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EFFECT OF DIFFERENT ORGANIC MEDIA ON BLACK TURMERIC (*Curcuma caesia*) PLANT GROWTH AND SOIL ENRICHMENT

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Abstract: Black turmeric is an excellent species with a wide range of potential therapeutic applications. However, the propagation and production of black turmeric have been limited due to the lack of knowledge on suitable planting methods. This study aimed to determine the appropriate growth medium that produces the optimal growth of black turmeric. The treatments were T0 = Topsoil (control), T1 = Topsoil + peat moss (1:1), T2 = Topsoil + peat moss (3:2), T3 = Topsoil + peat moss (2:3), T4 = Topsoil + cocopeat (1:1), T5 = Topsoil + cocopeat (3:2), and T6 = Topsoil + cocopeat (2:3). All plants were consistently watered and received similar amounts of nitrogen (N), phosphorus (P), and potassium (K) fertiliser (15:15:15). This study concluded that T5 consistently resulted the greatest plant height, stem diameter, and crown diameter, establishing it as one of the most effective treatments. T2 also performed well, particularly in terms of crown diameter and plant height, with outcomes comparable to T5. T0 consistently exhibited the lowest values across all parameters. The addition of organic media to the soil is beneficial because it provides macro nutrients such as nitrogen and phosphorus, which help turmeric grow well by altering soil properties.

Keywords: Black turmeric, propagation, peat moss, cocopeat, plant growth.

Introduction

Curcuma caesia, commonly known as black turmeric, “kali haldi”, or “kunyit hitam” belongs to the Zingiberaceae family and is an endangered species native to northeast and central India. It is also cultivated in Malaysia (Bhupendra *et al*., 2016). In its native regions, black turmeric is traditionally used as a spice for food preservation (Mukunthan *et al*., 2017). All parts of the plant are useful, but the rhizomes of black turmeric are economically significant because of their therapeutic activities. The rhizomes have a bluish-black colour, bitter, spicy flavour, and strong odour (Liu *et al*., 2013). Black turmeric rhizomes have a wide range of medicinal applications.

Meanwhile, the leaves have the potential to enhance rice seed germination (Lalitha *et al*., 1995) and can be eaten raw as salad or boiled to treat cough (Awang-Kanak *et al*., 2018). Black turmeric contains proteins, tannins, steroids, glycosides, anthraquinones, cardiac glycosides, reducing sugars, and other compounds (Prasanthi *et al*., 2015).

Black turmeric is propagated vegetatively, where rhizomes are separated into mother rhizomes and storage roots. It grows well in sandy or clay loam soil, rich in humus (Patrick, 2015). Topsoil typically consists of a mixture of sand, silt, clay, and organic matter, which supports plant growth. According to Brady and Weil (2016), soil texture is determined by the relative proportions of these components, influencing water retention, drainage, and nutrient availability. This plant is cultivated in warm and damp climates. It can be cultivated up to 4,000 ft above sea level (Chitra *et al*., 2022). This plant takes nine months to mature before it is fully harvested. As noted by Narendhiran *et al*. (2023), from April to August, small, bud-laden rhizome segments are nestled three inches deep into the earth. By December or January, the plants signal their readiness for harvest as their vibrant green leaves transform into a golden hue and gracefully fall away, marking the end of the growing season. Plants rely on growth media to obtain the essential nutrients and water necessary for their growth and development (Raviv *et al*., 2019). High-quality growth media can boost plant yield by providing optimal water retention, adequate nutrition, and disease-free seedlings (Gruda, 2019).

Soil conditions can also affect plant nutrient availability. The arrangement of soil particles into aggregates affects water and air movement, which in turn influences nutrient availability. Well-structured soil promotes good root growth and efficient nutrient uptake. Soil nutrients are accessible to plants because they are loosely bound to the soil and easily exchangeable with plants (Jones & Olson-Rutz, 2016).

Peatmoss and cocopeat are examples of notable organic planting media used commercially in the agricultural industry. Peat moss is created through the long-term carbonisation of sphagnum moss and silver grass that accumulate in oxygen-poor wetlands, resulting in a material rich in organic matter, which is over 90% by composition (Kim & Kim, 2011). Coco peat, derived from the fibrous husks of coconuts is a popular and cost-effective planting material worldwide. Noteworthy for its superb air permeability, water-holding ability, nutrient retention, low bulk density, high cation exchange capacity, and significant expansion up to four to five times its original volume when hydrated, coco peat offers a versatile and beneficial alternative (Kim, 2003; Kim *et al*., 2021).

Black turmeric is not a plant that originates from Malaysia and there is little commercial cultivation of black turmeric in Malaysia; there are also very few studies on its cultivation methods. Black turmeric is difficult to find in the market because of its low multiplication rate (Behar, 2013), which results in low market supply. Optimising growth conditions for black turmeric by identifying the most effective growth media is essential, as the choice of media significantly impacts both the planting process and the resulting yield. The current understanding of how different growth media affect growth rates and yields is insufficient, leading to suboptimal growth performance in various applications.

Furthermore, most of the land in Malaysia has been used for various purposes, resulting in diverse soil characteristics. According to Lee *et al*. (2014), the soil properties in Malaysia have changed over the years owing to the degradation process and declining soil fertility caused by improper agricultural activities and climate change. For instance, deforestation for agricultural expansion has significantly contributed to soil erosion and nutrient depletion.

In 2020, Malaysia lost approximately 118,000 hectares of natural forest, leading to an estimated 148 million tonnes of CO_2 emissions (Global Forest Watch, 2020). This study aimed to investigate the effect of different growth media and to determine the appropriate combination of media mixture that could enhance plant growth. Studies on the cultivation media for black turmeric are scarce, despite their importance for better understanding its growth requirements. This study opts for a mixture of commercial planting media, specifically cocopeat and peat soil in varying ratios, as these materials are widely available, commonly used in Malaysia and easy to apply when cultivating black turmeric.

