the holocellulose content by the lignin content.

2.3 FTIR and TGA Assessments of Initial Lignocellulosic Components of Mixtures and Composts

Spent mushroom substrates (SMS), hazelnut pruning waste (HPW), spent coffee grounds (SCG), and composts were air-dried, milled, and sieved to 40-mesh for the measurements of FTIR and TGA. SMS, HPW, and SCG were sampled as raw (control), and K1, K2, and K3 compost fertilizers were sampled at the end of the composting process for evaluation of biodegradation characteristics of raw materials. FTIR analyses were performed using the KBr (potassium bromide) method (Böhm 2009). 5–10 mg of the sample was mixed with 1% KBr and pressed for the measurements. For TGA, a 5 mg sample was combusted in a platinum pan at a heating rate of 10 °C min^{-1} from 0 to 800 °C under an oxidizing atmosphere (Shimadzu, DTG 60 H-DSC 60) (Dell'Abate et al. 2000).

2.4 Physicochemical and Biological Analyses of Composts

The total nitrogen (N) and total organic carbon (TOC) contents of the composts were determined by the Kjeldahl method and by dividing the organic matter by a conversion factor of 1.72, respectively. Ash content was determined after combustion of composts in a muffle furnace at 550 °C. Organic matter (OM) was calculated as weight loss at the end of combustion. Total phosphorus (P), potassium (K), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), molybdenum (Mo), calcium (Ca), magnesium (Mg), sodium (Na), nickel (Ni), cadmium (Cd), and lead (Pb) were measured by ICP-OES according to the standard procedure of ISO 22036:2024. Microbial (bacterial and fungal) biomass (MB) of composts was evaluated using the Microbiometer kit (USA) according to the manufacturer's instructions. Phytotoxicity tests and seed germination index (SGI) of composts, chicken manure, and spent coffee grounds were performed according to (Ajmal et al. 2021) with *Lepidium sativum*, *Lactuca sativa*, and *Lycopersicon lycopersicum* seeds. All seeds were purchased from Istanbul Seed Growing, Türkiye.

2.5 Physicochemical Analysis of Plant Growth Media and Cultivation of Tomato Seedlings and Microgreens

Plant growth media (v v^{-1}) were prepared with fresh K1, K2, and K3 composts and peat moss for the cultivation of tomato seedlings and microgreens (Table 2). pH, EC, bulk density (BD), total porosity (TP), water holding capacity (WHC), and aeration capacity (AC) were determined according to (Dede and Özdemir 2018). Plant growth media were filled into four pots (3 L) for each mixture for tomato cultivation. Peat moss with 15+15+15 fertilizer (15% N, 15% P, 15% K; compound fertilizer) was used only for tomato cultivation. The 15+15+15 fertilizer, calculated as 3 g L^{-1}, was added to the pot of the 15+15+15 fertilizer treatment. One 15-day-old tomato seedling (cv. Tomato H2274, purchased from Istanbul Seed Growing) was transferred to each pot. Eight aluminum trays (20 cm length, 11 cm width, 2.5 cm deep) were filled with each mixture for microgreen cultivation. Four trays were filled with 4 g of seeds (8.9 seeds cm^{-2}) of *Lepidium sativum* (garden cress), and the other four trays were filled with 4 g of seeds (20.6 seeds cm^{-2}) of *Lactuca sativa* (lettuce). The height of tomato seedlings and the weight of garden cress and lettuce microgreens were measured at 3, 6, 9, and 12 weeks and 15 days after the start of cultivation, respectively. The dry biomass of tomato seedlings was weighed at the end of the cultivation. After 6 weeks from the start of cultivation, pots were supported with each compost more. SMS1, HPW1, and SCG1 were filled with 0.5 L of compost; SMS2, HPW2, and SCG2 were filled with 0.25 L; and SMS3, HPW3, and SCG3 were filled with 0.125 L. At this stage, the same amount of 15+15+15 fertilizer was added to the pots of the 15+15+15 fertilizer treatment one more time. For microgreens, mean fresh weight of shoots (mg $shoot^{-1}$), fresh yield (kg m^{-2}), and dry biomass (g m^{-2}) were measured according to the method in (Poudel et al. 2023). For tomato seedlings, shoot dry biomass was determined after drying fresh shoots and leaves at 70 °C for 72 h in a drying oven. The cultivation of tomato seedlings was processed from June to August 2024; microgreens for 15 days in August 2024 in open field conditions. Tomato seedlings and microgreens were watered daily.

2.6 Statistical Analysis

Differences between mean height and dry biomass of the tomato seedlings of each application, mean fresh weight of shoot, fresh yield, and dry biomass of microgreens were analyzed by one-way analysis of variance using the GraphPad Prism 6 statistical program. Differences between means were compared using Tukey's multiple-comparison test with a significance level of $P<0.05$. Differences between mean extractive content, holocellulose, lignin, and the holocellulose/lignin ratio of the initial mixtures and final composts were analyzed by unpaired t-test at $P<0.05$.

3 Results and Discussions

3.1 Physicochemical Analysis of Composting Process

Measuring temperature, pH, and EC are traditional chemical or physical indicators for the evaluation of the maturity of the composts (Chang et al. 2023). In this study, temperatures of all composts reached 50–60 °C in the first 5 days and gradually decreased to ambient temperature by turning the piles during the total 90 days of the bio-oxidative composting process (Fig. S1D). These temperature increases are necessary for the degradation of lignocellulosic wastes in composts (Yu et al. 2022). One month later, after starting composting, K1 and K2 had pH>9 and 2000 µS cm^{-1} EC;

Table 2 Ratios of compost and peat moss in plant growth media

Plant growth media	Compost (% v v^{-1})	Peat moss (% v v^{-1})	Sand (% v v^{-1})
SMS1	90% K1	-	10%
SMS2	45% K1	45%	10%
SMS3	20% K1	70%	10%
HPW1	90% K2	-	10%
HPW2	45% K2	45%	10%
HPW3	20% K2	70%	10%
SCG1	90% K3	-	10%
SCG2	45% K3	45%	10%
SCG3	20% K3	70%	10%
Control	-	90%	10%
15+15+15 fertilizer	-	90%	10%

v: volume; SMS1, SMS2, and SMS3 were prepared by K1 (compost from spent mushroom (reishi) substrate and fresh chicken manure); HPW1, HPW2, and HPW3 were prepared by K2 (compost from hazelnut pruning waste and fresh chicken manure); SCG1, SCG2, and SCG3 were prepared by K3 (compost from spent coffee grounds and hazelnut pruning waste). Control was watered only with tap water. 15+15+15 fertilizer was used only for the cultivation of tomato seedlings

K3 had 6.5 pH and less than 1000 EC (Fig. S1A and B). pH of K1 and K2 decreased gradually to 8 at the end of composting, and pH of K3 increased to 8 within the first three months. EC of K1 and K2 was approximately 2300 µS cm^{-1}, but K3 had no more than 1000 µS cm^{-1} (Fig. S1B). EC of compost fertilizers is very important for not being toxic for plant cultivation. It should not be more than 4000 µS cm^{-1}. It could be toxic for salt-sensitive crops, even in the range of 2000–4000 µS cm^{-1} (Gondek et al. 2020).

