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Improvement of Growth Media Quality Using Coconut Coir Dust, Coconut Ash, and Palm Kernel Shell Biochar

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Abstract

The sustainable management of agricultural waste is vital for addressing environmental challenges while enhancing resource efficiency in agriculture. This study aimed to evaluate the potential of agricultural residues, specifically coconut and oil palm by-products, as growth media components. Growth media mixtures were formulated using coconut coir dust (CCD), coconut shell ash (CSA), and palm kernel shell biochar (PKSB), and their physicochemical properties were analyzed. The experiment was conducted in a completely randomized design with three replications. The results indicated that a growth media mixture consisting of 100% CSA demonstrated high pH (7.89), electrical conductivity (2.70 dS m^{-1}), cation exchange capacity (12.57 cmolc kg^{-1}), and significant concentrations of P (13.90 mg l^{-1}) and K (191.70 mg l^{-1}), which suggests its suitability as a liming agent. However, this mixture exhibited limitations in aeration and water retention due to low porosity (24.3%). Furthermore, increasing the proportions of CSA and PKSB significantly enhanced the growth media's bulk density and particle density. These findings provide valuable insights into developing efficient growth media from agricultural by-products, thereby contributing to sustainable waste management and innovative farming practices.

Keywords: agricultural residues; biochar utilization; growth media development; sustainable waste management

INTRODUCTION

Agricultural waste management is crucial in addressing environmental sustainability and resource efficiency challenges. As a leading agricultural producer in Malaysia, a substantial volume of biomass waste is generated annually from crops such as oil palm, rubber, rice, cocoa, and coconut. However, despite its potential, only a tiny fraction of these residues is repurposed, with the majority either burned or discarded. Consequently, this results in environmental degradation and the underutilization of valuable resources (Abdullah and Sulaiman, 2013). Therefore, harnessing this agricultural biomass presents an opportunity to develop eco-friendly and cost-effective solutions for sustainable agriculture.

For instance, the oil palm industry alone contributes approximately 70 million tons of biomass annually, including palm fronds, empty fruit bunches, and palm kernel shells (Mohammed et al., 2011). These residues can be converted into biochar through pyrolysis, a thermal decomposition process that enhances carbon stability, pH, and nutrient retention (Fredriksson and Johansson, 2016). Similarly, the coconut industry generates significant residues, including

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shells and coir dust. Specifically, coconut shell ash (CSA), obtained through carbonization, is rich in potassium, calcium, and silicon. Consequently, it improves soil pH, cation exchange capacity (CEC), and microbial activity (Oluwole et al., 2017). Furthermore, coconut coir dust (CCD), a widely used soilless medium, offers advantages such as high water-holding capacity and porosity. However, amendments must address its low aeration and nutrient imbalances (Oagile et al., 2016).

In addition, the growing media industry increasingly relies on sustainable and cost-effective alternatives to peat and other traditional substrates. As a result, blending agricultural residues such as CSA, CCD, and palm kernel shell biochar (PKSB) offers a promising approach to developing efficient growth media. These mixtures can support plant propagation by improving aeration, nutrient availability, and water retention while reducing environmental waste.

Nevertheless, limited research has been conducted to comprehensively evaluate the physico-chemical properties of these materials when combined as growth media. Therefore, understanding their properties is essential to optimize their use in soilless culture systems. Accordingly, this study aimed to determine the physicochemical properties of different mixtures of agricultural waste materials and assess their suitability as growth media for sustainable soilless culture.

MATERIALS AND METHOD

Selection of raw materials and experimental sites

The samples for this experiment consisted of CCD, CSA, and PKSB. The CCD and chili seeds (planting material) were collected from Bumi Hijau (M) Sdn. Bhd., Teluk Panglima Garang, Selangor. KY Global Sdn. Bhd. supplied the CSA and PKSB. Agro-waste media was prepared at Agrotechnology Farm, Taman Pertanian Putra, Universiti Putra Malaysia (UPM). In contrast, the chemical and physical analyses were performed at the Analytical Laboratory and Soil Physic Laboratory, Faculty of Agriculture, UPM.

Preparation of soilless growth media

Agro-waste soilless growth media were prepared using different ratios (v/v) of CCD, CSA, and PKSB, as shown in Table 1. Nine different growth media mixtures were prepared by varying the volume ratios of these materials. These mixtures include T1 (100% CCD), T2 (100% CSA), T3 (100% PKSB), T4 (3CCD:1CSA), T5 (2CCD:1CSA), T6 (1CCD:1CSA), T7 (3CCD:1PKSB), T8 (2CCD:1PKSB), and T9 (1CCD:1PKSB). T1, T2, and T3 represent the pure forms of each material. At the same time, T4, T5, and T6 include varying ratios of CSA combined with CCD, and T7, T8, and T9 include different ratios of PKSB combined with CCD. This diverse set of mixtures was designed to explore various combinations suitable for fertigation practices.

Table 1. Agro-waste soilless growth media ratios

Growth media	CCD	CSA	PKSB
T1	1	-	-
T2	-	1	-
T3	-	-	1
T4	3	1	-
T5	2	1	-
T6	1	1	-
T7	3	-	1
T8	2	-	1
T9	1	-	1

Determination of physical properties

To evaluate the physical properties of the media, researchers analyzed particle size, bulk density, particle density, porosity, and water retention. Pre-soil samples were collected for these analyses.

Particle size

Particle size distribution was determined using the sieve analysis method (Pope and Ward, 1998), where the media sample was sifted through a series of wire mesh sieves to separate it into discrete size fractions.

Bulk density, particle density, and porosity

Bulk density was determined using the core sampling method (Abu-Hamdeh and Al-Jalil, 1999). The media was placed inside a core sampler, trimmed flush with the edges, and weighed before and after drying. The bulk density was calculated using Equation 1.

$$BD = \frac{B-A}{V}\ \text{g cm}^{-3} \qquad (1)$$

Where, BD = Bulk density; B = Weight of the sample ring containing soil after being oven; A =

Weight of empty sample ring; V = Sample ring volume (22/7 x 2.4 x 2.4 x 5) (Oshins et al., 2022).

Particle density was determined using the pycnometric method (Mohsenin, 1986). The pycnometer was used to measure the mass of the sample and the displaced water. The particle density was calculated using Equation 2.

$$\text{PD} = \frac{\text{Absolute dry weight of soil}}{\text{Total volume of soil grains}} \text{ g cm}^{-3} \quad (2)$$

Where, PD = Particle density (Rühlmann et al., 2006).

Water retention

Water retention capacity was measured using the Ceramic Pressure Plate Method (Richards, 1948). The media was placed in a retainer ring, and the sample was saturated with water and subjected to various pressures (1, 10, 33, and 1,500 kPa). The moisture content was calculated as a percentage of the oven-dried weight.

Determination of chemical properties

Chemical properties, including pH, electrical conductivity, total organic C, N, S, CEC, and exchangeable cations, were analyzed using standard methods.

pH and electrical conductivity

pH and electrical conductivity were measured electrometrically in a 1:1 soil/water ratio using a pH/EC meter (Hogg and Henry, 1984; Khorsandi and Yazdi, 2007). A 10-gram media sample was mixed with 25 ml of distilled water, shaken for one hour, and left overnight. A digital electrode pH/EC meter recorded the pH and electrical conductivity.

Total organic C, N, and S

Total organic C, N, and S content were determined using the Walkley-Black wet oxidation method (Walkley and Black, 1934). Samples were analyzed using CNS TruMac Determinators (LECO) after combustion at 1,350 °C.

CEC and exchangeable cations

CEC and exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) were determined using a 1 M NH^{4-} acetate solution.

Data analysis

Before applying ANOVA, a normality test (Shapiro-Wilk test) was performed to assess whether the data followed a normal distribution. The data were analyzed using one-way ANOVA to determine significant differences between the growth media treatments. If significant differences were found, post hoc tests were conducted to identify specific differences between treatments.

RESULTS AND DISCUSSION

Physical properties analysis

Particle size

Particle size plays a crucial role in influencing the physical properties of growth media, including water movement and retention. It also affects soil moisture characteristics, hydraulic conductivity, and other properties critical for plant growth and classification (Bittelli et al., 1999; Srinivasarao et al., 2004; Khodaverdiloo et al., 2011). Therefore, accurate estimation of soil properties depends on precise particle size determination. The materials used in this study exhibit different particle size ranges (Table 2). CSA has a very coarse particle size ranging from 600 µm to 4.75 mm, while CCD has a medium particle size range of 500 µm to 2 mm. PKSB is the finest material, with a particle size range of 300 to 600 µm. Similar findings were reported by Jaguaribe et al. (2005), who classified coconut shell-activated carbon particles between 1.0 and 2.36 mm. For CCD, studies by Fornes et al. (2003) and Noguera et al. (2003) found that more than 90% of particles were smaller than 8 mm, predominantly derived from pith tissues. Ahmad et al. (2014) and Abbas et al. (2019) reported particle size ranges for PKS and biochar that align with this study. Fine particle sizes in growth media enhance water retention due to increased small pore volume. However, combining particles of varying sizes is critical for maintaining total porosity and aeration. Smaller particles filling spaces between larger ones may reduce aeration space but increase water-holding capacity (Spomer, 1979; Ansorena, 1994). These considerations are essential for optimizing growth media properties for soilless culture.