Soil pH is a crucial factor as it significantly impacts various soil properties and processes that are vital for plant growth. Specifically, it affects microbial activity and the solubility and availability of nutrients, which are essential for optimal plant development (Gentili *et al*., 2018). Soil Water Holding Capacity (WHC) is a critical property that affects resource use efficiency, nutrient cycling, crop productivity, yield stability, and overall environmental quality (Ogle *et al*., 2019; Dey *et al*., 2020). Enhancing soil Water Holding Capacity (WHC) improves soil resilience to climate variability and aids agro-ecosystem adaptation to extreme weather events like heavy rainfall and droughts (Williams *et al*., 2018). Therefore, this study will also involve soil analysis to determine the pH, Water Holding Capacity (WHC), and macro nutrients (N, P, and K).

Materials and Methods

Study Area and Planting Materials

This study was conducted in a mini nursery near Universiti Malaysia Terengganu, Kuala Nerus, Terengganu, Malaysia. The size of the nursery was 4 m x 6 m. The planting period, spanning from March to October 2022, consisted of a two-month sowing period and a six-month growing period. The study period had to be shortened as November and December mark the monsoon season in Terengganu, resulting in flooding of the study area. To prevent damage to the plants, the study was halted.

Healthy rhizomes that were free from defects such as decay, mould, and others were used in this study. Rhizomes were collected directly from mature black turmeric clumps. The rhizome was cut to a size of 2 cm long and weighed approximately 10 g, sown in a sowing pod. All plants were consistently watered twice a day and received similar amounts of NPK fertiliser every two weeks throughout their growth. In this study, NPK green 15:15:15 was used. After two months, all seedlings were transplanted to the polybag filled with growing media, which had been set up.

Growth Medium Application

In this study, seven types of media were used: Topsoil only (control) as T1, topsoil + peat moss (1:1) as T2, topsoil + peat moss (3:2) as T3, topsoil + peat moss (2:3) as T4, topsoil + cocopeat (1:1) as T5, topsoil + cocopeat (3:2) as T6, and topsoil + cocopeat (2:3) as T7. All growing media were mixed well before being placed in a 12 cm × 10 cm polybag. Topsoil was chosen in this study as a control because it is typically a blend of sand, silt, and clay. The proportions of these particles determine whether the soil is sandy, loamy, or clayey. Loamy soil, which has a balanced mix of all three is often considered ideal for most plants.

Experimental Design

Extraction study plots were allocated using a Completely Randomised Design (CRD) with a total of three replicates, as shown in Table 1. In total, 21 plants were included in the study.

Table 1: Mixtures of planting media treatments used in the study

Treatments	Ratio of Mixtures
T1 (Control)	Topsoil only (5:0)
T2	Topsoil + peat moss (1:1)
T3	Topsoil + peat moss (3:2)
T4	Topsoil + peat moss (2:3)
T5	Topsoil + cocopeat (1:1)
T6	Topsoil + cocopeat (3:2)
T7	Topsoil + cocopeat (2:3)

Data Collection

Growth Parameters

Fortnightly, data collection was performed to gather the pre-harvest information. Plant height was measured using a measuring tape. Measurements were taken from the base of the plant (soil level) to the top of the plant (the highest point). The stem diameter was measured using a digital calliper 5 cm above the ground. For the number of leaves, each leaf grown was counted by recursively summing over each of the subtrees. For the number of rhizome buds, each rhizome bud that grew around the mother plant was counted. For the observation of crown diameter, the radial branch spread at the four cardinal compass points was used to calculate the size of the crown. The radial measurements were combined and divided to obtain the average crown diameter (Coombes *et al*., 2019).

Absolute Growth Rate (AGR)

Absolute Growth Rate (AGR) is the rate of increase in the growth variable at time ‘t’. To measure AGR, the differential coefficient of growth variable with respect to time ‘t’ was calculated. In this study, three growth variables, which are height, diameter of stem, and size of crown were calculated by using the following equation:

$$AGR = P2\text{-}P1/\ T2\text{-}T1 \qquad (1)$$

where P1 and P2 refer to the growth variable (cm) at the time T1 and T2, respectively. AGR is expressed in cm/week.

Soil Analysis and Soil Testing

Before planting, the soil sample was collected just after the soil mixture was filled into a polybag. For the 'after' planting soil sample, the sample was collected when the plant was harvested, which is 6 months after transplant.

Measuring pH Value

A total of 10 g of each planting medium was placed in a bottle. Then, 25 mL of distilled water was added, the bottle was shaken for 30 minutes, and left on the table at room temperature for one hour. This allows soil to settle and the solution to equilibrate at atmospheric CO_2. The pH value was determined using a pH meter.

Measuring Water Holding Capacity (WHC)

Soil Water Holding Capacity (WHC) is one measure of a soil's ability to store water and is the mass of water a given soil can store or hold per unit of mass (Lane & D'Amico, 2010; Wong *et al*., 2015). This study applied the funnel, filter paper, and drainage (MWHC FFPD) method.

The MWHC FFPD method allows one to measure the mass of water a sieved soil (< 2 mm) can hold after drainage in a funnel with filter paper. The Water Holding Capacity (WHC) of the soil was determined by first weighing 25 g of the soil sample and placing it in an oven for 24 hours at a temperature of 70°C. The tubing was attached to the bottom of the funnel and clamped shut. The funnel attached to the ring stands, suspended above the graduated cylinder. The funnel is lined with filter paper. 100 mL of air-dried samples was placed into the funnel. Using the graduated cylinder, 100 mL of water was measured. Enough water was poured gradually into the funnel to cover the compost/soil samples. The amount of "Water Added" recorded. The samples were stirred gently and allowed to sit until they were saturated. When the compost was soaked, the clamp was removed, allowing extra water to pour into the graduated cylinder. The amount of "Water Drained" in the graduated cylinder was measured once the leaking stopped. The Water Holding Capacity was determined for each sample. Calculation:

- Water retained in the 100-mL sample of compost or soil:
- Water retained in 100 mL compost or soil = water added - water drained (mL) (2)
- Water holding capacity expressed as the amount of water retained per litre of soil:
- Water holding capacity = 10 x (water retained in 100 mL compost or soil) (mL/L) (3)

Measuring Nitrogen, Phosphorus, and Potassium Content

Nitrogen (N) content in the planting media was determined using the Kjeldahl method (Sáez-Plaza *et al*., 2013). Kjeldahl methods were carried out through three steps, which are digestion, distillation, and titration. First, 1 g of dry soil/compost is placed into digestion tubes and then added with 1 tablet of the catalyst known as the Kjeldahl tablet. Add 12 mL of concentrated sulphuric acid (H_2SO_4) into the digestion tubes and shake them thoroughly. Heated the plate of the digestion machine to 420°C first before starting the digestion of the samples.