3.2 Results for Degradation Levels of Initial Components during Composting

3.2.1 Chemical Composition of Lignocellulosic Materials during Composting

The holocellulose/lignin ratio is one of the indicators for determining the decomposition potential of organic soil amendments (Wei et al. 2020). Thus, this ratio could be an indicator to assess the maturity and stability of compost fertilizers at the end of the composting process. It was stated that a high holocellulose/lignin ratio indicates a higher decomposition rate (Vandecasteele et al. 2016). In our study, the highest holocellulose/lignin ratio among initial mixtures and the lowest ratio among final compost fertilizers were found in K3 (Table 3). In all composts, while holocellulose rate decreased, lignin rate increased. It was consistent with the study of (Vandecasteele et al. 2014), which determined the decreasing of the holocellulose/lignin ratio at the end product compared to the starting materials of composting. Except for K2, extractives of final compost in K1 and K3 were decreased compared to their initials.

3.2.2 FTIR Assessments during Composting

FTIR spectroscopy could be used to identify the metabolic structures of lignocellulosic materials with functional groups in the composting process (Böhm 2009). Liu et al. (2017) stated that properties of basic molecular structure in compost fertilizers could be seen between 800 and 1800 cm^{-1} in the FTIR spectrum. Through the composting process, carbohydrates (cellulose, hemicellulose, and lignin) and aliphatic compounds (fats) decompose into CO_2 (carbon dioxide) and proteins; nitrogen compounds, peptides, and amino acids break down into CO_2, NH_4^+, NO_3^-, and amide nitrogen (Xiang et al. 2016). As the maturity and stability of compost increase during the composting process, organic matter becomes more complex. There is a decrease in the amount of polysaccharides and an increase in aromaticity and carboxylate concentration (Zahra El Ouaqoudi et al. 2015). FTIR spectra of the raw materials (SMS, HPW, and SCG) and composts (K1, K2, and K3) of this study were presented in Fig. 1.

The broad absorption bands observed between 3400–3200 cm^{-1} are attributed to the O-H and N-H stretching vibrations in the materials (Santos et al. 2022). The peak intensity of these bands has increased during the composting process. The two bands observed between 2920 and 2850 cm^{-1} are attributed to asymmetric and symmetric C-H stretching vibrations belonging to aliphatic structures in composts and lignocellulosic materials. For SCG material, the C-H stretching vibrations in these bands are attached from caffeine and lipids (Pujol et al. 2013). It was observed that after the degradation of SCG material, this band weakens for K3 and reaches a constant height, similar to K1 and K2 materials (Böhm 2009). The weak bands observed between 1750–1720 cm^{-1} are attributed to the C=O stretching vibrations of aldehyde, ketone, carboxylic acid, and ester structures in the lignocellulosic materials (Tandy et al. 2010). These bands were visible in SMS and HPW but weakened or disappeared in K1 and K2 (Fig. 1) (Böhm 2009). The intense band observed at 1743 cm^{-1} in the SCG material was attributed to the C=O stretching vibrations of ester groups derived from kinic acid and lipids (Craig et al. 2015; Munyendo et al. 2022), and the band intensity was observed to weaken in K3 (Fig. 1). The bands observed between 1660–1630 cm^{-1} are attributed to C=O and C=C stretching vibrations of aromatic chains, carboxylates, alkenes, and amides (Tandy et al. 2010; Xiang et al. 2016), as well as the C=O and C=C stretching vibrations of caffeine, fatty acids, and lipids (for SCG) (Craig et al. 2018). The peak intensity of this band increased in K1, K2, and K3. Similarly, Zahra El Ouaqoudi et al. (2015) mentioned that there was an increase in aromaticity and carboxylate

Table 3 Chemical composition of initial and final lignocellulosic materials during composting

	K1		K2		K3	
	Initial mixture	Final compost	Initial mixture	Final compost	Initial mixture	Final compost
Extractive (%)	2.17±0.19	2.03±0.51	1.27±0.08	1.49±0.09	8.99±0.33	0.91±0.36
Holocellulose (%)	51.41±1.73	44.22±1.71	52.10±1.74	45.38±1.72	61.45±0.68	34.18±1.31
Lignin (%)	48.59±0.66	55.66±1.71	47.90±0.74	54.62±0.70	38.55±0.68	65.82±1.31
Holocellulose/Lignin	1.05	0.79	1.08	0.83	1.59	0.51
Ash (%)	15.77±0.21	22.57±0.15	13.50±0.10	20.33±0.21	3.86±0.15	9.73±0.49

Values after "±" indicate standard deviation. K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste

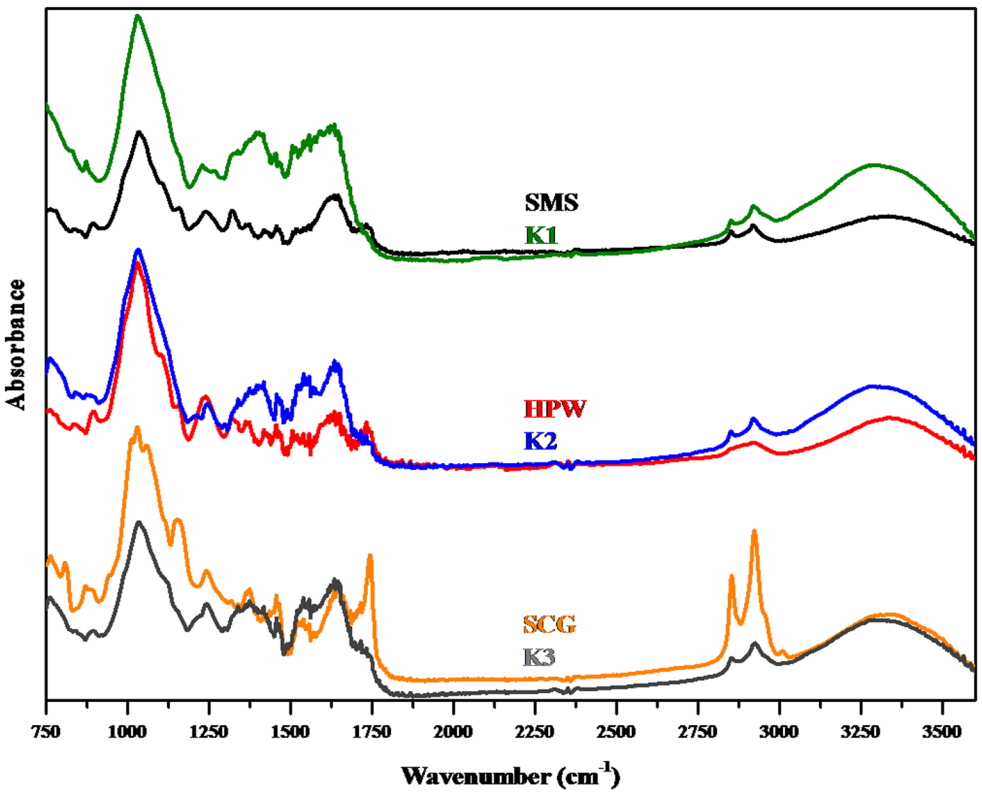


Fig. 1 FTIR spectra of raw materials (SMS, HPW, and SCG) and the composts (K1, K2, and K3). SMS: spent mushroom (reishi) substrate; HPW: hazelnut pruning waste; SCG: spent coffee grounds; K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste; SMS, HPW, and SCG were controls of K1, K2, and K3, respectively

concentration in the 1600–1650 cm^{-1} region in FTIR spectra of composts made from date palm waste and couch grass waste from 3rd to 14th month of composting. The bands observed between 1540–1500 cm^{-1} are attributed to the C–O and C=C stretching vibrations of the aromatic chain of lignin and the NO_2 structures, as well as the CH_2 deformation of lignin (Adapa et al. 2011; Pujol et al. 2013; Tandy et al. 2010). It was observed that there were changes in the wavelengths and an increase in peak intensities of these bands. Xiang et al. (2016) indicated that the absorption band at 1510 cm^{-1} was characteristic of lignocellulosic fungal waste. This band of SMS was observed at 1517 cm^{-1}. The bands at 1456 and 1416 cm^{-1} are attributed to the vibrations of inorganic NH_4^+, NO_3^-, and organic carboxylic acid salts (Xiang et al. 2016); CH_2 and CH_3 deformations of lignin and hemicellulose, and the CH_2 in-plane bending vibrations of cellulose and lignin (Lun et al. 2017; Pujol et al. 2013). The 1370 cm^{-1} band is attributed to the C-H symmetric and asymmetric deformation of cellulose and the N-O stretching vibrations of nitrates, while the 1320 cm^{-1} band is attributed to the C-N stretching vibrations of aromatic and amine structures (Tandy et al. 2010) and the C-H and C-O absorption bands (Xiang et al. 2016). During the composting process, the degradation of carbohydrates and nitrogen compounds in the structure resulted in an increase in the peak intensities of these bands in K1, K2, and K3 (Zahra El Ouaqoudi et al. 2015). The band observed at 1240 cm^{-1} is attributed to the C-O stretching vibrations of carboxylic acids and the C-N stretching vibrations of amides in SMS, HPW, and SCG (Akcay et al. 2023). These bands in K1, K2, and K3 had weakened in that the organic matter stabilizes at the end of the composting process (Böhm 2009). In SMS and HPW, the weak bands observed at 1157 and 1103 cm^{-1} are attributed to the stretching and bending vibrations of C-O-C and C-OH in polysaccharides, as well as the asymmetric stretching vibrations of Si-O-Si (Böhm 2009; Santos et al. 2022; Lin et al. 2022). The medium- and weak-intensity bands of SCG observed at 1151 and 1059 cm^{-1} are attributed to chlorogenic acids, a broad family of esters formed by kinic acid and some transcinnamic acids (Pujol et al. 2013). It is observed that these bands weaken or completely disappear in the K1, K2, and K3 at the end of the composting process. The bands observed in the 1030, 890, and 850–700 cm^{-1} regions are attributed to the C-O stretching vibration of polysaccharides and the Si-O-Si asymmetric stretching vibrations (Raspolli Galletti et al. 2015); the C-O out-of-plane bending vibration (Tandy et al. 2010), and the N-H vibrations of primary and secondary amine groups (Böhm 2009), respectively. In K1 and K2, the band intensity at 1030 cm^{-1} was increased, while it was decreased in K3.

3.2.3 TGA Assessments during Composting

Thermogravimetric analysis is one of the techniques used to characterize the maturity of compost materials and to investigate organic matter (Smidt and Lechner 2005). As a result of the evaporation of carbohydrates and aliphatic molecules in an oxidizing air atmosphere and the oxidation of high molecular weight components, endothermic and exothermic peaks are observed in the TGA curves (Dell'Abate et al. 2000). The TGA curves of the raw materials (SMS, HPW, and SCG) and the composts (K1, K2, and K3) used in this study are shown in Fig. 2, and the weight losses occurring in four different temperature ranges due to endothermic and exothermic reactions are presented in Table S2.