Table 2. The particle size of the materials

Material	Particle size
CCD	500 µm – 2 mm
CSA	600 µm – 4.75 mm
PKSB	300 µm – 600 µm

Bulk density, particle density, and porosity

Bulk density is soil mass divided by unit volume. Meanwhile, the particle density represents the average density of all the soil minerals. Porosity is that portion of the soil volume occupied by pore spaces (Thien and Graveel, 2003). Different growth media affected the bulk density, particle density, and porosity significantly (*p* ≤ 0.05). According to Figure 1, T3 was recorded as the maximum value of bulk density and particle density of 0.88 and 1.07 g cm^{-3}, followed by T2, demonstrated as the second maximum value of bulk density and particle density of 0.79 and 1.04 g cm^{-3}. Meanwhile, T1 has revealed the minimum value below the optimum bulk density range (0.08 g cm^{-3}) and particle density (0.12 g cm^{-3}). Thus, it has a higher porosity, about 32.0%, than in T2 (24.3%) and T3 (17.7%), as illustrated in Figure 2. According to Abad et al. (2005) and Asiah et al. (2004)**,** the normal range of bulk density and particle density in soilless media is 0.25 to 0.75 g cm^{-3} and 0.26 to 1.07 g cm^{-3}. Meanwhile, the optimum range of porosity is between 5 to 30%.Thus, the optimum range of bulk density, particle density, and porosity in proper growth media conditions caused better support of water and nutrient elements for plants, leading to good growth (Olympious,1992; Kumar and Goh, 1999). Sarkar et al. (2021) proved that CCD contained a high porosity of 22.63%. In contrast, T3 also demonstrated the lowest amount of porosity compared to the other growth media, as shown in Figure 2. George and Jayachandran

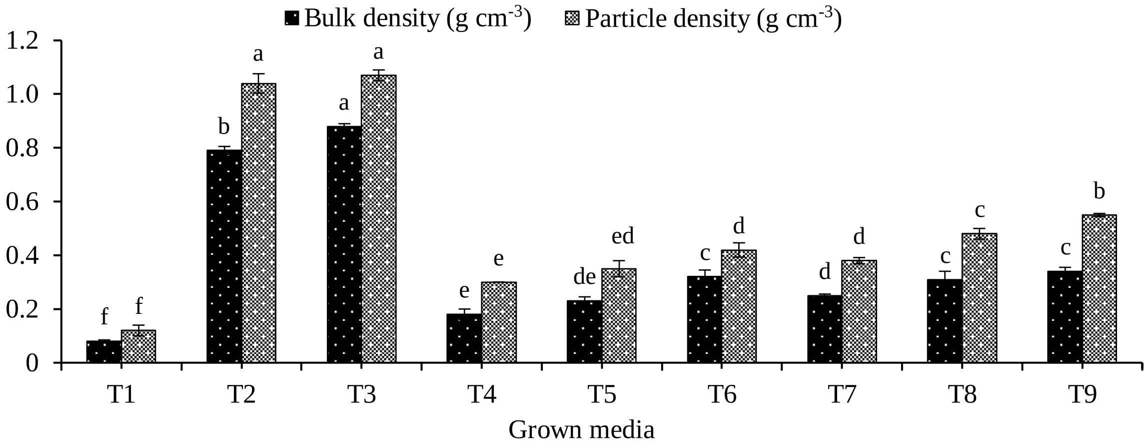


Figure 1. The bulk density and particle density of different growth media

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

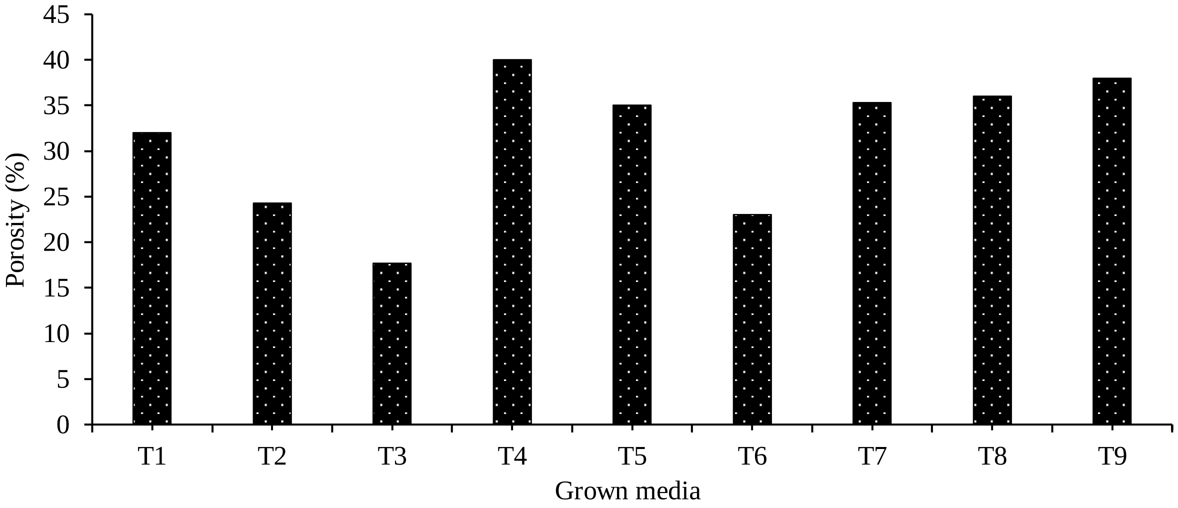


Figure 2. The percentage of porosity on different growth media

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

(2013) proved that CCD contained low bulk and particle densities but high porosity. Krishnapillai et al. (2020) also found that CCD contained low bulk density (0.18 g cm^{-3}), particle density (0.8 g cm^{-3}), and high CEC. Thien and Graveel (2003) stated that the relationship of bulk density and particle density with porosity is reciprocal. This is because bulk density and particle density typically increase as the ratio of solids in soil increases and conversely decreases as the ratio of solids decreases. Bulk density considers both the solids and the pore space, whereas particle density considers only the mineral solids.

Particle density was used with bulk density to calculate the pore space (porosity) in growth media occupied by air and water. Table 2 also shows that the increased rate of CSA and PKSB resulted in increased bulk density and particle density in growth media. Fernandes and Corá (2004) found that increasing the bulk density value has decreased the total porosity and aeration space and increased buffering water and remaining water. These findings were associated with increased growth media mass that occupied part of the air-filled pore space, changing the pore size distribution. The particles occupied the air space because of the increase of the substrate mass, which was the cause of the reduction of the total porosity and the change in the pore size distribution. The tiny particles have probably occupied the void space among the large particles, transforming large pores into small ones and increasing the growth media’s water-hold capacity (Spomer, 1979; Ansorena, 1994). Moreover, mixing and transporting low bulk-density media is much easier than high bulk density.

However, media with a low bulk density does not provide adequate support for the plant, which may be heavy at the top, as Nagaraj et al. (2018) reported. Raviv et al. (2008) also reported that an increase in bulk density is associated with a decrease in total pore space and thus affects growth mainly through reduced free pore space. Reducing total pore space will often decrease oxygen transport and root penetration. A decrease in total pore space may also increase water retention as pore diameters decrease, which means that loss of physical structure often increases water retention of the remaining material. The texture, structure, and level of induced compaction are the main properties governing the soil’s amount and type of pore space. Organic matter affects porosity through its enhancement of soil aggregation.

Water retention

Soil organic matter and texture heavily affect water-holding capacity or water retention. It significantly influences applications such as regulating plant growth, soil drainage, and soil functional attributes (Bordoloi et al., 2019). The pressure potential (in kPa) represented the crop stress level on soil or media. Different growth media affected the water retention across the pressure potential ($p \leq 0.05$). Water retention of all growth media showed a significant ($p \leq 0.05$) decrease across the pressure potential, as in Figure 3. According to Figure 3, T1 possessed the highest water retention range of 94% on -1 kPa, which is nearly twice times more than the water retention of T2 (51%) and T3 (56%) due to increased porosity of water hyacinth and a high proportion of micropores (indicated by high volumetric water content at -1.0 kPa suction) reported by Awang (2009).

Meanwhile, growth media T5 demonstrated the second-highest water retention of 87% on pressure potential -1 kPa, followed by growth media T7 (85%). According to Abad et al. (2005) and Asiah et al. (2004), the optimum range of water retention in soilless media is 20 to 60%. Thus, all growth media contain the optimum range except growth media T1, T4, T5, and T7, which exceed the normal range of water retention in soilless media. These findings proved that the increased rate of CCD has increased the water retention in growth media, as referred to in the line graph in Figure 3. Alves et al. (2024) state that organic matter affects water retention at higher matric potentials by altering structural parameters.