Digested the mixtures in each tube in the digestion machine in the fume hood until they became a clear solution/light green solution for one hour. Then, leave the mixture to cool down for an hour. Transfer the mixtures to the distillation tube, add 75 mL of distilled water, and pour slowly 50 mL of 40% NaOH. After that, the ammonia gas (NH_3) was released into a conical flask (which already contained 25 mL 4% boric acid (H_3BO_3) mixed with five drops of indicators) and the data was collected. Titrate the acid boric solution with 0.01 N HCL until the solutions become blue greyish or light indigo to determine the percentage of nitrogen present in the soil.

Dry weights of phosphorus (P) and potassium (K) were measured using the dry-ashing method (Sahrawat *et al*., 2002). For the dry-ashing method, weigh 2 g of growing media samples and place them into the crucible. The samples in the muffle furnace were burnt at 500°C for about eight hours. After that, cool down the samples to room temperature. 2 mL of concentrated HCl is added into each crucible and evaporated to dryness on a hot plate in the fume hood. Cool down the samples, add 10 mL of 20% HNO_3, and locate in a water bath at 70°C for an hour. Then, filter the mixtures of samples into a 100 mL volumetric flask using filter paper, Whatman No. 2, with the addition of deionised water to the calibrated marks. Finally, the flasks were shaken and 10 mL of the samples was put into a centrifuge tube in order to analyse using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

Data Analysis

The data was analysed using a Complete Randomised Design (CRD) with three replications. Using SPSS software version 20.0, the data were submitted to a One-way ANOVA test as well as a Tukey test. The goal is to see if there is a substantial difference between medium treatment and medium ratio.

Results and Discussion

Growth Performance of the Plant

The results reflect the mean plant height (in cm) for different treatments (T1 to T7), along with their standard deviations. T6 with treatment of topsoil and cocopeat at a ratio of 3:2 recorded the highest plant height with 78.33 cm and a significant difference compared to the control with only 27 cm. The second highest was indicated by T3 at 75.67 cm, followed by T2 at 74.33 cm. The T5 and T7 had lower results, grouped as "ab", with plant heights of 66.00 cm and 64.67 cm, respectively. The *P*-value of 0.015 shows a statistically significant difference in plant height across the treatments, suggesting that the treatments had a substantial impact on plant height. Overall, treatments T2, T3, and T6 resulted in significantly taller plants compared to T1, some overlap exists between the other treatments based on the letters "a", "ab", and "b".

Encouraging results (highest) were shown by a mixture of topsoil and cocopeat with a ratio of 3:2; the media conditions were favourable for the growth of *C. caesia*. Cocopeat can act as a reservoir of water and consists of essential nutrient elements, including calcium, magnesium, potassium, sodium, and phosphorus (Soeparjono, 2016). Meanwhile, peat moss, as one of the important growing media can hold air and water in high quantities (Robertson, 1993).

Peat moss adds additional organic matter to the soil. This increases the soil's nutrient-holding capacity and improves its fertility, providing plants with more of the essential nutrients needed for healthy leaf development, like nitrogen. The data suggest that both peat moss and cocopeat are effective at enhancing plant height compared to topsoil alone, with peat moss generally resulting in greater plant growth. The specific ratios of topsoil to peat moss or cocopeat also influence plant height, with certain mixtures leading to significantly better growth than others.

For the result of stem diameter sizes, as presented in Table 2, the same treatment, T6 significantly showed the highest size with 2.16 cm compared to the control (0.63 cm), followed by T2, T3, and T7, recorded mean stem diameters of 2.16 cm, 2.14 cm, 1.98 cm, and 1.97 cm, respectively, all marked with "b". This indicates that their stem diameters are significantly larger than T1 and comparable to each other within this group. The *P*-value of 0.007 indicates a statistically significant difference in stem diameter across the treatments. This means the treatments had a notable impact on stem diameter.

Meanwhile, the number of leaves and rhizome buds did not show any significant difference among all treatments, as the *P*-values were 0.781 and 0.443. This result suggests that the media treatments did not have a notable effect on the number of leaves and rhizome buds.

The data provided in Table 2 shows the mean crown diameter (in cm) for different treatments (T1 to T7), along with their standard deviations. T1 (Control) have the smallest mean crown diameter, which is 22.00 cm, marked with "a", indicating it is significantly smaller than some other treatments. This suggests that topsoil alone is less effective in promoting crown growth compared to mixtures with peat moss or cocopeat. T3 presented the largest crown diameter (62.50 cm), followed by T6 with 61.17 cm, which was marked with "b", meaning it is significantly larger than T1 and other "ab" groups (T2, T7, T5, and T4). Treatments T2, T4, T5, and T7 have intermediate values, showing some overlap in significance but generally larger crown diameters than T1. The *P*-value of 0.011 indicates a statistically significant difference in crown diameter between treatments, it suggests that the treatments had a notable impact on crown diameter, with T3 and T6 showing the most pronounced effects.

Differences in plant and rhizome growth were assumed to be caused by differences in planting media components and ratios (Pitaloka *et al*., 2023). Growth nutrients available to plants in growth media vary based on media type and conditions (Tan *et al*., 2020). With varying media components and ratios, there are changes in water-holding capacity, porosity, drainage, nutrient content, and chemical characteristics (Ismail-Embong *et al*., 2021). According to Pertuzé (2004), healthy plants with larger crowns, longer roots, and higher starch content have a better chance of becoming productive.

Absolute Growth Rate (AGR)

Table 3 shows the analysis of the Absolute Growth Rate (AGR). As noted in the table, all parameters analysed showed a significant effect at $P < 0.05$. For plant height, the highest AGR was black turmeric plants grown in T6 planting media (2.91 cm per week), followed by T3 (2.86 cm per week), T2 (2.77 cm per week), T5 (2.53 cm per week), and the lowest was T1 (1.04 cm per week). For stem diameter, the highest AGR was noted by T2 (0.08 cm per week), secondly T6 (0.079 cm per week), followed by T3 (0.075 cm per week) while the lowest was indicated by T1 (0.02 cm per week).