The endotherm observed between 25 and 150 °C is related to dehydration reactions (Som et al. 2009); the exotherm observed between 150 and 375 °C is related to the decomposition of carbohydrates and aliphatic compounds (Fernandez et al. 2012); the exotherm observed between 375 and 500 °C is related to the decomposition of complex aromatic structures (Teh et al. 2014); the endotherm observed between 500 and 750 °C is related to the thermal decomposition of carbonates (Atanasov and Rustschev 1985). According to the results in Table S2, there was a decrease in weight loss at the exothermic peak at 150–375 °C of the compost materials (K1, K2, and K3) compared to the raw materials (SMS, HPW, and SCG). In the study conducted by Som et al. (2009), it was stated that there was a 24.6% reduction in weight loss at the exothermic peak at 150–375 °C of compost made from green waste and biological waste after 195 days compared to the initial material. In a similar study, it was stated that there was a reduction from 57.1 to 33.6% in weight loss. This result was explained by the gradual decomposition of carbohydrates, aliphatic compounds, and aromatic structures (Zahra El Ouaqoudi et al. 2015). In the results related to the exothermic peak at

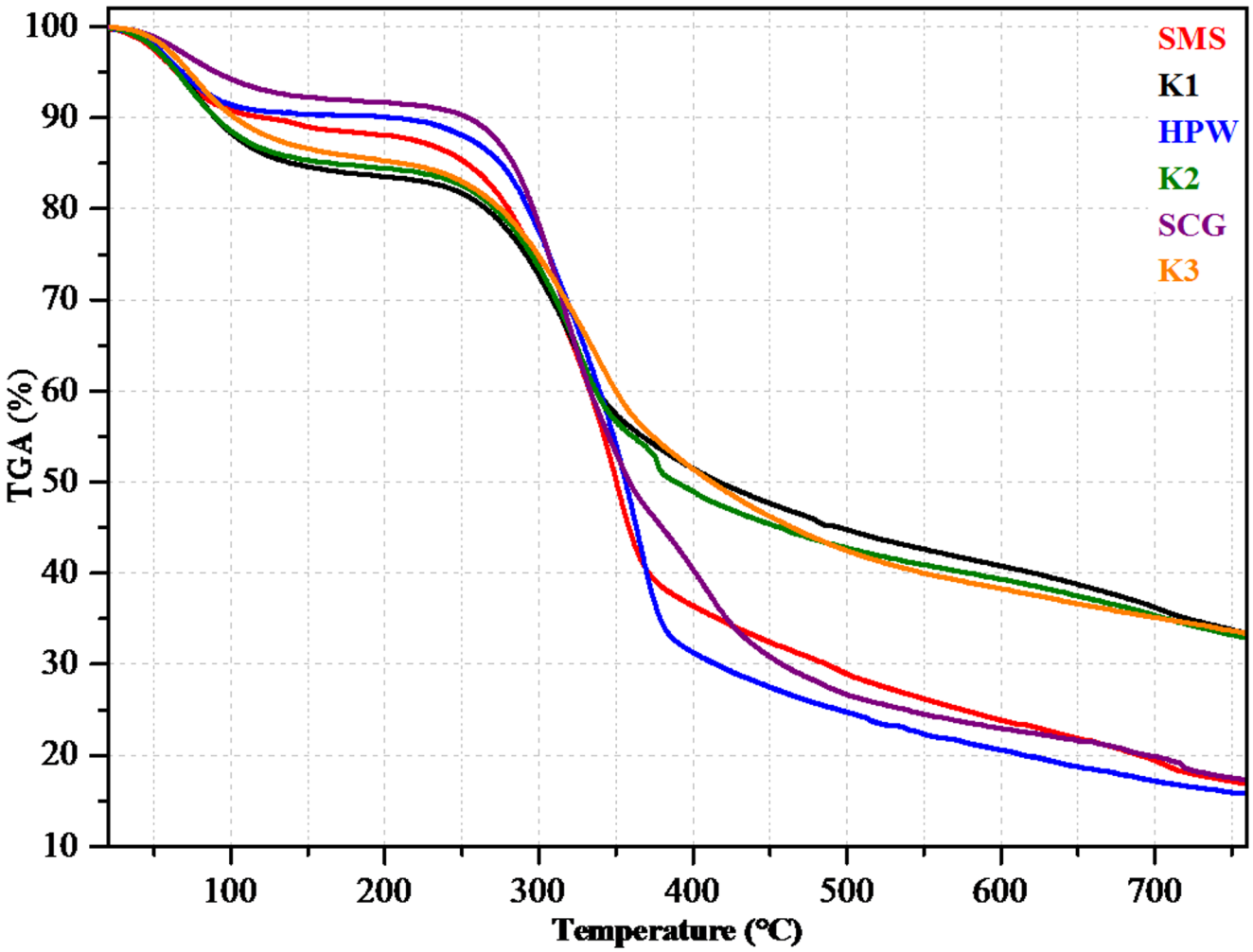


Fig. 2 TGA curves of the raw materials (SMS, HPW, and SCG) and the composts (K1, K2, and K3). SMS: spent mushroom (reishi) substrate; HPW: hazelnut pruning waste; SCG: spent coffee grounds; K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste; TGA: thermogravimetric analysis; SMS, HPW, and SCG were controls of K1, K2, and K3, respectively

375–500 °C, no decrease in weight loss was observed after the formation of K1 and K2 composts from SMS and HPW raw materials. This result is associated with the lower biological degradation of complex aromatic structures (Som et al. 2009). At this exothermic peak, the decrease in weight loss of the K3 sample was greater compared to the other samples. The presence of chlorogenic acids in the structure of the SCG raw material could have been contributed to this result. When examining the total weight losses of the materials between 25 and 750 °C, it was observed that the weight losses decreased by 16–17% compared to the raw materials with the formation of compost. The decreases in the ash results given in Table 3 supported this conclusion.

3.3 Chemical and Biological Properties of Composts

According to average limit values of European Union countries, concentrations of heavy metals of Ni, Cd, Pb, Cu, and Zn in composts are not allowed to exceed 47, 1.4, 121, 143, and 416 mg kg^{-1}, respectively (EU 2004). In our study, all composts had these elements in the acceptable limits. Concentrations of Mn, Ca, and Ni nutritional elements in K1 were the highest levels. Only Fe concentration was the highest in K3 and Cu, Zn, Mo, Mg, and Na in K2 (Table 4). N and organic matter contents of K3 were the highest values among compost fertilizers. C/N ratios of all compost fertilizers in this study were determined to be below 20/1, which is one of the indicators of compost maturity (Table 4). Microbial biomass of K3 was the highest value among all composts, but microbial biomass values in our study were very low levels according to microbiometer kit supplier, which indicated that lower microbial biomass was 500 ug C g^{-1} and below (Microbiometer 2021).