Meanwhile, organic matter increases soil adsorbing capacity to retain water atlower matric potentials. Alves et al. (2024) also found that correlation coefficients between bulk density and organic water contents decreased as matric potential decreased and thus became a poorer predictor of soil water retention. Sarkar et al. (2021) also found that CCD contained the highest water-holding capacity at 89.50%.The increased CCD in the mixture increased the water-holding capacity because it acts as an absorbent that can hold a large volume of water. Thus, the CCD-based media acted as an absorbent with

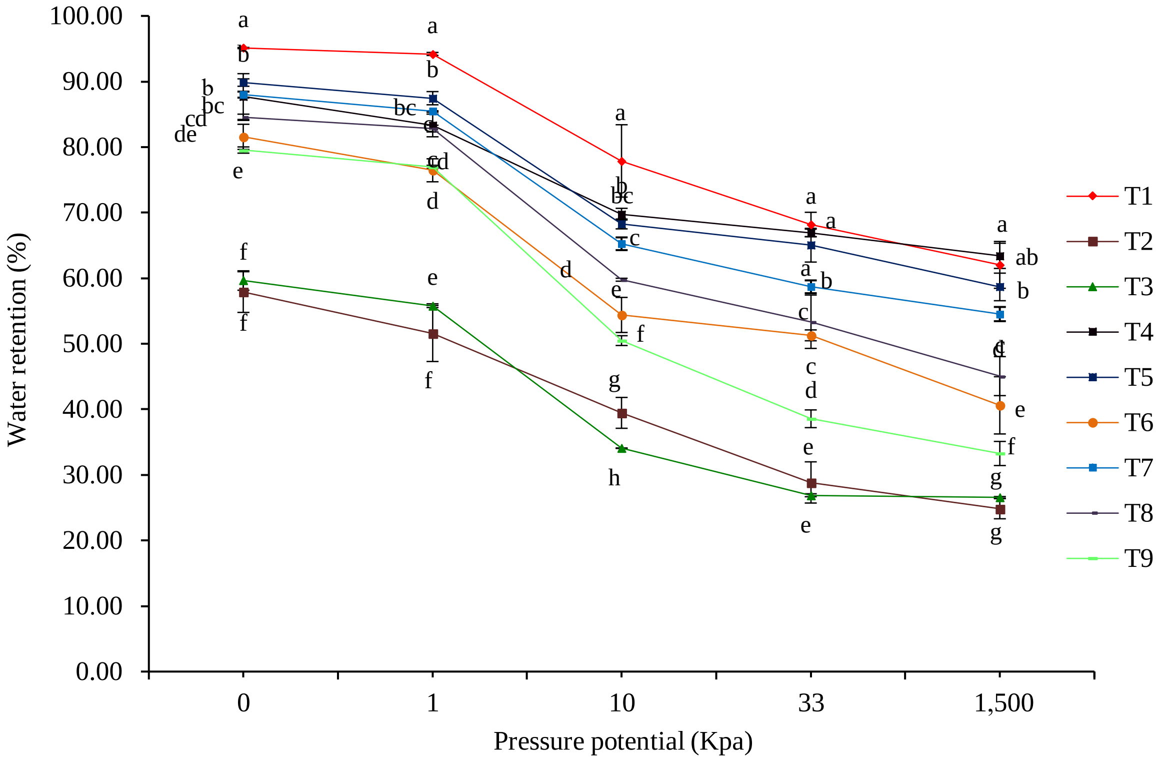


Figure 3. The interaction between different growth media and pressure potential on water retention

Note: Within the pressure potential, means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

significantly more moisture than other growth media. The hygroscopic properties of CCD make it an excellent water-absorbent material that is very effective in increasing the water-holding capacity of soil in dry periods (Liyanage et al., 1993; Sherin et al., 2004; Subramanian et al., 2006).

Moreover, bulk density and particle size closely correlate with total porosity and water retention (Wösten et al., 2001; Ruehlmann and Körschens, 2009). Londra et al. (2018) stated that CCD comprises spongy parenchyma cells and will hold up to 80% water once the excess drains. Krishnapillai et al. (2020) also studied that CCD contained high moisture retention capacity, low bulk density (0.18 g cm^{-3}), particle density (0.8 g cm^{-3}), and high CEC. These characteristics also make CCD ideal for mulch and soil amendment (especially for dry and sandy areas with low water retention). The finding also indicates the ease of the uptake of water and nutrition by plants and the wetness in various growing systems. Growth is highest at low water retention forces. Still, meager water retention forces are sometimes avoided, for example, when air-filled pores become too low for proper oxygen transport. The air content recommendations for optimal growth are found by Kipp et al. (2000).

Chemical properties analysis

pH value

Knowing the soil and the crop is essential in managing soil pH for the best crop performance. The optimum pH range for most plants is from 5.5 to 7.0, but some plants will grow in more acidic soil or require a more alkaline level. Plant nutrients leach from the soil much faster at pH values below 5.5 than from soils within the 5.5 to 7.0 range. In some mineral soil, aluminum can dissolve at pH levels below 5.0, becoming toxic to plant growth. Soil pH may also affect the availability of plant nutrients. Different growth media affected the pH value significantly ($p \leq 0.05$). Figure 4 shows the pH value range on different growth media between 4.55 and 7.89. From Figure 4, T2 reached the highest pH value of 7.89 and leaves the T3 as the second higher pH value of 6.63.

Meanwhile, T1 has the lowest pH value of 4.55 compared with other growth media. Moreover, T4 to T8 exhibited the optimum pH range between 6.29 to 5.63. According to Piash

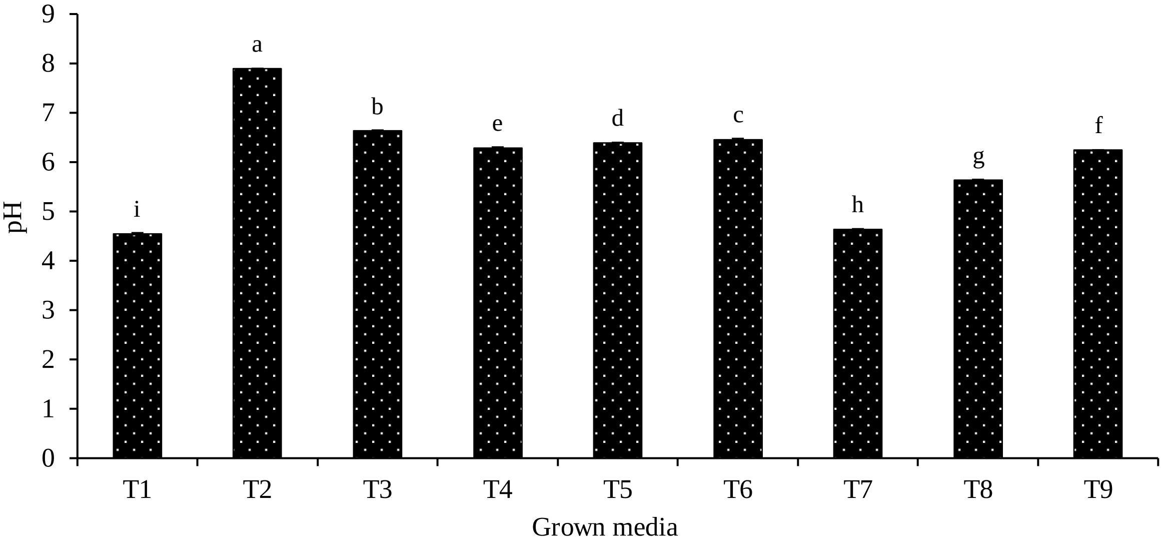


Figure 4. The pH value on different growth media

Note: Means with different letterssignificantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

et al. (2016), CSA and PKSB were alkaline due to the high dissolution of base cations. Burnt or charred plant residues contain a larger amount of alkalinity due to the volatilization of organic constituents under thermal conditions, leading to alkaline constituents' concentration (Cao et al., 2024). Cheah et al. (2014) proved that CSA and biochar alkalinity can be attributed to four broad categories: surface organic functional groups, carbonates, soluble organic compounds, and other inorganic alkalis, including oxides, hydroxides, sulfates, sulfides, and orthophosphates. Piash et al. (2016) also stated that increased pH of coconut ash and biochar-amended acid soils might help to reduce Al toxicity and increase P availability and liming agent. Njoku and Mbah (2012) also reported that organic amendment can stabilize soil pH by buffering against undesirable pH fluctuations in soil. However, a higher pH than recommended for plant growth in soilless media of 5.0 to 6.5 can harm plant growth (Bunt, 2012). Meanwhile, Al-Ajlouni et al. (2024) proved that the pH of 100% cocopeat and 70 cocopeat: 30 kenaf core fiber were higher at about 6.6 pH than that of the other media. Thus, cocopeat needs to do some liming to reach the plant's suitable pH.

Electrical conductivity

Electrical conductivity measures an aqueous solution's salinity (total salt level). Electrical conductivity showed significant ($p \leq 0.05$) differences between growth media. Figure 5 shows the electrical conductivity of different growth media. T2 contained the highest electrical conductivity value of 2.7 dS m^{-1}, followed by T6 at 1.7 dS m^{-1}. Meanwhile, T7 indicated growth media containing the lowest electrical conductivity value of 0.29 dS m^{-1}. Al-Ajlouni et al. (2024) reported that the acceptable range of initial electrical conductivity of a good soilless media should be between 0.4 to 1.5 dS m^{-1}. According to Balamurugan et al. (2024), electrical conductivity values reflect the total inorganic ion concentration in the media extracts. Higher electrical conductivity of T2 reflects that coconut ash contains a relatively high concentration of soluble salts, which could benefit plant growth. Al-Ajlouni et al. (2024) also stated that a low electrical conductivity value indicates that the media did not contain excessive salt that could cause plant salinity injury. However, at the same growth media with low electrical conductivity value, it contains insufficient amounts of nutrients to support plant growth.