Table 2: Effects of different mixtures of planting media on the growth of black turmeric

Treatments	Plant Height	Stem Diameter	Number of Leaves	Number of Rhizome Buds	Crown Diameter
	Mean (cm)	Mean (cm)	Mean	Mean	Mean (cm)
T1	27.000 ± .0000a	0.63 ± .0000a	6.00 ± .0000a	1.00 ± .0000a	22.00 ± .0000a
T2	74.33 ± 2.1858b	2.14 ± .0717b	6.67 ± .3333a	2.00 ± 1.0000a	50.33 ± 6.9302ab
T3	75.67 ± 6.3333b	1.98 ± .0727b	6.67 ± .3333a	2.00 ± 1.0000a	62.50 ± 2.2913b
T4	54.67 ± 20.3333ab	1.41 ± .5465ab	5.33 ± .8819a	1.00 ± 0.000a	36.00 ± 12.0139ab
T5	66.00 ± 8.5049ab	1.65 ± .3357ab	6.67 ± .3333a	1.33 ± .3333a	42.50 ± 10.2510ab
T6	78.33 ± 3.8442b	2.16 ± .0260b	6.33 ± .3333a	1.33 ± .3333a	61.17 ± 2.3154b
T7	64.67 ± 2.0276ab	1.97 ± .1244b	5.67 ± .8819a	1.33 ± .3333a	45.17 ± 4.3429ab
P-value	0.015*	0.007*	0.443^{ns}	0.781^{ns}	0.011*

Mean values with the same letter in the same column for each attribute are not significantly different at $P \leq 0.05$, *: significant at $P \leq 0.05$, ns = not significant.

Table 3: Effects of different mixtures of planting media on the Absolute Growth Rate (AGR) of black turmeric

Treatments	Plant Height AGR	Stem Diameter AGR	Crown Diameter AGR
	Mean (cm)	Mean (cm)	Mean (cm)
T1	1.04 ± .0000a	0.024 ± .0000a	2.20 ± .0000a
T2	2.77 ± .2648b	0.08 ± .0056b	1.07 ± 0.3055ab
T3	2.86 ± .4922b	0.075 ± .0050b	2.08 ± .6351b
T4	2.09 ± 1.3404ab	0.025 ± .0333ab	1.58 ± .6212ab
T5	2.53 ± .5551ab	0.063 ± .0223ab	1.65 ± .6789ab
T6	2.91 ± .28493b	0.079 ± .0059b	2.78 ± 1.5987b
T7	2.41 ± .1848ab	0.068 ± .0075b	0.48 ± .6789ab
P-value	0.024*	0.008*	0.05*

Mean values with the same letter in the same column for each attribute are not significantly different at $P \leq 0.05$, *: significant at $P \leq 0.05$, ns = not significant.

For crown diameter, the mixture of topsoil + cocopeat ratio 3:2 (T6) noted the highest absolute growth rate of crown size, followed by T1 (2.2 cm per week), T3 (2.08 cm per week) while the lowest was indicated by T7 (0.48 cm per week).

Soil Analysis

Soil analysis is essential for improving the quality and/or quantity of rhizomes produced as well as the effectiveness of soil management. This is primarily motivated by the requirement to analyse and regulate soil fertility. For example, the capacity of soil to deliver an appropriate quantity of nutrients and trace elements is essential for plant sustenance. It is also necessary to monitor the transfer of fertilisers and other soil amendments from the agricultural areas, where they have been applied (Worsfold *et al*., 2008).

Table 4 provides an analysis of soil parameters before and after planting for six different treatments (T1 to T7). The parameters measured include pH, Water Holding Capacity (WHC), Nitrogen (N), Phosphorus (P), and Potassium (K), with both before and after values recorded. The table also indicates statistically significant differences between the treatments.

For soil pH, all the treatments (T2-T7) showed a pH value range of 5.2 to 6.13 before and after planting. Meanwhile, control (T1) has the lowest pH value with 4.58, which is more acidic. This characteristic might be one of the reasons black turmeric indicated unfavourable growth in T1 for almost all parameters studied in this research. Ravindra (2004) reported that rhizomatous plants grow well at pH 6.5. T2, T3, T5, T6, and T7 showed significantly higher pH values both before and after planting, with pH increasing after planting. For example: T2: pH increased from 6.03 to 6.37, T3: pH increased from 6.06 to 6.33, T5: pH increased from 6.13 to 6.69. T4 had an intermediate pH, increasing from 5.23 to 5.99. The *P*-value was 0.000, indicating a statistically significant difference in pH across treatments both before and after planting.

The pH of the soil affects a wide range of biological, chemical, and physical aspects, as well as plant development and biomass output (Minasny *et al*., 2016). The balance between acidity and alkalinity in soil is crucial for providing plant nutrients. When the soil becomes more acidic or alkaline, specific reactions occur that involve the release, supply, and exchange of positive (cationic) and negative (anionic) particles between plants and the soil (Khaidem & Meetei, 2018). These interactions