3.4 Phytotoxicity Tests and Seed Germination Index

One easy and cheap biological indicator is the calculation of seed germination index for the checking of compost maturity. For saying the non-phytotoxicity of composts, seed germination index should be more than 80% (Zucconi et al. 1981). In this study, K1, K2, and K3 had no phytotoxicity for the *Lepidium sativum* seeds (Table 5). On the other hand, only K3 has no phytotoxic effect on the *Lactuca sativa* seeds rather than other composts. However, all composts had phytotoxicity for *Lycopersicon lycopersicum*. Fresh chicken manure decreased seed germination index compared to all composts and was phytotoxic for the germination of seeds of all species in this study. Spent coffee grounds were phytotoxic for *L. sativum* rather than *L. lycopersicum* and *L. sativa*, and its SGI for *L. sativum* was nearly fresh chicken manure. Surprisingly, SGI of spent coffee grounds was highest for *L. lycopersicum* and *L. sativa*. Similarly, Vitale et al. (2024) indicated that spent coffee grounds promoted the biomass of cucumber seedlings and could be used as a natural fertilizer.

Table 4 Chemical and biological properties of composts. Values after "±" indicate standard deviation

Physicochemical and biological properties	Compost name		
	K1	K2	K3
N (%)	2.79±0.11	2.57±0.09	3.05±0.05
TOC (%)	45.02±0.09	46.32±0.12	52.48±0.29
C/N	18.64	18.02	17.20
OM (%)	77.43±0.15	79.67±0.21	90.27±0.49
P (%)	0.11±0.01	0.12±0.02	0.03±0.01
K (%)	1.09±0.02	1.07±0.03	0.76±0.01
Cu (mg kg^{-1})	44.85±0.04	50.73±0.09	22.00±0.12
Fe (mg kg^{-1})	189.8±0.11	198.7±0.15	212.3±0.10
Mn (mg kg^{-1})	189.2±0.14	170.6±0.19	75.89±0.16
Zn (mg kg^{-1})	19.67±0.05	22.73±0.10	2.49±0.08
Mo (mg kg^{-1})	4.94±0.07	5.08±0.15	4.74±0.13
Ca (mg kg^{-1})	4150.1±15.07	3591.1±21.11	1376.9±47.03
Mg (mg kg^{-1})	4601.0±42.81	5147.4±35.61	2258.7±48.41
Na (mg kg^{-1})	819.7±11.21	915.3±54.72	86.32±41.38
Ni (mg kg^{-1})	2.47±0.08	2.42±0.14	1.50±0.37
Cd (mg kg^{-1})	-	-	-
Pb (mg kg^{-1})	6.77±0.84	6.95±0.72	6.51±1.21
MB (ug C g^{-1})	469.33±23.43	297.66±17.00	550.00±18.35

TOC: total organic carbon; OM: organic matter; C/N: carbon to nitrogen ratio; K: potassium; P: phosphorus; N: nitrogen; Fe: iron; Mn: manganese; Zn: zinc; Mo: molybdenum; Ca: calcium; Mg: magnesium; Cu: copper; Na: sodium; Ni: nickel; Cd: cadmium; Pb: lead; MB: microbial biomass; K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste

Table 5 Seed germination index of composts, chicken manure, and spent coffee grounds

Fertilizers	SGI (%)		
	Lepidium sativum	*Lactuca sativa*	*Lycopersicon lycopersicum*
K1	101,71 ± 5,27	71.21 ± 2.05	50,00 ± 8,15
K2	82,42 ± 9,66	61.04 ± 4.11	76,48 ± 5,63
K3	114.42 ± 6.98	87.20 ± 5.03	46,67 ± 5,38
Fresh chicken manure	68.5 ± 8.70	50.74 ± 3.17	32.41 ± 9.12
Spent coffee grounds	69.38 ± 9.29	163.32 ± 11.9	81,77 ± 11,82

Values after "±" indicate standard deviation. SGI: seed germination index; K1: compost from spent mushroom (reishi) substrate and fresh chicken manure; K2: compost from hazelnut pruning waste and fresh chicken manure; K3: compost from spent coffee grounds and hazelnut pruning waste

Table 6 Physicochemical properties of plant growth media

PGM	pH	EC (mS cm^{-1})	BD (g cm^{-3})	TP (%)	WHC (ml L^{-1})	AC (%)	OM (%)
Ideal (Abad et al. 2001)	5.3–6.5	≤0.5	<0.4	>85	600–1000	20–30	>80
SMS1	7.72 ± 0.08	1.35 ± 0.07	0.365 ± 0.01	86.11 ± 1.20	615.82 ± 11.23	24.52 ± 0.81	33.59 ± 5.58
SMS2	7.56 ± 0.07	0.94 ± 0.03	0.406 ± 0.01	84.45 ± 1.60	580.72 ± 8.12	26.38 ± 0.96	33.00 ± 6.51
SMS3	7.41 ± 0.07	0.56 ± 0.01	0.359 ± 0.01	86.39 ± 0.95	631.19 ± 8.12	23.27 ± 0.77	35.08 ± 4.33
HPW1	8.06 ± 0.13	2.00 ± 0.08	0.405 ± 0.01	84.15 ± 1.16	584.57 ± 14.93	25.69 ± 2.41	34.28 ± 3.56
HPW2	7.84 ± 0.06	1.25 ± 0.06	0.360 ± 0.00	86.55 ± 0.87	621.07 ± 32.37	24.44 ± 2.77	34.08 ± 4.93
HPW3	7.58 ± 0.08	0.63 ± 0.05	0.333 ± 0.02	87.44 ± 2.17	613.38 ± 5.87	26.10 ± 2.72	35.22 ± 7.00
SCG1	6.04 ± 0.03	1.31 ± 0.02	0.448 ± 0.00	80.68 ± 0.76	537.21 ± 27.58	26.96 ± 3.46	37.63 ± 3.94
SCG2	6.13 ± 0.06	0.81 ± 0.08	0.400 ± 0.02	84.95 ± 0.95	566.10 ± 22.21	28.34 ± 3.14	31.85 ± 3.64
SCG3	6.31 ± 0.02	0.46 ± 0,02	0.340 ± 0.01	87.96 ± 1.57	624.26 ± 35.77	25.54 ± 4.83	31.88 ± 5.37
Control	7.09 ± 0.15	0.27 ± 0.07	0.136 ± 0.01	94.09 ± 0.73	717.55 ± 8.78	22.34 ± 1.26	54.05 ± 4.18