CEC and exchangeable cations

CEC measures the soil's ability to hold positively charged ions. It is a significant soil property that influences soil structure stability, nutrient availability, soil pH, and the soil's reaction to fertilizers and other ameliorants (Suryaningtyas et al., 2024). Figure 6 demonstrates the CEC on different growth media (T1 to T9). T2 contained the highest CEC level of 12.57 cmolc kg^{-1}, followed by T1 as the second highest CEC value of 10.86 cmolc kg^{-1}. Meanwhile, Figure 7 shows the exchangeable cations K, Ca, Mg, and Na on different growth

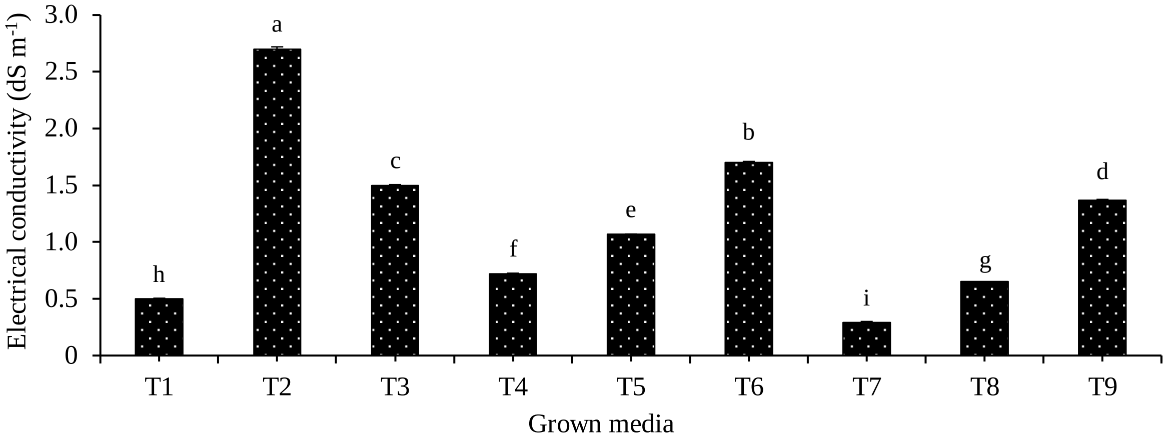


Figure 5. The electrical conductivity on different growth media

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

media. The principal ions associated with CEC in soils are the exchangeable cations potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and sodium (Na^+), generally referred to as base cations (Rayment and Higginson, 1992). T2 contained the highest CEC level of 12.57 cmolc kg^{-1} with high exchangeable K^+ (3.07 cmolc kg^{-1}) and exchangeable Mg^{2+} (0.52 cmolc kg^{-1}) compared to other growth media. Angalaeeswari and Kamaludeen (2017) found that the CSA (biochar) results in high CEC (11.93 cmolc kg^{-1}) due to containing highly negatively charged and the presence of a high number of functional groups. Ogeleka et al. (2017) reported coconut ash contained high exchangeable cations K and Mg. Krishnapillai et al. (2020) studied that CCD contained high moisture retention capacity, high potassium content, low bulk density (0.18 g cm^{-3}) and particle density (0.8 g cm^{-3}) and high CEC, enabling it to retain high amounts of exchangeable K, Na, Ca, and Mg.

George and Jayachandran (2013) found that CCD has a high CEC, which enables it to retain large amounts of N and the absorption complex has high exchangeable K, Na, Ca, and Mg content. Hidayat et al. (2024) stated that growth media considerably, according to the nature of the cation used, the salt concentration applied, and the equilibrium pH level with optimum CEC values, can retain cationic fertilizers (K^+ and NH_4^+) and prevent nutrient leaching. Meanwhile, Scott (2006) and Orji (2012) reported that the low exchangeable bases and lower pH in the media indicate heavy leaching of soil essential nutrients. Figure 6 and 7 also demonstrated that T9 contained the lowest CEC (3.34 cmolc kg^{-1}) with low exchangeable cations K (0.86 cmolc kg^{-1}), Mg (0.29 cmolc kg^{-1}), and Na (0.022 cmolc kg^{-1}). However, exchangeable Ca was highest in T9 (2.96 cmolc kg^{-1}) compared to other growth media, as shown in Figure 7. Growth media T2 and T1 have large quantities of negatively charged sites on the surfaces, which adsorb and hold positively charged ions (cations) by electrostatic force, whereas T9 only has a few quantities of negatively charged sites on the surfaces (Ogeleka et al., 2017). According to Sumner and Davidtz (1965) and Arnold (1977), the amount of CEC measured varied.

Nutrient content

The ANOVA of macronutrients (including nutrient gaseous elements), C/N ratio, micronutrient elements, and heavy metal showed significant ($p \leq 0.05$) differences between growth media. However, only Cd content is not significantly different between all growth media. Table 3 shows the chemical composition of nine different growth media (T1 to T9). This chemical composition can be compared by three categories: macronutrient, micronutrient element, and heavy metal. Macronutrients are nutrients that plants require more significant amounts of, such as C, H, N, O, P, K, Ca, S, and Mg (Syamsiyah et al., 2024). Table 3 shows that T2 mostly contained the maximum amount of macronutrient elements of N (0.58%), S (0.15%), P (13.90 mg l^{-1}), Ca (62.4 mg l^{-1}), K (191.70 mg l^{-1}), Mg (36.67 mg l^{-1}), followed by T3 that contained the highest level of C element of 73.96% and C/N ratio (232.33) but contained the low amount of S (0.079%) compared to other growth media. Micronutrients are elements that

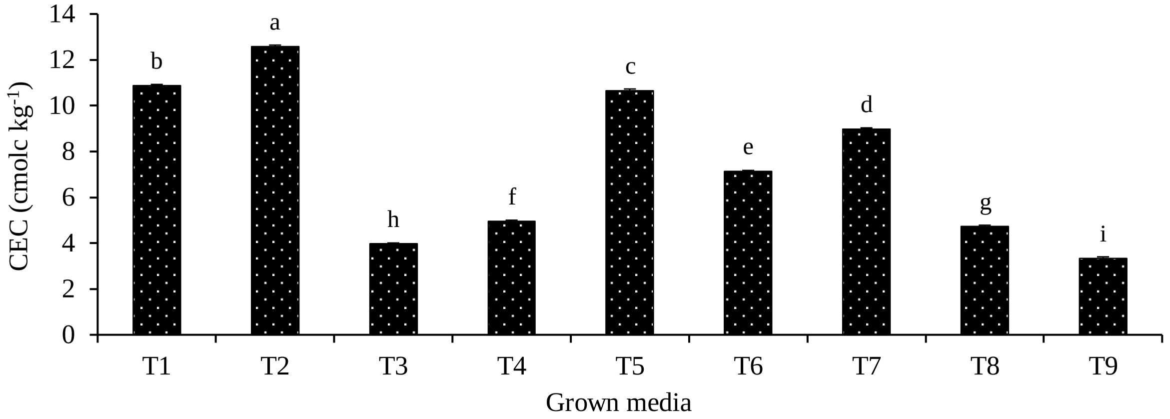


Figure 6. The CEC on different growth media

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

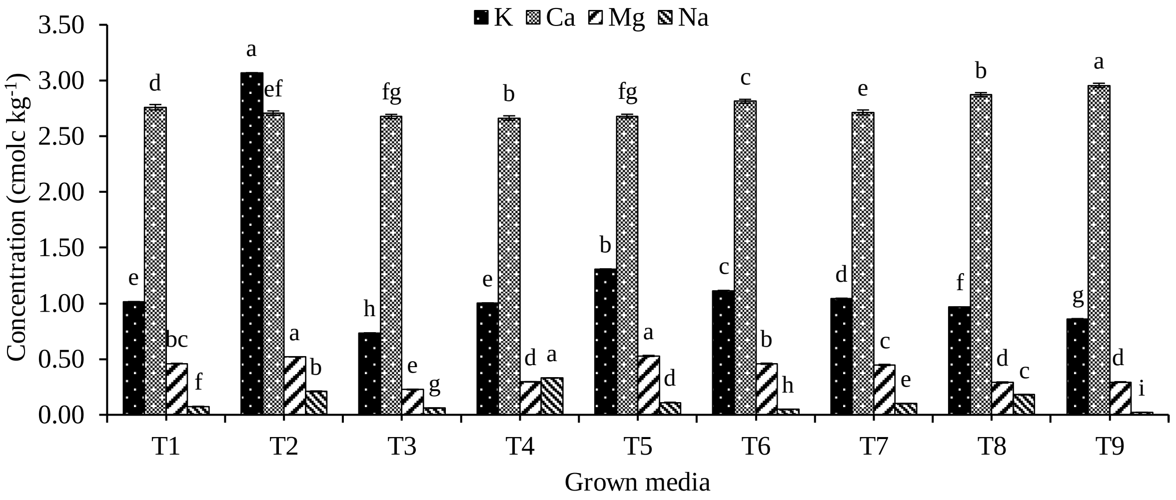


Figure 7. The exchangeable cations K, Ca, Mg, and Na on different growth media

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

plants require in smaller quantities, such as Fe, Na, Al, Ni, B, Cl, Cu, Mn, Mo, and Zn (Römheld and Marschner, 1991). Table 3 illustrated that T2 also revealed the maximum level of micronutrient elements of Al (101.20 mg l^{-1}), Cu (0.54 mg l^{-1}), Fe (71.10 mg l^{-1}), Mn (3.30 mg l^{-1}), Zn (7.63 mg l^{-1}) but not contained with the element boron, followed by T3 was contained the highest concentration of micronutrient elements Ni (2.56 mg l^{-1}) as well as lowest in B (0.033 mg l^{-1}), Na (8.56 mg l^{-1}) compared with other growth media. Heavy metals include essential and non-essential trace metals, which may be toxic to the plant depending on their properties, availability (chemical speciation), and concentration levels. Heavy metals such as B, Cd, Cr, Cu, Mn, Ni, Pb, and Zn are toxic or poisonous, although in a low concentration.