Table 4: Effects of different mixtures of planting media on soil analysis

Treatments	pH		WHC (%)		Nitrogen (%)		P (mg/kg)		K (mg/kg)	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
T1	4.58 ± 0.0145a	4.58 ± 0.0145a	66.67 ± 0.8819c	66.6667 ± 0.8819a	2.00 ± 0.5774a	2.00 ± 0.5774a	30.37 ± 0.0145a	30.37 ± 0.0145a	0.39 ± 0.0005a	0.39 ± 0.0005a
T2	6.03 ± 0.0333c	6.37 ± 0.0433cd	61.00 ± 0.5774bc	71.00 ± 1.0000bc	18.33 ± 0.3333c	31± 0.5774d	69.81 ± 0.0074d	243.41 ± 12.3735ab	1.16 ± 0.0003d	1.63 ± 0.2401ab
T3	6.06 ± 0.0333c	6.33 ± 0.0829cd	64.00 ± 0.5774b	72.67 ± 0.3333c	17.67 ± 0.3333c	22.33 ± 1.2019d	49.35 ± 0.0222b	160.28 ± 34.2864b	1.12 ± 0.0005c	0.96 ± 0.2782a
T4	5.23 ± 0.0371b	5.99 ± 0.0644a	55.00 ± 0.5774b	67.67 ± 0.8819ab	7.67 ± 1.4529b	10.67 ± 0.8819b	67.64 ± 0.0097c	170.53 ± 36.4346ab	0.8362 ± 0001b	1.02 ± 0.2694a
T5	6.13 ± 0.0145c	6.69 ± 0.0500d	59.33 ± 0.8819b	70.33 ± 0.3333abc	15.67 ± 1.2019c	24 ± 0.5774c	73.62 ± 0.0319e	392.71 ± 107.4258b	1.4651 ± 0.0008e	3.10 ± 0.7641b
T6	6.11 ± 0.0636c	6.65 ± 0.0252de	59.33 ± 0.8819b	69.67 ± 0.6667abc	16.00 ± 0.5774c	22.67 ± 1.2019c	138.35 ± 0.0500f	195.78 ± 35.0341ab	2.0316 ± 0.0002f	1.68 ± 0.3700ab
T7	6.13 ± 0.0819c	6.29 ± 0.0906c	61.00 ± 0.5774bc	69.00 ± 1.0000abc	9.00 ± 0.5774b	15.33 ± 2.1858b	155.06 ± 0.0318g	201.49 ± 12.9696ab	4.4034 ± 0.0002g	1.84 ± 0.0943ab
P-value	0.000*	0.000*	0.000*	0.002*	0.000*	0.000*	0.000*	0.005*	0.000*	0.004*

Mean values with the same letter in the same column for each attribute are not significantly different at $P \leq 0.05$, *: significant at $P \leq 0.05$, ns = not significant.

are essential for ensuring that plants can access the nutrients they require from the soil. Micronutrients, including calcium, magnesium, sulfur, phosphorus, potassium, and nitrogen are more readily available in soils with slightly higher pH, ranging from 6.5 to 8.0. This suggests that the acidity or alkalinity of the soil can influence the availability of different types of nutrients for plant uptake.

The Water Holding Capacity (WHC) of the growth medium is proportional to its particle size and pore size. The surface area of the smaller particles was greater than that of the larger particles. WHC among the growth media was significantly different ($P < 0.05$). T1 (Control) remains the same amount before and after planting, which is 66.67%, indicating no change. T2, T3, T5, T6, and T7 showed an increase in WHC after planting, with values rising to around 69% to 72% while T4 showed a slight increase in WHC from 55% to 67.67% after planting.

The *P*-value was 0.000 (before planting), 0.018 (after planting), indicating a significant change in WHC across treatments. According to Urra *et al*. (2019), organic amendment of topsoil is necessary to increase soil nutrients. A larger surface area allows the medium to retain more moisture. While appropriate WHC is needed for plant growth, an excessive amount might disturb the air-water balance in the soil, leading to poor aeration and reduced oxygen transfer to the roots (Mohammadi, 2015).

Sohi *et al*. (2009) demonstrated that soils with a high-water retention capacity provide higher agricultural yields while requiring less irrigation. This medium has strong porosity to enable excess water to drain away and minimise waterlogging, resulting in plants with roots that serve functions such as absorbing nutrients and water, providing anchorage, and storing food (Nair, 2019). Inadequate WHC, on the other hand, results in stunted growth, poor air-water connection, low aeration, and an influence on oxygen diffusion to the roots (Mohammadi, 2015). It is also true that soil texture affects water retention capacity (Nath, 2014).

Availability of N, P, and K in the Growth Medium

The macronutrient content of Nitrogen (N), Phosphorus (P), and Potassium (K) in control (T1) soil was the lowest compared to other treatments. Meanwhile, other treatments showed diverse concentrations of N, P, and K, based on the type of medium and ratio. T2 significantly had the highest N content before and after planting, followed by T5 with 24.00% after planting. For P content, T7 significantly had the highest value before planting and increased by 29.9% to reach 201.49 mg/kg. In contrast, T5 treatment experienced a remarkable increase of 433%, rising to 392.17 mg/kg after planting.

T7 treatment showed the highest K content with 4.4034 mg/kg; however, after planting, the content reduced by 58% to reach 1.84 mg/kg. This is contrary to the T5 treatment that showed the highest K content after planting, measuring 3.1 mg/kg, which represents an increase of 111.6%. Nitrogen (N) is the single most significant limiting nutrient for crop development; hence, adequate N availability is a critical aspect in improving agricultural productivity (Singh, 2009). It is regarded as crucial because it performs multiple critical functions in plants' metabolic and regulatory processes.

Nitrogen intake is thought to be associated with rhizome vegetative growth activity, according to Shibasaki *et al*. (2021). The presence of organic compounds in the growth media such as nitrogen resulted in an increase in height, number of leaves, and root biomass output. Previous studies have shown a positive and significant impact of N on *Zingiber officinale* Rosc (Singh *et al*., 2014). This demonstrated that nitrogen-supplemented plants exhibited a significant response in yield attributes such as the number of primary fingers per plant, the number of secondary fingers per plant, and rhizome yield per plant. T2 also generated the maximum plant height, number of leaves, and number of buds compared to the other media.

Phosphorus is a crucial component of photosynthesis and carbohydrate metabolism and acts as a regulator of photosynthate partitioning between the source and reproductive organs (Reshma & Sarath, 2017). According to Aldana (2005), increasing the phosphorus content in chilli plants increases plant height and stem diameter because P is involved in the process of photosynthate transmission to plant vegetative organs. According to Albuquerque *et al*. (2016), examining different phosphorus sources and dosages can lead to increased stem diameter and dry matter after 120 days.

Potassium is taken up by plant roots in the form of K^+ ions, which are required for plant root growth. When plants lack K, their photosynthetic rate decreases (Prajapati & Modi, 2012). In a comparative study on fibre and cocopeat from young and old coconut husks, Nordin and Ahamad (2022) found that cocopeat with a high K concentration outperformed other nutritional content. According to Asmaa and Magda (2010), increasing the dose of potassium treatment progressively and considerably boosted vegetative growth metrics such as plant height.