Values after "±" indicate standard deviation. PGM: plant growth media, EC: electrical conductivity, BD: bulk density, TP: total porosity, WHC: water holding capacity, AC: aeration capacity, OM: organic matter. SMS1, SMS2, and SMS3 were prepared by K1 (compost from spent mushroom (reishi) substrate and fresh chicken manure); HPW1, HPW2, and HPW3 were prepared by K2 (compost from hazelnut pruning waste and fresh chicken manure); SCG1, SCG2, and SCG3 were prepared by K3 (compost from spent coffee grounds and hazelnut pruning waste). Control was watered only with tap water

3.5 Physicochemical Results of Plant Growth Media

Ideal plant growth media should have some properties such as pH, EC, bulk density (BD), total porosity (TP), water holding capacity (WHC), aeration capacity (AC), and organic matter (OM) content (Abad et al. 2001). In this study, only PGM obtained from composts with spent coffee grounds had an ideal pH range due to the pH value of fresh spent coffee grounds (Table 6). EC of media of all composts gradually decreased with decreasing compost amount. Only SCG3, which has 20% K3, and control had an ideal EC value. SMS1, SMS3, HPW2, HPW3, SCG3, and control had an ideal bulk density, total porosity, and water holding capacity. All media had an appropriate range of aeration capacity, but none of them had an ideal organic matter content because of the sand content in all media.

3.6 Growth Results of Tomato Seedlings on Different Plant Growth Media

Peat moss is a globally used organic material as plant growth media for the cultivation of seedlings of crops and ornamental plants in soilless cultivation (Chrysargyris et al. 2018). Organic fertilizers are alternative organic materials that are cost effective, do not effect CO_2 emissions as much as peat moss, and promote the growth of seedlings (Chrysargyris et al. 2020). In this study, at the sixth week, mean height of tomato seedlings in SMS2, SMS3, and SCG2 was significantly different compared to control at $P<0.001$, $P<0.05$, and $P<0.01$ statistical levels, respectively (Fig. 3). On the other hand, media with SMS2, SMS3, HPW2, SCG1, SCG2, SCG3, and 15 + 15 + 15 fertilizer increased the mean height of tomato seedlings at $P<0.001$, $P<0.05$, $P<0.01$, $P<0.05$, $P<0.01$, $P<0.01$, and $P<0.05$ statistical levels compared to control at the ninth week, respectively. There was no significantly different mean height of tomato seedlings in different plant growth media at the third and twelfth weeks. Supporting more composts at the sixth week to the pots supplied the significant difference in HPW2, SCG1, and SCG3 at the ninth week compared to the control. Özenç (2008) found that the highest height of tomato seedlings was 45 cm at 50% composted hazelnut husk and 50% peat treatment. Similarly, Ronga et al. (2016) measured the highest height as 41 cm at the treatment of 20% compost of spent coffee grounds and 80% commercial peat. On the other hand, 82.82 cm was measured as the highest height in the 20% vermicompost tea treatment by (Sugino Souffront et