Heavy metals mainly had the highest T2 levels, though they have high macronutrients. T2 contained the highest concentration of heavy metals of Cd (0.03 mg l^{-1}), Cr (1.42 mg l^{-1}), Cu (0.54 mg l^{-1}), Mn (3.30 mg l^{-1}), Pb (0.81 mg l^{-1}), Zn (7.63 mg l^{-1}) except for elements B and Ni. Furthermore, T1 contained the highest B (0.35 mg l^{-1}) content but the lowest concentration of heavy metal Mn (0.13 mg l^{-1}), followed by T3 has the lowest concentration of B (0.033 mg l^{-1}) and Cr (0.074 mg l^{-1}). Meanwhile, T7 indicated the lowest concentration of Pb (0.012 mg l^{-1}) compared to other growth media. Table 3 indicates increases in related macronutrients, micronutrients, and heavy metals. Isa et al. (2024) reported that coconut ash was found to contain a large amount of K (26%), P (0.89%), Ca (1.34%), Mg (4.58%), Na (4.11%), S (0.56%),

Table 3. Chemical composition on different growth media by using AAS and ICP-OEs

Growth media	K (mg l^{-1})	Ca (mg l^{-1})	Cd (mg l^{-1})	Cr (mg l^{-1})	Cu (mg l^{-1})
T1	149.60±0.011^{b}	43.59±0.000^{b}	0.002±0.001^{a}	0.07±0.001^{i}	0.29±0.002^{c}
T2	191.70±0.010^{a}	62.40±0.000^{a}	0.003±0.001^{a}	1.42±0.001^{a}	0.54±0.002^{a}
T3	62.88±0.006^{f}	42.94±0.001^{c}	0.002±0.001^{a}	0.07±0.002^{g}	0.34±0.001^{b}
T4	96.68±0.002^{e}	21.87±0.001^{h}	0.003±0.002^{a}	0.62±0.002^{b}	0.27±0.000^{e}
T5	116.70±0.012^{d}	24.81±0.002^{g}	0.001±0.000^{a}	0.23±0.001^{f}	0.28±0.002^{d}
T6	126.50±0.003^{c}	26.45±0.003^{f}	0.001±0.000^{a}	0.38±0.000^{c}	0.29±0.001^{d}
T7	40.74±0.003^{i}	17.21±0.000^{i}	0.001±0.001^{a}	0.21±0.003^{g}	0.17±0.000^{g}
T8	42.24±0.002^{h}	28.07±0.003^{e}	0.001±0.000^{a}	0.26±0.000^{e}	0.16±0.000^{g}
T9	55.69±0.001^{g}	28.37±0.002^{d}	0.001±0.001^{a}	0.35±0.002^{d}	0.18±0.001^{f}
HSD ($p \leq 0.05$)	8,256.36***	601.52***	0.00***	0.52***	0.04***

Growth media	C (%)	N (%)	C/N ratio	S (%)	P (mg l^{-1})
T1	43.33±0.002^{i}	0.41±0.000^{e}	105.32±0.004^{h}	0.10±0.002^{c}	2.85±0.000^{g}
T2	59.48±0.000^{f}	0.58±0.001^{a}	102.09±0.140^{i}	0.15±0.001^{a}	13.90±0.002^{a}
T3	73.96±0.004^{a}	0.32±0.001^{g}	232.33±0.830^{a}	0.08±0.000^{e}	4.22±0.000^{e}
T4	50.59±0.010^{h}	0.45±0.000^{d}	113.79±0.031^{g}	0.10±0.002^{c}	4.59±0.001^{d}
T5	57.47±0.011^{g}	0.46±0.000^{c}	125.56±0.025^{f}	0.11±0.001^{b}	5.15±0.003^{c}
T6	63.97±0.008^{e}	0.48±0.002^{b}	132.06±0.560^{e}	0.10±0.000^{c}	5.26±0.000^{b}
T7	65.14±0.012^{d}	0.30±0.002^{h}	220.97±1.520^{b}	0.08±0.000^{e}	2.05±0.003^{i}
T8	66.05±0.006^{c}	0.32±0.002^{g}	205.58±0.980^{d}	0.09±0.001^{d}	2.31±0.002^{h}
T9	73.84±0.000^{b}	0.35±0.000^{f}	214.35±0.044^{c}	0.08±0.002^{e}	3.29±0.001^{f}
HSD ($p \leq 0.05$)	306.42***	0.03***	9,143.88***	0.00***	38.76***

Growth media	Al (mg l^{-1})	Fe (mg l^{-1})	Mg (mg l^{-1})	Mn (mg l^{-1})	B (mg l^{-1})
T1	4.14±0.001^{i}	5.74±0.003^{i}	11.95±0.006^{g}	0.13±0.000^{i}	0.35±0.002^{a}
T2	101.20±0.000^{a}	71.10±0.004^{a}	36.67±0.003^{a}	3.30±0.002^{a}	-
T3	13.54±0.000^{e}	47.09±0.001^{c}	17.66±0.002^{b}	0.88±0.001^{b}	0.03±0.001^{g}
T4	55.92±0.003^{d}	30.58±0.000^{e}	12.10±0.000^{f}	0.51±0.000^{e}	0.04±0.001^{f}
T5	65.63±0.002^{c}	32.91±0.003^{d}	12.48±0.003^{d}	0.52±0.000^{d}	0.12±0.002^{b}
T6	97.62±0.002^{b}	64.97±0.002^{b}	13.70±0.000^{c}	0.63±0.002^{c}	0.09±0.003^{c}
T7	4.93±0.003^{g}	15.12±0.000^{h}	9.23±0.003^{i}	0.31±0.002^{h}	0.07±0.001^{e}
T8	6.07±0.005^{f}	22.95±0.002^{f}	10.27±0.000^{h}	0.38±0.003^{g}	0.08±0.002^{d}
T9	4.31±0.000^{h}	22.65±0.002^{g}	12.23±0.000^{e}	0.47±0.001^{f}	0.07±0.000^{e}
HSD ($p \leq 0.05$)	5,104.59***	1,470.13***	212.12***	2.78***	0.03***

Growth media	Pb (mg l^{-1})	Ti (mg l^{-1})	Ni (mg l^{-1})	Zn (mg l^{-1})
T1	0.03±0.000^{e}	0.10±0.000^{h}	0.31±0.000^{c}	0.22±0.000^{g}
T2	0.81±0.001^{a}	0.54±0.001^{b}	0.75±0.002^{b}	7.63±0.001^{a}
T3	0.02±0.000^{f}	0.25±0.004^{d}	2.56±0.002^{a}	0.57±0.000^{e}
T4	0.04±0.002^{d}	0.61±0.000^{a}	0.28±0.003^{d}	0.69±0.002^{c}
T5	0.05±0.000^{c}	0.60±0.002^{a}	0.11±0.000^{h}	0.66±0.000^{d}
T6	0.24±0.000^{b}	0.50±0.003^{c}	0.19±0.001^{e}	1.37±0.002^{b}
T7	0.01±0.002^{g}	0.11±0.000^{g}	0.11±0.000^{h}	0.24±0.003^{f}
T8	0.01±0.002^{g}	0.23±0.001^{e}	0.14±0.003^{g}	0.22±0.001^{g}
T9	0.02±0.000^{f}	0.14±0.000^{f}	0.18±0.002^{f}	0.20±0.000^{h}
HSD ($p \leq 0.05$)	0.21***	0.14***	1.88***	17.26***

Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD). * and *** significantlydifferent at $p \leq 0.05$, and 0.001 respectively, NS = Not significant

Fe (1.64%). A similar result was found by Baon (2009), where plant-derived ash (PDAsh) contained high K (40%), Mg (13%), S (7%), and Ca (7%) contents. The high nutrient content of K (45.01%), P (4.64%), Na (15.42%), Ca (6.26%), and Mg (1.32%) was found in CSA (Amu et al., 2011). The chemical composition of CSA consists of Al (24.12%), Fe (15.48%), Ca (4.98%), Mg (1.89%), Na (0.95%), K (0.83%), Mn (0.81%), S (0.71%), and P (0.32%) reported by Bhartiya and Dubey (2018). Isa et al. (2024) also found that the oxides composition of CSA contained high Al (14.60%), Fe (12.40%), Ca (4.57%), Mg (14.20%), Mn (0.22%), Na (0.45%), K (0.52%), and Zn (0.3%). Meanwhile, the Ti content in CSA is 0.32% (Satheesh et al., 2019). Moreover, Hanudin et al. (2021) also found 1.85% of K-total content, 1.02% of Ca-total content, and 0.51% of Mg-total content in coconut ash. CSA contained Al (5.45%), Ca (0.57%), Fe (12.4%), K (0.52%), Mg (16.2%), and Na (0.45%), as reported by Debnath et al. (2013).