Overall, for soil analysis, pH values generally increased after planting for most treatments, indicating an improvement in soil acidity. WHC also increased for most treatments, suggesting improved soil structure or water retention. Nitrogen, Phosphorus, and Potassium levels increased significantly in most treatments, with the most notable improvements in T5 and T6, highlighting their effectiveness in nutrient enrichment.

The table demonstrates significant differences in soil parameters before and after planting across different media treatments. T5 and T6 stand out for their higher nutrient content (N, P, K) after planting while T1 (Control) shows the least improvement in soil quality. These results suggest that the planting media used in treatments T5 and T6 were more effective in enhancing soil fertility, which likely contributes to better plant growth.

Conclusions

Based on this study, it can be concluded that T6 consistently produced the largest plant height, stem diameter, and crown diameter, making it one of the most effective treatments. T3 also performed well, especially for crown diameter and plant height, with results similar to T6. T1 (Control) consistently showed the lowest values across all parameters, indicating that the other treatments significantly promoted better growth. The number of leaves and rhizome buds did not show significant differences between treatments, indicating that the treatments had less impact on these particular growth attributes. The data show that treatments had a significant impact on plant height, stem diameter, and crown diameter, with T6 and T3 being the most effective for promoting growth in black turmeric plants.

However, the number of leaves and rhizome buds remained relatively unaffected by the different media treatments. Generally, crown diameter, which reflects the expansion of the shoot system plays a crucial role in enhancing light interception and photosynthetic efficiency, thereby contributing to overall plant growth and biomass accumulation. However, the number of leaves and rhizome buds remained relatively unaffected by the different media treatments, suggesting that these parameters were less influenced by substrate composition.

Black turmeric thrives in a soil mix with more topsoil because it provides better nutrient availability, microbial activity, and overall soil fertility. While peat moss and cocopeat help with moisture retention, they lack the essential nutrients and structural benefits that topsoil offers. This preference for topsoil highlights the importance of maintaining a nutrient-rich and well-balanced growing medium for black turmeric cultivation.

We recommend that additional research be conducted on NPK uptake by plants and other micronutrients. Aside from that, research on planting and management methods such as medium, fertiliser, irrigation, pesticides, and others should be conducted in the field because there may be changes in growth rate and yield if planted in situ. Our findings demonstrate that growing black turmeric in polybags with the appropriate soil mix promotes plant growth, particularly in terms of height, stem thickness, and crown size. This implies polybag planting is ideal for early growth and controlled situations. However, planting in the field may be necessary for increased production since it allows the roots to develop freely and interact with natural soil conditions. We suggest more investigation into both strategies to determine which is ideal for large-scale farming.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

Abirami, S., Gnanamuthu, G., & Nagarajan, D. (2022). Bioconversion of shrimp shell waste into compost preparation and its plant growth study. *Indian Journal of Agricultural Research*, *56*(5), 588-593. https://doi.org/10.18805/IJARe.A-5214

Aldana, M. E. (2005). *Effect of phosphorus and potassium fertility on fruit quality* [LSU Master's Theses, Lousiana State University]. http://digitalcommons.lsu.edu/gradschool_theses

Asmaa, R. M., & Magda, M. H. (2010). Increasing productivity of potato plants by using potassium fertiliser and humic acid application. *International Journal of Academic Research*, *2*, 83-88.

Awang-Kanak, F., Abu Bakar, M. F., & Mohamed, M. (2018). Ethnobotanical survey on plants used as traditional salad food (ulam) in Kampung Taun Gusi, Kota Belud Sabah, Malaysia. *AIP Conference Proceedings 2002*, 020024. https://doi.org/10.1063/1.5050120

Behar N., Tiwari K., & Jadhav, S. (2013). Effect of explant type in development of *in-vitro* micropropagation protocol of an endangered medicinal plant: *Curcuma caesia* Roxb. *Biotechnology*, *13*(1), 22-27. https://doi.org/10.3923/biotech.2014.22.27

Bhupendra, S., Rameshroo, K., & Shashikant, C. (2016). Medicinal value of Curcuma cassia roxb: An overview. *Pharmaceutical and Biosciences Journal*, 69-74. https://doi.org/10.20510/ukjpb/4/i6/134671

Brady, N. C., & Weil, R. R. (2016). *The nature and properties of soils* (15th ed.). Pearson.

Chitra, R., Janaki, D., & Jansirani, P. (2022). Conservation strategy for endangered medicinal plant - black turmeric (*Curcuma caesia*). *Indian Forester*, *148*(1), 41. https://doi.org/10.36808/if/2022/v148i1/153548

Coombes, A., Martin, J., & Slater, D. (2019). Defining the allometry of stem and crown diameter of urban trees. *Urban Forestry & Urban Greening*, *44*, 126421. https://doi.org/10.1016/j.ufug.2019.126421

De Albuquerque, A. W., De a Sá, L., Rodrigues, W. A. R., Moura, A. B., & Filho, M. D. S. O. (2016). Growth and yield of sugarcane as a function of phosphorus doses and forms of application. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *20*(1), 29-35. https://doi.org/10.1590/1807-1929/agriambi.v20n1p29-35

Dey, A., Dwivedi, B. S., Bhattacharyya, R., Datta, S. P., Meena, M. C., Jat, R. K., Gupta, R. K., Jat, M. L. Singh, V. K., & Das, D. (2020). Effect of conservation agriculture on soil organic and inorganic carbon sequestration and lability: A study from a rice–wheat cropping system on a calcareous soil of the eastern Indo-Gangetic Plains. *Soil Use Management*, *36*, 429-438.