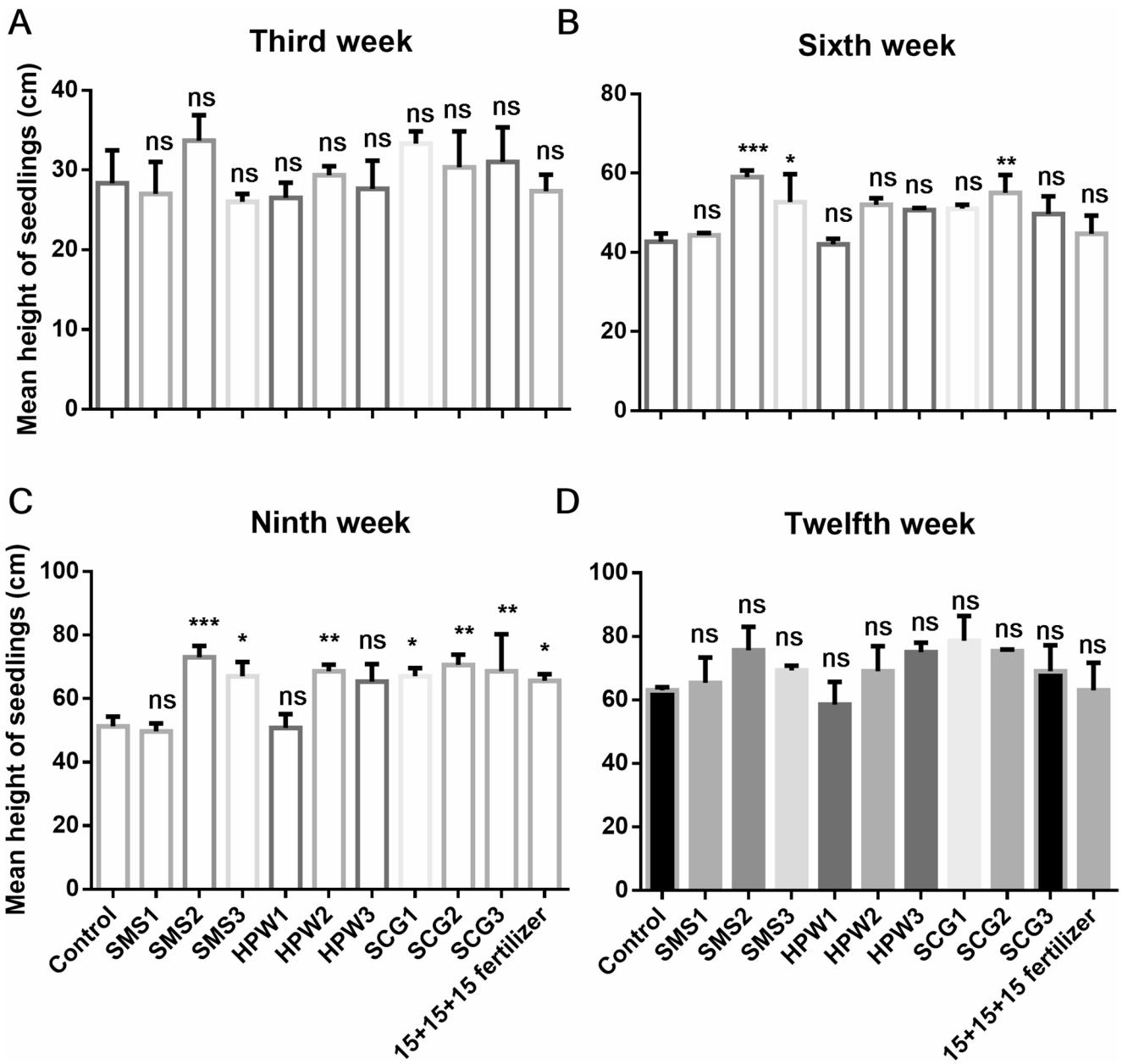


Fig. 3 Mean height of tomato seedlings at third (**A**), sixth (**B**), ninth (**C**), and twelfth (**D**) weeks in different plant growth media. ***: $P<0.001$, **: $P<0.01$, *: $P<0.05$, ns: not significant. SMS1, SMS2, and SMS3 were prepared by K1 (compost from spent mushroom (reishi) substrate and fresh chicken manure); HPW1, HPW2, and HPW3 were prepared by K2 (compost from hazelnut pruning waste and fresh chicken manure); SCG1, SCG2, and SCG3 were prepared by K3 (compost from spent coffee grounds and hazelnut pruning waste). Control was watered only with tap water. 15+15+15 fertilizer was used as positive control

al. 2022). In our study, this height was 78.67 cm in SCG1 treatment.

Dry biomass of tomato seedlings in SCG1, SCG2, and 15+15+15 fertilizer was significantly high compared to control at $P<0.01$, $P<0.05$, and $P<0.001$ statistical levels, respectively (Fig. 4A). On the other hand, there were significant differences in dry biomass of seedlings of SMS3, HPW1, and HPW3 compared to 15+15+15 fertilizer at $P<0.01$, $P<0.05$, and $P<0.05$, respectively (Fig. 4B). There were no significant differences between some of our organic fertilizers (SMS1, SMS2, HPW2, SCG1, SCG2, and SCG3) and 15+15+15 fertilizer. Zhou et al. (2023) found that dry biomass of tomato seedlings treated with compost was 2.07 times higher than control. In our study, we measured seedling dry biomass in 15+15+15 fertilizer, SMS1, SCG1, and SCG2 as 3.16, 2.4, 2.62, and 2.6 times higher than control.

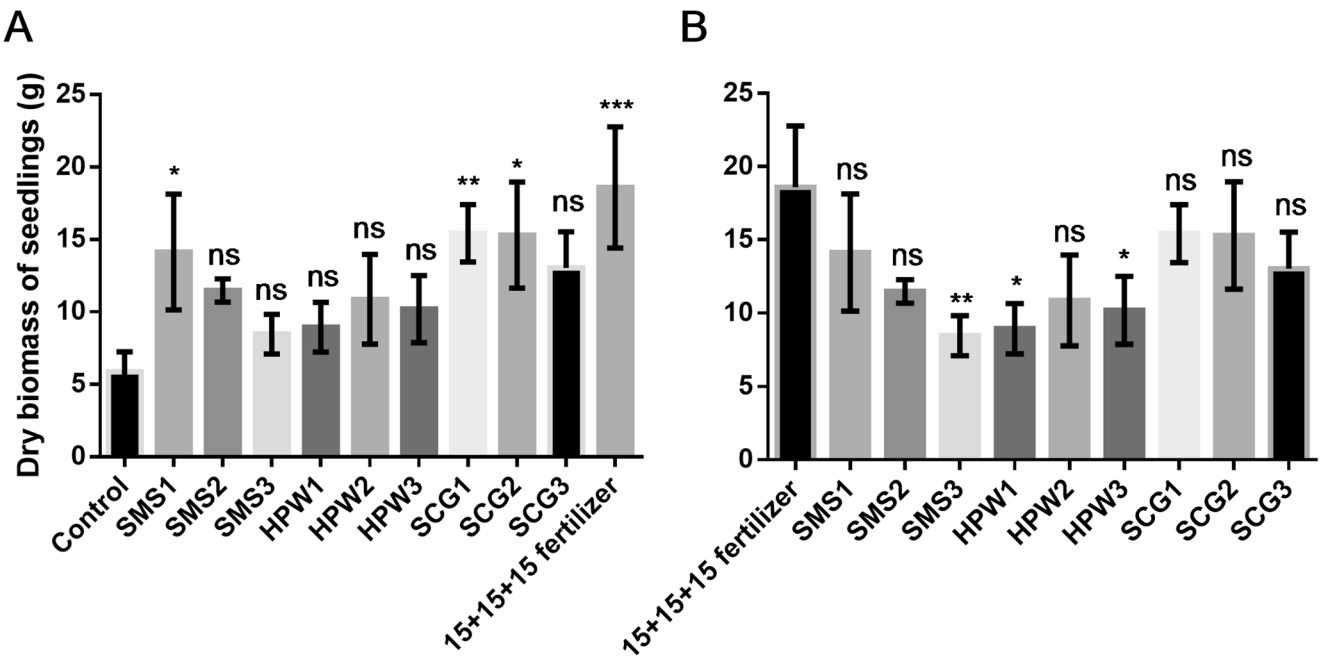


Fig. 4 Dry biomass of tomato seedlings in different plant growth media. Statistical analysis performed compared to control (**A**) and 15 + 15 + 15 fertilizer (**B**). ***: $P<0.001$, **: $P<0.01$, *: $P<0.05$, ns: not significant. SMS1, SMS2, and SMS3 were prepared by K1 (compost from spent mushroom (reishi) substrate and fresh chicken manure); HPW1, HPW2, and HPW3 were prepared by K2 (compost from hazelnut pruning waste and fresh chicken manure); SCG1, SCG2, and SCG3 were prepared by K3 (compost from spent coffee grounds and hazelnut pruning waste). Control was watered only with tap water. 15 + 15 + 15 fertilizer was used as positive control