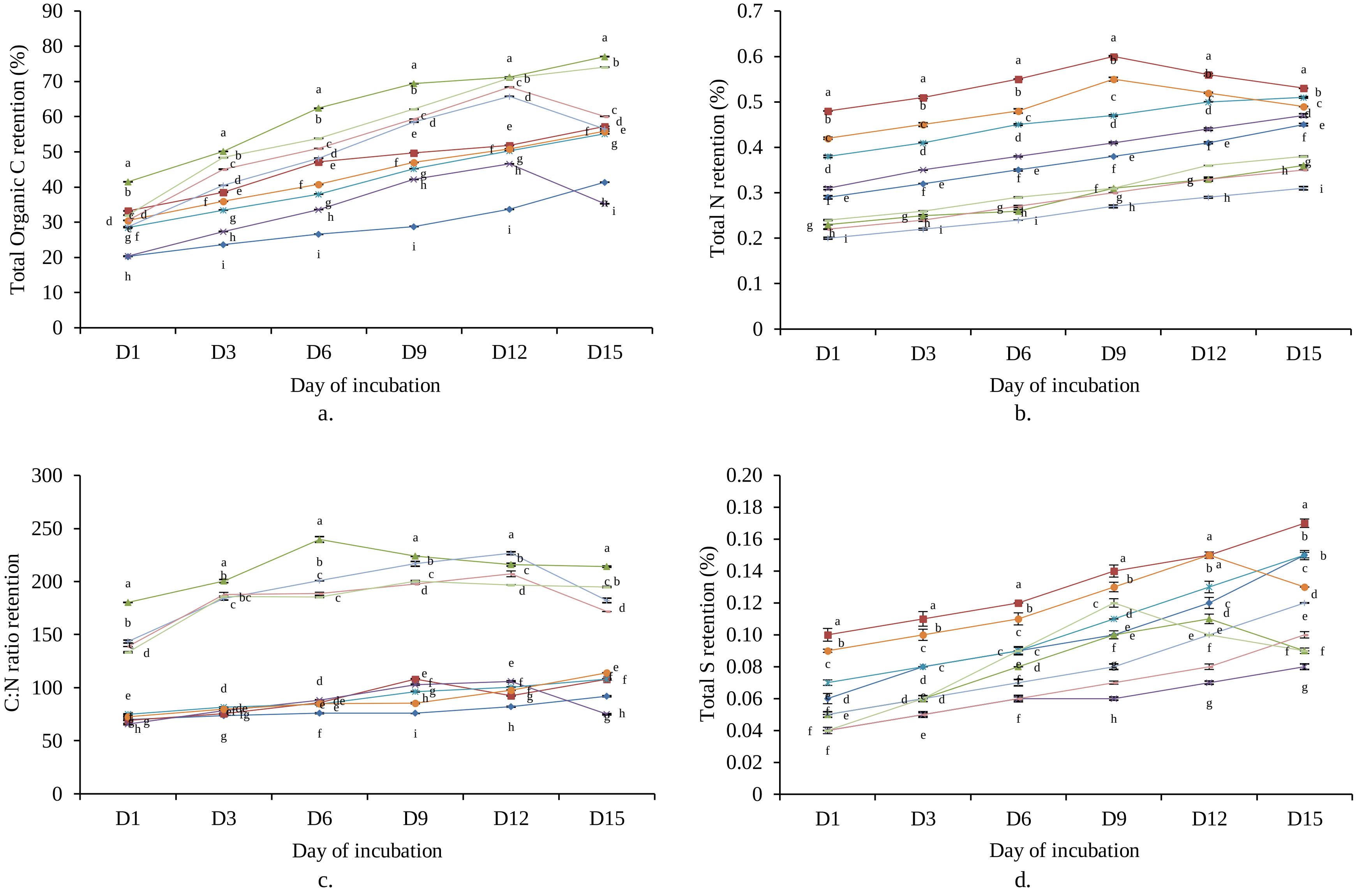
Kamga et al. (2024) found that coconut shell carbon (CSC) has similar results with CSA in Table 3, which contained the high total C (64.87%), total N (0.84%), and total S (0.09%). High organic C (14.33 g kg^{-1}), N (0.73 g kg^{-1}), and P (1.72 g kg^{-1}) were also found in 6-week incubations of 10 tons ha^{-1} coconut ash (Awotoye et al., 2014a). Moreover, Awotoye et al. (2014b) also reported that coconut ash's nutrient status was higher than its unleashed counterparts.

However, it also contains a high concentration of heavy metal that can cause toxic effects on a wide variety of organisms (Marcovecchio et al., 2007). According to Halmi and Simarani (2021), PKSB contained a high content of total C (434.1 g kg^{-1}), total N (5.07 g kg^{-1}), total P (1.56 g kg^{-1}), and C/N (85.62). The C/N ratio is one of the most critical factors affecting the composting process and compost quality, as reported by Golueke (1991). The C/N ratio is usually employed to indicate the maturity degree of compost Bernai et al. (1998). A decrease in the C/N ratio implies an increase in the degree of humification of organic matter. Generally, composting was carried out under a wide range of initial C/N ratios from 11 to 105, depending on the raw materials (Eiland et al., 2001; Ghosh et al., 2007).

Tripetchkul et al. (2012) and Loh et al. (2013) suggested that 20:1 C/N and 25:1 C/N formulation is the ideal ratio for high microbial activities that lead to rapid degradation of organic matter of the compost. The C/N ratio of biochar indirectly relates to N mineralization or immobilization during biochar-soil-microorganism interactions in decomposing organic materials (Ameloot et al., 2015). Cayuela et al. (2014) stated that the C/N ratio is the main element to indicate N_2O emission, where a high C/N ratio influences the reduction of soil N_2O emission (Brassard et al., 2016). Biochar with a low C/N ratio showed negative effects on N_2O emissions compared to high C/N, which can reduce N_2O emissions in the soil (Ameloot et al., 2013). The C/N ratio of PKSB produced by Haryati et al. (2018) were between 110 to 332, indicating that N_2O emissions from PKS-amended soil are low. Kalaivani and Jawaharlal (2019) proved that cocopeat contained N (0.41%), P (0.81%), K (1.32%), Ca (0.21%), Mg (0.31%), Fe (23.0 mg l^{-1}), and Zn (22.0 mg l^{-1}). Wira et al. (2011) also found that cocopeat contained N (0.53 mg l^{-1}), P (17.43 mg l^{-1}), K (9.63 mg l^{-1}), Ca (4.77 mg l^{-1}), Mg (0.19 mg l^{-1}), Fe (0.15 mg l^{-1}), Mn (0.02 mg l^{-1}), Zn (0.05 mg l^{-1}), Cu (0.03 mg l^{-1}). Meanwhile, Spehia et al. (2019) stated that low Mn (0.32%) content was found in cocopeat.

Nutrient retention

The ANOVA of nutrient retentions of total organic C, total N, total S, C/N ratio, S, K, P, Al, Ca, Fe, Mg, Mn, Na, and Zn showed significant ($p \leq 0.05$) differences between growth media across the incubation days. Figure 8 shows the nutrient retention in different growth media across the incubation days from day 1 to 15. Figure 8a shows that all growth media's total organic C retention increased across the incubation days. However, total C retention T4, T7, and T8 declined when it reached 15 days. Meanwhile, all growth media showed an upward pattern in total N retention across incubation days, except total N retention dropped in T2 and T6 when reaching the incubation days of 12 and 15, as illustrated in Figure 8b. According to Figure 8c, the C/N ratio in all growth media was increased across incubation days. In contrast, the C/N ratio in T3 decreased from incubation day 9 to 15, followed by the C/N ratio T2 and T9 when reached incubation day 12 to 15.