Donipati, P., & Sreeramulu, S. H. (2015). Preliminary phytochemical screening of *Curcuma Caesia*. *International Journal of Current Microbiology and Applied Sciences*, *4*(11), 30-34. https://www.ijcmas.com/vol-4-11/Prasanthi%20Donipati%20and%20S.%20Hara%20Sreeramulu.pdf

Gentili, R., Ambrosini, R., Montagnani, C., Caronni, S., & Citterio, S. (2018). Effect of soil pH on the growth, reproductive investment and pollen allergenicity of *Ambrosia artemisiifolia* L. *Frontiers in Plant Science*, *9*, 1335. https://doi.org/10.3389/fpls.2018.01335

Global Forest Watch. (2020). *Malaysia Deforestation Rates & Statistics*. https://www.globalforestwatch.org/dashboards/country/MYS/

Gruda, N. (2019). Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*, *9*(6), 298. https://doi.org/10.3390/agronomy9060298

Hidayat, C., Frasetya, B., & Syamsudin, I. N. (2018). Adjustment of phosphorus concentration to increase growth and yield of cherry tomato using hydroponic drip system pengaturan konsentrasi fosfor untuk meningkatkan pertumbuhan dan hasil tanaman tomat cherry pada sistem hidroponik irigasi tetes. *Jurnal Agro*, *5*(2), 140-147. https://doi.org/10.15575/3658

Hossain, A. M., Ishimine, Y., Akamine, H., & Motomura, K. (2005). Effects of seed rhizome size on growth and yield of turmeric (*Curcuma longa* L.). *Plant Production Science*, *8*(1), 86-94. https://doi.org/10.1626/pps.8.86

Imas, P. (1999). Quality aspects of K nutrition in horticultural crops. Workshop on recent trends in Nutrition Management in Horticulture Crops., 11-12 February, Dapoli, Maharashtara, India.

Ismail-Embong, N., Manan, N. A., Md Salleh, N. A., & Pa'Ee, F. (2021). The effect of different growing media on growth performance of *Clinacanthus nutans*. *IOP Conference Series: Earth Environment Science*, *736*(1), 012026. https://doi.org/10.1088/1755-1315/736/1/012026

Jackson, K., Thounaojam, T., & Thomas, M. T. (2018). Influence of soil pH on nutrient availability: A review. *International Journal of Emerging Technologies and Innovative Research*, *5*(12), 707-713. http://www.jetir.org/papers/JETIRDZ06090.pdf

Jafarnia, S., Hatamzadeh, A., & Tehranifar, A. (2010). Effect of different substrates and varieties on yield and quality of strawberry in soilless culture. *Advances in Environmental Biology*, 325-329.

Jones, C., & Olson-Rutz, K. (2016). *Soil nutrient management for canola*. EB0224. Montana State University Extension, Bozeman, MT.

Karmakar, I., Dolai, N., & Haldar, P. K. (2014). Anxiolytic and CNS depressant activities of methanol extract of *Curcuma caesia* rhizome preclinical evaluation and molecular mechanism of phyto molecules against type-2 diabetic rats. View project. https://www.researchgate.net/publication/215638726

Kim, L. Y. (2003). Characteristics of cocopeat and peatmoss. *Soil Fertilizer*, *13*, 14-21.

Kim, H. S., & Kim, K. H. (2011). Physical properties of the horticultural substrate according to mixing ratio of peatmoss, perlite and vermiculite. *Korean Journal of Soil Science Fertilizer*, *44*, 321-330. http://doi.org/10.7745/KJSSF.2011.44.3.321

Kim, Y. S., Park, I. S., Park, E., Cho, B. K., Lee, C. W., & Choi, J. M. (2021). Changes in the chemical properties of coir dust with increasing aging time and development of a method for determining moderate aging degree. *Horticulture Environment and Biotechnology*, *62*, 547-557. http://doi.org/10.1007/s13580-021-00339-w

Lalitha, C. R., Raveendran, K., & Salim, N. (1995). Effect of *Curcuma caesia* leaves on rice seed germination and seedling establishment. *Ancient Science of Life*, *15*(2), 115-118. https://www.semanticscholar. org/reader/9b3c3673b3b954d8a7edc4536f19f6b4

Lee, K. L., Ong, K. H., King, P. J. H., Chubo, J. K., & Su, D. S. A. (2014). Stand productivity, carbon content, and soil nutrients in different stand ages of *Acacia mangium* in Sarawak, Malaysia. *Turkish Journal of Agriculture and Forestry*, *39*(1), 154-161. https://doi.org/10.3906/tar-1404-20.

Liu, Y., Roy, S. S., Nebie, R. H. C., Zhang, Y., & Nair, M. G. (2013). Functional food quality of *Curcuma caesia*, *Curcuma zedoaria* and *Curcuma aeruginosa* endemic to Northeastern India. *Plant Foods for Human Nutrition*, *68*(1), 72-77. https://doi.org/10.1007/s11130-013-0333-5\

Minasny, B., Hong, S. Y., Hartemink, A. E., Kim, Y. H., & Kang, S. S. (2016). Soil pH increase under paddy in South Korea between 2000 and 2012. *Agriculture, Ecosystems & Environment*, *221*, 205-213. http://dx.doi.org/10.1016/j.agee.2016.01.042

Mohammadi-Ghehsareh, A. (2015). Effect of plant growth on some physical properties of potting culture media. *International Journal of Recycling of Organic Waste in Agriculture*, *4*(3), 205-209. https://doi.org/10.1007/s40093- 015-0100-8.

Mukunthan, K. S., Satyan, R. S., & Patel, T. N. (2017). Pharmacological evaluation of phytochemicals from south Indian black turmeric (*Curcuma caesia* Roxb.) to target cancer apoptosis. *Journal of Ethnopharmacology*, *209*, 82-90. https://doi.org/10.1016/j.jep.2017.07.021

Naderi, D., & Golparvar, A. R. (2018). The effects of tuff combination with conventional organic media on some vegetative and flowering characteristics of potted alstroemeria. *Journal of Horticulture Science*, *32*(2). http://dx.doi.org/10.22067/jhorts4.v32i2.66183

Nair, K. P. (2013). The botany of turmeric. In *The agronomy and economy of turmeric and ginger* (pp. 7-32). Elsevier. https://doi.org/10.1016/B978-0-12-394801-4.00002-8

Nair, K. P. (2019). The botany of turmeric in turmeric (*Curcuma longa* L.) and ginger (*Zingiber officinale* Rosc.). In *World's invaluable medicinal spices* (pp. 7-35). Cham: Springer.

Narendhiran, V., Madhavan, S., Anuja, S., & Thiruppathi, M. (2023). Evaluation of black turmeric (Curcuma Caesia) genotypes for growth, yield and quality. *Rivista Italiana di Filosofia Analitica Junior*, *14*(2).