3.7 Growth Results of Microgreens on Different Plant Growth Media

Growth media affect microgreens' yields, and compost fertilizers could be used as plant growth media for the cultivation of them. In this context, Najera et al. (2024) found that using 50% compost and 50% peat as growth media produced the highest microgreen fresh yields of *Brassica rapa*. Pea microgreens, which were cultivated on spent mushroom compost and organic compost fertilizers, had decreased yields compared to substrate with peat. Other than this, it was revealed that there were increases in yields of radish microgreens at substrates of compost fertilizers and mixtures with peat and perlite (Poudel et al. 2023). In our study, fresh yield of *Lepidium sativum* microgreens was higher and significantly different in media of SCG (SCG1, $P<0.01$; SCG2, $P<0.01$; SCG3, $P<0.05$) compared to control, and this finding was consistent with the seed germination index. Conversely, although K1 and K2 were not phytotoxic for the seeds of *L. sativum*, media of SMS and HPW, except for HPW2, had significantly lower fresh yields compared to control (Table 7). There is no significant difference between the mean fresh weight of *L. sativum* shoots of all media. Di Gioia et al. (2023) found that fresh yield and shoot fresh weight of *L. sativum* microgreens were 994.7 g m^{-2} and 30.22 mg $shoot^{-1}$, respectively. We determined the fresh yield of *L. sativum* at 0.371 kg m^{-2} as the lowest in SMS1 and 1.908 kg m^{-2} as the highest in SCG2. Dry biomass of *L. sativum* in SCG1 ($P<0.05$) was higher, and in SMS1 ($P<0.0001$), SMS2 ($P<0.01$), SMS3 ($P<0.01$), and HPW1 ($P<0.05$) was lower compared to control. We calculated the dry biomass of *L. sativum* at 29.57 g m^{-2} as the lowest in SMS1 and 124.5 g m^{-2} as the highest in SCG1.

A fresh yield of *Lactuca sativa* microgreens was found previously as 1.5 kg m^{-2} in control, which was watered with only water, and more than 2 kg m^{-2} in hoagland treatment (Pannico et al. 2020). In our study, we calculated the fresh yield of *L. sativa* at 1.925 kg m^{-2} as the lowest in SMS2 and 4.360 kg m^{-2} as the highest in SCG1 (Table 7). Rather than other media, there were significant differences in fresh yield ($P<0.01$) and mean fresh weight of shoot ($P<0.05$) of *L. sativa* in SCG1 compared to control.

4 Conclusions

Holocellulose/lignin ratios and content of holocellulose and extractives of all compost fertilizers were lower than their initial mixtures. These decreasing parameters signed the biodegradation of lignocellulosic materials due to the composting process in the frame of chemical characterization of lignocellulose. On the other hand, results of FTIR spectra showed molecular characteristics of biodegradation of lignocellulosic wastes such as spent mushroom (reishi)

Table 7 Effect of plant growth media on cultivation of *Lepidium sativum* and *Lactuca sativa* microgreens

PGM	*Lepidium sativum*			*Lactuca sativa*		
	MFWS	FY	DB	MFWS	FY	DB
Control	32.13 ± 2.27	1.246 ± 0.167	91.18 ± 17.25	2.419 ± 0.227	128.80 ± 13.75	2.419 ± 0.227
SMS1	32.17 ± 4.79 ns	0.371 ± 0.153 ****	29.57 ± 10.70 ****	1.947 ± 0.653 ns	93.42 ± 29.80 ns	1.947 ± 0.653 ns
SMS2	29.10 ± 5.50 ns	0.525 ± 0.048 **	46.03 ± 2.90 **	1.925 ± 0.489 ns	95.36 ± 21.96 ns	1.925 ± 0.489 ns
SMS3	30.65 ± 4.93 ns	0.685 ± 0.032 *	53.15 ± 4.84 **	2.036 ± 0.968 ns	105.05 ± 38.53 ns	2.036 ± 0.968 ns
HPW1	23.10 ± 1.75 ns	0.663 ± 0.039 **	57.91 ± 2.26 *	3.230 ± 0.346 ns	153.02 ± 11.46 ns	3.230 ± 0.346 ns
HPW2	21.58 ± 1.94 ns	0.882 ± 0.175 ns	75.13 ± 14.61 ns	3.316 ± 0.167 ns	155.54 ± 8.92 ns	3.316 ± 0.167 ns
HPW3	28.03 ± 1.94 ns	0.712 ± 0.069 *	61.02 ± 6.96 ns	2.704 ± 0.388 ns	134.39 ± 19.84 ns	2.704 ± 0.388 ns
SCG1	38.37 ± 8.58 ns	1.890 ± 0.252 **	124.5 ± 12.14 *	4.360 ± 0.577 **	184.65 ± 11.49 ns	4.360 ± 0.577 **
SCG2	45.22 ± 4.44 ns	1.908 ± 0.196 **	115.5 ± 11.99 ns	3.590 ± 0.454 ns	151.85 ± 19.98 ns	3.590 ± 0.454 ns
SCG3	39.12 ± 5.21 ns	1.799 ± 0.282 *	115.2 ± 11.01 ns	3.475 ± 0.209 ns	143.21 ± 13.00 ns	3.475 ± 0.209 ns

****: $P<0.0001$, **: $P<0.01$, *: $P<0.05$, ns: not significant. Values after "±" indicate standard deviation. PGM: plant growth media; MFWS: mean fresh weight of shoot (mg shoot^{-1}); FY: fresh yield (kg m^{-2}); DB: dry biomass (g m^{-2}). SMS1, SMS2, and SMS3 were prepared by K1 (compost from spent mushroom (reishi) substrate and fresh chicken manure); HPW1, HPW2, and HPW3 were prepared by K2 (compost from hazelnut pruning waste and fresh chicken manure); SCG1, SCG2, and SCG3 were prepared by K3 (compost from spent coffee grounds and hazelnut pruning waste). Control was watered only with tap water

substrate, hazelnut pruning waste, and spent coffee grounds that were biodegraded during the composting process. Although all compost fertilizers had phytotoxicity for *Lycopersicon lycopersicum*, cultivation results indicated that our compost fertilizers could be used partially as plant growth media substitutes for the peat mosses for the cultivation of tomato seedlings and *Lepidium sativum* and *Lactuca sativa* microgreens in sustainable soilless agriculture (hydroponic systems, etc.). In conclusion, this study showed that spent mushroom (reishi) substrate, hazelnut pruning waste, and spent coffee grounds are promising components for generating alternative plant growth media from compost fertilizers within the scope of zero waste. Further researches could be about the effects of compost fertilizers in plant growth media on the nutrient contents of vegetables and microgreens cultivated in different soilless agriculture systems.

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Declarations

Ethics Approval Not applicable.

Consent To Participate All authors agree to participate.

Consent for Publication All authors have read the manuscript and agree for publishing.

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