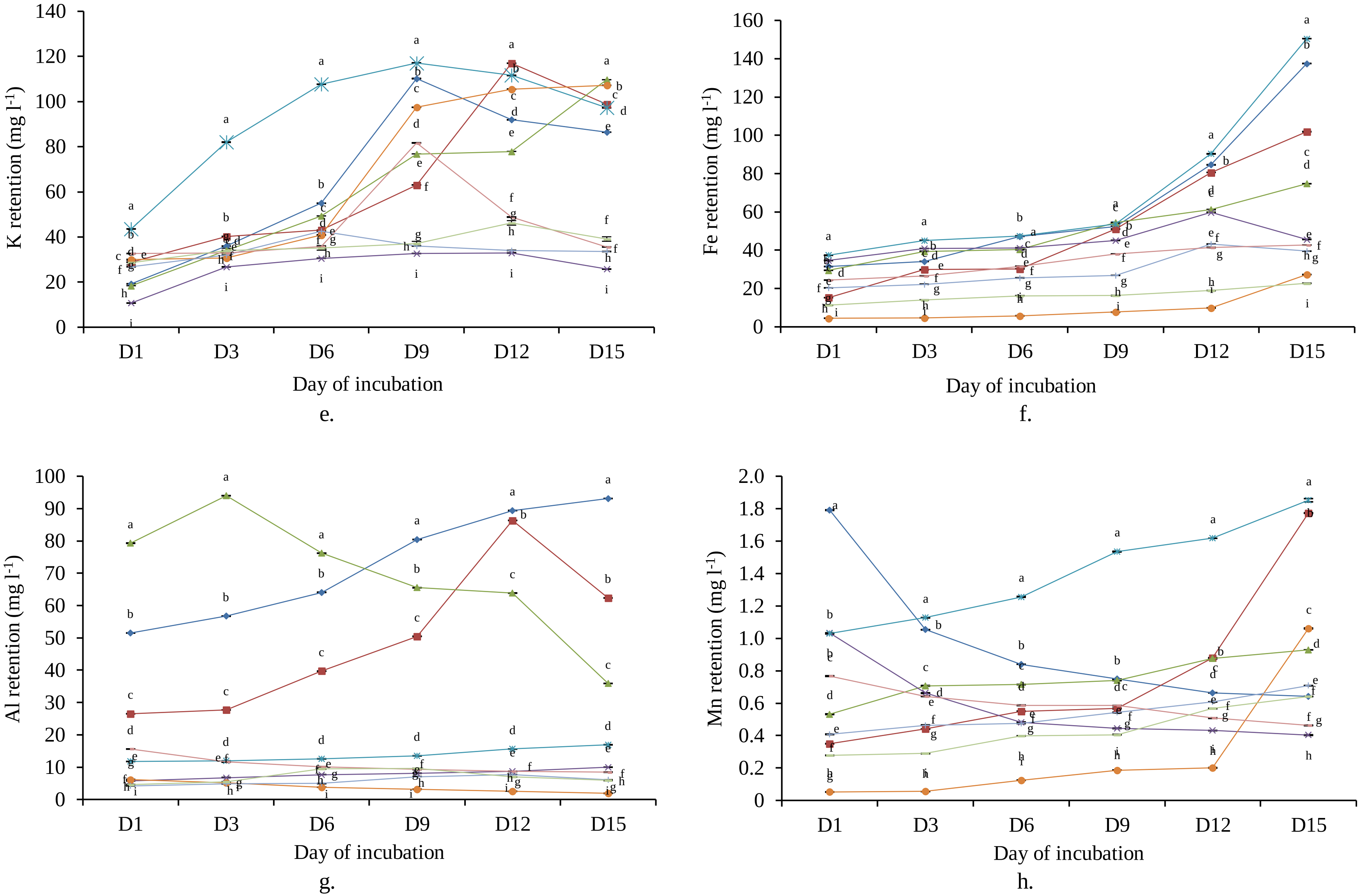

Total Organic C retention (%)
0
10
20
30
40
50
60
70
80
90
D1
D3
D6
D9
D12
D15
Day of incubation
Total N retention (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
D1
D3
D6
D9
D12
D15
Day of incubation
C:N ratio retention
0
50
100
150
200
250
300
D1
D3
D6
D9
D12
D15
Day of incubation
Total S retention (%)
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
D1
D3
D6
D9
D12
D15
Day of incubation

a.

b.

c.

d.

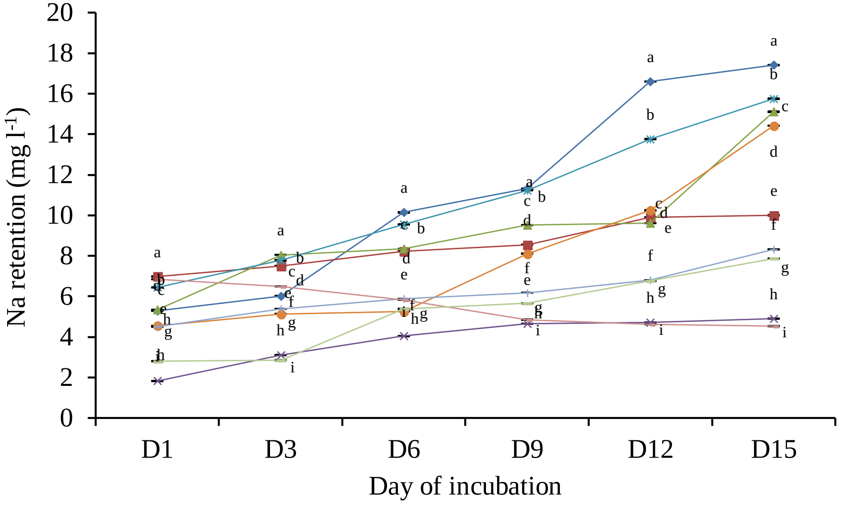

K retention (mg l-1)
0
20
40
60
80
100
120
140
D1
D3
D6
D9
D12
D15
Day of incubation
Fe retention (mg l-1)
0
20
40
60
80
100
120
140
160
D1
D3
D6
D9
D12
D15
Day of incubation
Al retention (mg l-1)
0
10
20
30
40
50
60
70
80
90
100
D1
D3
D6
D9
D12
D15
Day of incubation
Mn retention (mg l-1)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
D1
D3
D6
D9
D12
D15
Day of incubation

e.

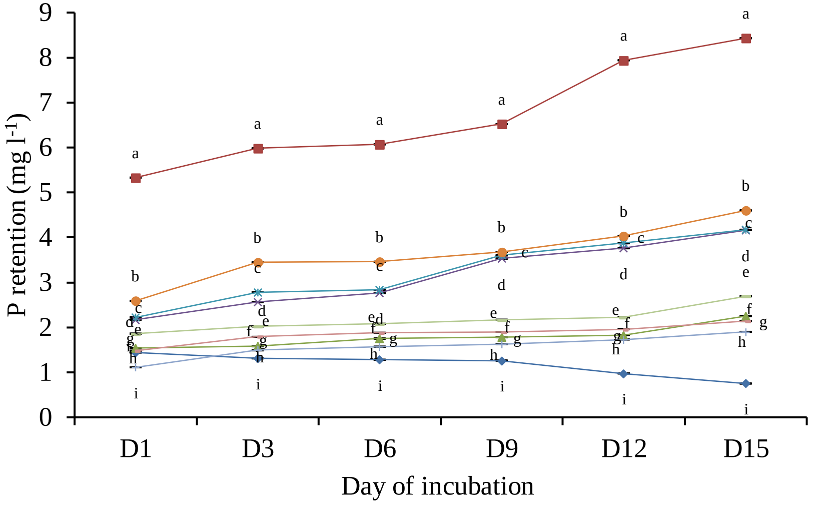
f.

g.

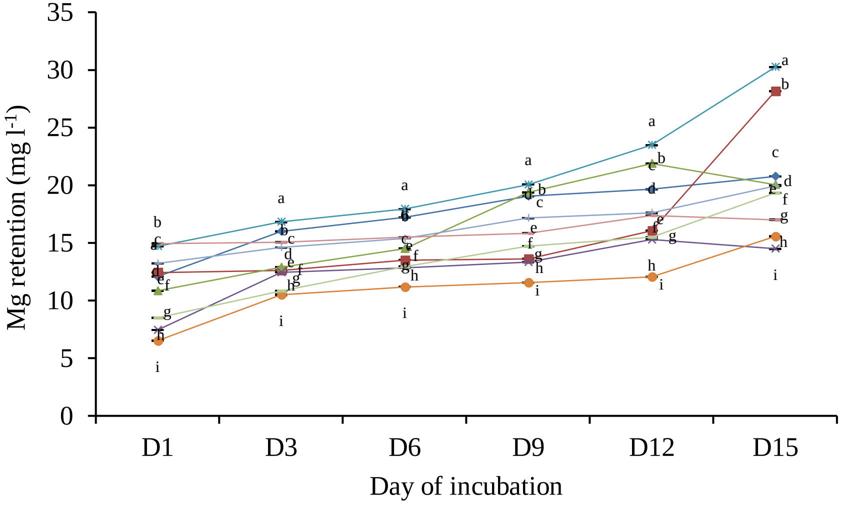
h.


Na retention (mg l-1)
0
2
4
6
8
10
12
14
16
18
20
D1
D3
D6
D9
D12
D15
Day of incubation

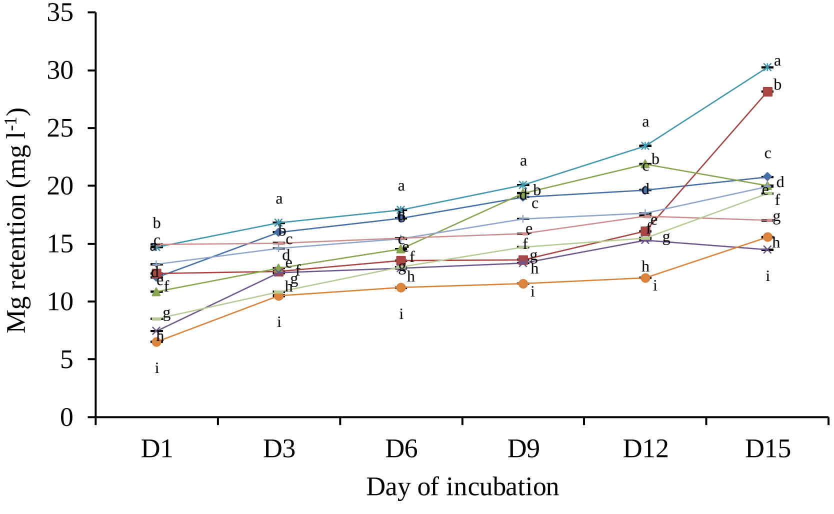
i.