Nasir, N. M., Shahari, R., & Tajudin, N. S. M. (2020). The effect of different growing medium combination on growth and yield of *Boesenbergia rotunda*. *Malaysian Journal of Halal Research Journal*, *3*(2), 41-42.

Nath, T. N. (2014). Soil texture and total organic matter content and its influences on soil water holding capacity of some selected tea growing soils in sivasagar district of assam, India. *International Journal of Chemical Sciences*, *12*(4), 1419-1429. https://www.tsijournals.com/articles/soil-texture-and-total-organic-matter-content-and-its-influences-on-soil-water-holding-capacity-of-some-selected-tea-gro.pdf

Nordin, M. N., & Ahamad, W. M. A. W. (2021). Comparison study on fiber and cocopeat from young coconut husks and old coconut husks. *Advances in Agricultural and Food Research Journal*, *2*(2). https://doi.org/10.36877/aafrj.a0000216

Ogle, S. M., Alsaker, C., Baldock, J, Bernoux, M., Breidt, F. J., McConkey, B., Regina, K.,

& Vazquez-Amabile, G. G. (2019). Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports*, *9*, 1-8.

Oke, E. O., Okolo, B. I., Nwosu-Obieogu, K., Osoh, K. O., & Udeh, C. J. (2020). Optimising proximate composition of dried turmeric rhizome in a tray dryer using response surface technique. *Annals of the Faculty of Engineering Hunedoara-International Journal of Engineering*, (3). https://annals.fih.upt.ro/pdf-full/2020/ANNALS-2020-3-14.pdf

Patrick, D. J. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulture*, *196*, 3-14.

Pertuzé, R., Barrueto, M., Díaz, V., & Gamardella, M. (2004). Evaluation of strawberry nursery management techniques to improve quality of plants. In *V International Strawberry Symposium 708* (pp. 245-248).

Pitaloka, N. D., Zahra, A. M., Nugroho, E., Simatupang, H. K., Sinaga, A. N. K., Annisa, H. N., & Rahmawati, L. (2023). The effect of light-emitting diode, planting medium, and nutrient concentration on the plant growth and chlorophyll content of lemon basil. *Advances in Biological Sciences Research*, 667-677. https://doi.org/10.2991/978-94-6463-122-7_63

Prajapati, K., & Modi, H. A. (2012). The importance of potassium in plant growth–A review. *Indian Journal of Plant Sciences*, *1*(02-03), 177-186. https://www.ijera.com/papers/Vol8_issue3/Part-5/0803054452.pdf

Ravindra, S. (2004). *Agro techniques of medicinal plant*s. Daya Publishing House. (8170353467, 9788170353461/page 72-76).

Raviv, M., Lieth, J. H., & Bar-Tal, A. (2019). *Soilless culture: Theory and practice*. Elsevier.

Reshma, T., & Sarath, P. S. (2017). Standardisation of growing media for the hydroponic cultivation of tomato. *International Journal of Current Microbiology and Applied Sciences*, *6*(7), 626-631. http://dx.doi.org/10.20546/ijcmas.2016.501.076

Robertson, R. A. (1993). Peat, horticulture and environment. *Biodiversity and Conservation*, *2*, 541-547.

Shelake, P. S., Yadav, S., Jadhav, M. L., & Dabhi, M. N. (2018). Effect of moisture content on physical and mechanical properties of turmeric (Curcuma longa) Rhizome. *Current Journal of Applied Science and Technology*, *30*, 1-7. http://doi.org/10.9734/CJAST/2018/44672

Shibasaki, K., Takebayashi. A., Makita, N., Kojima, M., Takebayashi, Y., Kawai, M., Hachiya, T., & Sakakibara, H. (2021). Nitrogen nutrition promotes rhizome bud outgrowth via regulation of cytokinin biosynthesis genes and an *Oryza longistaminata* ortholog of *FINE CULM 1*. *Frontiers in Plant Science*. http://doi.org/10.3389/fpls.2021.670101

Singh, M. (2009). *Influence of triacontanol, nitrogen and phosphorus on the growth, yield and quality of ginger* (*Zingiber officinale* Rosc.) *and turmeric* (*Curcuma longa* L.). [Ph.D. Thesis, Aligarh Muslim University, Aligarh, India].

Singh, M., Khan, M. M. A., & Naeem, M. (2014). Effect of nitrogen on growth, nutrient assimilation, essential oil content, yield and quality attributes in Zingiber Officinale Rosc, *Journal of The Saudi Society of Agricultural Sciences*. http://dx.doi.org/10.1016/j.jssas.2014.11.002

Soeparjono, S. (2016). The effect of media composition and organic fertiliser concentration on the growth and yield of red ginger rhizome (*Zingiber officinale* Rosc.). *International Conference on Food, Agriculture and Natural Resources, IC-FANRes 2015*. *Agriculture and Agricultural Science Procedia*, *9*, 450-455.

Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). Biochar, climate change and soil: A review to guide future research. *CSIRO Land and Water Science Report*, *5*(09), 17-31.

Urra, J., Alkorta, I., & Garbisu, C. (2019). Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. *Agronomy*, *9*(9), 542. https://doi.org/10.3390/agronomy9090542

Venugopal, A., Rinu, K. A., & Joseph, D. (2017). Medicinal properties of black turmeric: A review. *Innoriginal International Journal of Sciences*, *4*(3),1-4.

Weiner, J., & Fishman, L. (1994). Competition and allometry in Kochia scoparia. *Annals of Botany*, *73*(3), 263-271. https://www.jstor.org/stable/42764532

Williams, A., Jordan, N. R., Smith, R. G., Hunter, M. C., Kammerer, M., Kane, D. A., Koide, R. T., & Davis, A. S. (2018). A regionally adapted implementation of conservation agriculture delivers rapid improvements to soil properties associated with crop yield stability. *Scientific Reports*, *8*, 1-8.

Worsfold, P. J., McKelvie, I. D., & Hanrahan, G. (2008). Environmental applications: Waters, sediments and soils. In *Comprehensive analytical chemistry* (Vol. 54, pp. 685-760). Elsevier.