P retention (mg l-1)
0
1
2
3
4
5
6
7
8
9
D1
D3
D6
D9
D12
D15
Day of incubation

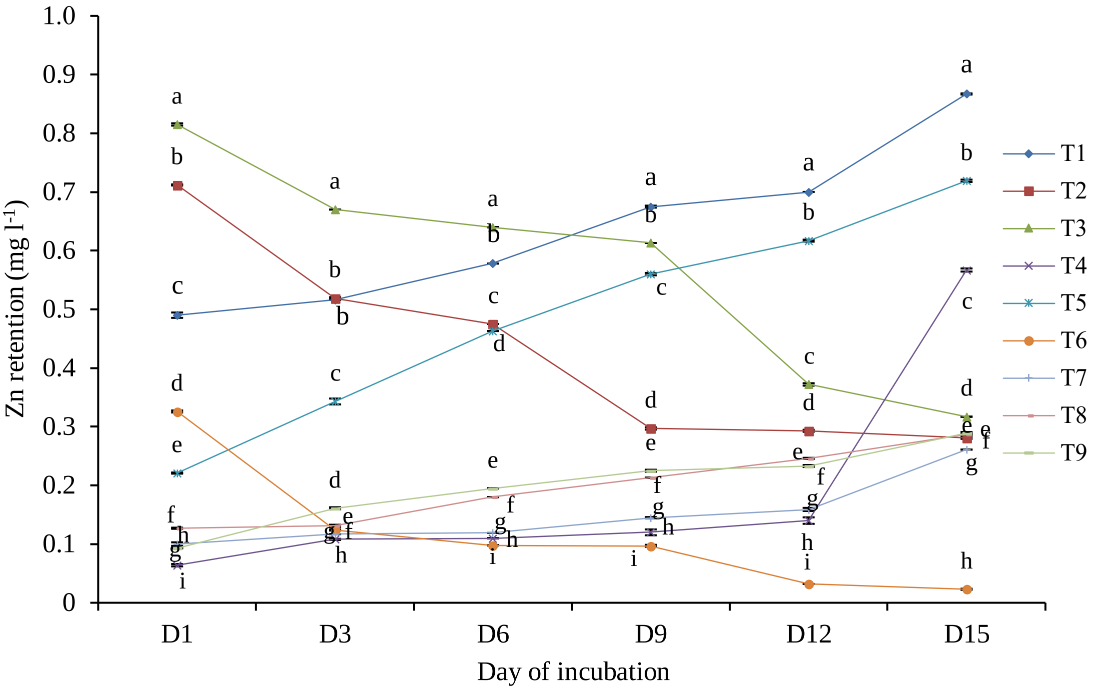
j.


Mg retention (mg l-1)
0
5
10
15
20
25
30
35
D1
D3
D6
D9
D12
D15
Day of incubation

k.


Mg retention (mg l-1)
0
5
10
15
20
25
30
35
D1
D3
D6
D9
D12
D15
Day of incubation

l.



m.

Figure 8. The nutrient retention in different growth media across the incubation days from day 1 to 15
Note: Means with different letters significantly differ at $p \leq 0.05$ using Tukey's Studentized Range (HSD)

Meanwhile, the C/N ratio in T4, T7, T8, and T9 were dropped at 15 days of incubation. According to Plaimart et al. (2021) found that coconut ash (biochar) retarded nitrate leaching via slower nitrification in digestate-amended soil. Wang et al. (2015) found that nitrification was retarded by peanut shell biochar amendment in an acidic orchard soil. Using biochar as a nitrification inhibitor could be a promising option for N-management in agriculture, which would be particularly relevant in co-application with a rich source of reduced N, such as anaerobic digestate (Plaimart et al., 2021). All growth media have shown an upward trend in total S retention across the incubation days (Figure 8d). However, total S retention in T9 declined at incubation days 12 and 15. The total S retention in T3 and T6 dropped at 15 days of incubation. Figure 8e indicated that K retention of all growth media showed an upward pattern along the incubation days from day 1 to 12. Still, K retention in most growth media declined when they reached incubation day 15 except for T3 and T6.

Meanwhile, all growth media showed an increased P retention pattern across the incubation days except P retention in T1, as referred to in Figure 8j. The amounts of P retained can be increased when the contact time between the growth media and the P supplied increases (Akinremi and Cho, 1991). However, in their study, Akhtar and Alam (2001) showed that P availability in organic matter decreased for both organic and inorganic P sources when increasing the incubation time.

The amount of P decreased in incubated organic matter between 1 and 6 weeks (Al-Rohily et al., 2013). The P fixation in organic matter can decrease the P amounts (Boukhalfa-Deraoui et al., 2015). According to Zhao et al. (2024), P adsorption of the soil samples increased as the initial P concentration increased at lower concentrations and then increased to a lesser extent at higher concentrations. In contrast, acids produced by the mineralization of fertilizers compete for adsorption with P, thereby reducing adsorption sites for P. Meanwhile, Novak et al. (2018) studied the fact that P and K associated with biochar are exposed to mineral weathering reactions at the surface and in pore spaces, potentially resulting in their dissolution and release. The additional incubation time would influence P and K release equilibrium reactions because of exposure to other microbes (nutrient mineralization and assimilation) and other chemical mechanisms (precipitation and binding by organic ligands) that can counter the bioavailability. According to Figure 8g, Al retention in growth media T3, T6, and T8 declined during the incubation days.

Meanwhile, Al retention in other organic matter increased across the incubation days, but Al retention decreased in T2, T7, and T9 when reached the 12-day and 15-day. All growth media were increased across the incubation days except Ca retention in T4, T5, T7, and T8, as presented in Figure 8m. The decreased trend of Fe retention was shown in all growth media on the incubation day (Figure 8f).

Figure 8k shows the Mg retention of all growth media, which is indicated by an upward trend across the incubation days. According to Figure 8h, the Mn retention showed an increased pattern in all growth media when the incubation days increased, except Mn retention in T1, T4, and T8. Na retention showed an upward trend in all growth media when the incubation days increased, except Na retention in T8, as referred to in Figure 8i. Meanwhile, Figure 8l illustrated that Zn retention in all growth media rose across the incubation day, except in T2, T3, T6, and T9. Nutrient retention capacity is of particular importance for the effectiveness of fertilizer applications, and it is especially relevant to intermediate- and high-input-level cropping conditions. Nutrient retention capacity refers to the capacity of the soil to retain added nutrients against losses caused by leaching. Plant nutrients are held in the soil on the exchange sites provided by organic matter (Fischer et al., 2008). Lehmann and Joseph (2024) reported that the nutrient retention capacity is attributed to the surface area, porosity, and extensive pore distribution of organic matter particles.

The particle-specific surface area (m^2 g^{-1}) determines nutrient retention. The number of cations that hold nutrient anions in the organic matter increases with the surface area. Meanwhile, the decreased nutrient retention in growth media was due to growth media reaching the optimum nutrient concentration and losing strength to hold excess nutrients. Thus, nutrient volatilization and leaching occur during incubation (Eghball et al., 1997; Ullah et al., 2017). According to Laird et al. (2010), nutrient leaching could diminish soil fertility, accelerate soil acidification, increase fertilizer costs for farmers, and reduce crop yields. Berek et al. (2018) reported that biochar can retain nutrients due to its numerous tiny pores and large surface area charge. Highly weathered soils are poor in nutrients because of leaching. Biochar is believed to have a high nutrient retention capacity. Such nutrient retention capacity is attributed to high surface area, porosity, and surface charge. For example, NH_4-N adsorption is due to cation exchange on the surface functional (phenolic and carboxylic) biochar groups and physical entrapment in biochar's porous structure. Applying biochar to soil could increase soil fertility and crop productivity by reducing leaching or supplying nutrients (Glaser et al., 2002; Lehmann et al., 2003; Major et al., 2010).

Moreover, biochar can enhance nutrient retention due to its surface charge density (Kongthod et al., 2015). Biochar mostly has negatively charged surfaces, increasing cation species' adsorption capacity (Lou et al., 2016). This can be partially attributed to effects on microbiology that reduce fertilizer losses via leaching (Atkinson et al., 2010; Tan et al., 2015).

CONCLUSIONS

This study identified T2 (100% CSA) as the most favorable organic waste due to its high pH, electrical conductivity, CEC, and macronutrient content, contributing to enhanced nutrient retention and potential soil fertility improvement. However, its limitations include a higher-than-recommended pH for soilless media, elevated heavy metal content, and lower water-holding capacity than CCD. Future research should focus on evaluating these findings under field conditions and using fertigation systems to assess the impact of different media on plant growth performance. Emphasis on exploring sustainable use of agro-wastes as soil amendments can support organic farming practices while addressing environmental and economic challenges.

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