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ORIGINAL ARTICLE

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Optimizing Soilless Growing Media for Red Amaranthus (*Amaranthus tricolor*) Production

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ABSTRACT

A pot culture experiment was conducted to evaluate seven media formulations using coirpith (CP), vermicompost (VC), and sand (S) in varying ratios to identify optimal combinations for growth, yield, and nutrient use efficiency of Red Amaranthus (*Amaranthus tricolor*), a widely consumed leafy vegetable in India. Media analysis revealed that sand inclusion reduced salinity, while vermicompost enriched nutrient availability. The treatment coirpith and vermicompost taken in equal proportion recorded the highest mean plant height (25.8 cm), maximum leaf area (63.79 cm²), and stem girth (2.8 cm). It also outperformed other treatments, producing the highest biomass (61.52 g fresh weight pot^{-1}; 17.42 g dry weight pot^{-1}) along with superior uptake of N (0.190 g pot^{-1}), P (0.085 g pot^{-1}), and K (0.160 g pot^{-1}) followed by the treatment CP:VC (2:1). The fresh weight recorded by CP:VC (1:1) was 203 percent higher than the coirpith alone. The highest apparent nutrient recovery percentage (5.411 for N, 10.587 for P and 30.700 for K) and response ratio (3.046 for N, 13.374 for P and 20.507 for K) was also registered by CP:VC (1:1). In contrast, coirpith alone restricted root growth (9.6 cm), lowest apparent nutrient recovery (3.074 for N, 6.565 for P and 20.067 for K) and response ratio (1.006 for N, 4.417 for P and 6.773 for K). The results validate CP:VC (1:1) as an effective substrate for enhancing growth and nutrient dynamics in urban cultivation of Red Amaranthus.

1 | INTRODUCTION

Vegetables are an essential element of the daily diet, especially in India. Out of common leafy vegetables, amaranthus is the most popular vegetable consumed by people all over India (Akbugro *et al*., 2007; Swamy, 2023). Red amaranth is a purple-red color leafy vegetable and is well known as an excellent food crop owing to its ability to grow under a wide range of climatic conditions, such as drought, heat, pests, and diseases. It grows in short duration, quick response to manures and fertilizers, high yielding, easy to cultivate, and has wide adaptability to diverse agroclimatic situations, making it a favourite crop to farmers (Srivastava, 2017). The leaves of red amaranth are a reasonable source of proteins, dietary fibers, fat, carbohydrates, minerals such as iron, calcium, phosphorus, magnesium, potassium, and zinc (Kachiguma *et al*., 2015; Sarker & Oba, 2019). Other nutrients like vitamins C, beta carotene, betalains, betaxanthins, and betacyanins are also present in the leaves of red amaranth (Sarker & Oba, 2019), making it a vital component of daily diets.

In urban contexts, Red Amaranthus has emerged as a preferred crop for terrace and container gardening due to its compact growth habit and responsiveness to organic inputs (Jacob *et al*., 2012). With increasing interest in urban farming and vertical gardening systems, there is a growing need to develop efficient, space-saving cultivation protocols that ensure consistent yield and nutrient quality. Soilless cultivation with organic substrates presents a promising approach for urban vegetable farming, especially in areas where land and soil quality are limiting factors. Vertical farming, which involves multitier cropping systems, can maximize the yield per square meter of land, addressing the increasing popularity for fresh food without overburdening agricultural land (Beecham *et al*., 2019).

Identifying an optimal combination of organic materials to formulate effective growing media is critical for ensuring adequate root anchorage and a sustained supply of water and nutrients, especially under urban cultivation systems. Soilless substrates such as coco coir, vermiculite, and organic manures like farmyard manure (FYM) and poultry manure have been widely adopted for microgreen production (Pradeepa *et al*., 2023). Among these, coirpith has shown promising results both as a standalone medium and in blends with other organic or inorganic components

(Poulter, 2014; Hongpakdee & Ruamrungsri, 2015; Xiong *et al*., 2017; Stewart-Wade, 2020; Mariotti *et al*., 2020). Vermicompost, when applied in moderate quantities, enhances substrate quality by improving its physical structure and chemical fertility, thereby promoting plant growth (Bachman & Metzger, 2007; Grigatti *et al*., 2007).

Despite the increasing use of organic substrates in urban horticulture, there remains a critical lack of standardized recommendations for optimal growing media composition and nutrient management explicitly tailored to Red Amaranthus cultivation under urban conditions. This pot culture experiment was therefore undertaken to identify the most effective media combination for enhancing growth, biomass yield, and nutrient use efficiency in Red Amaranthus. By integrating media analysis, plant performance metrics, and nutrient recovery indices, the study aims to establish a practical and replicable substrate recommendation for urban and semi-urban vegetable growers, contributing to sustainable intensification of leafy vegetable production in constrained spaces.

2 | MATERIALS AND METHODS

2.1 | Study Area Description

The location of the experimental site is the Central Farm Machinery Centre, Vanavarayar Institute of Agriculture, Pollachi, Tamil Nadu, India (10.6560° N, 77.0221° E, 293 m from the mean sea level), which falls under Western agroclimatic zone of Tamil Nadu, India, having a tropical climate with annual average rainfall of 715 mm. The monthly weather data corresponding to the entire course of the study period, viz., maximum temperature, minimum temperature, relative humidity at 08.30 IST, and monthly rainfall, were collected (*Fig.* 1).

2.2 | Crop Management

2.2.1 | Seeds and Sowing

The seeds of the Red Amaranthus variety CO-6 obtained from the Department of Vegetable Science, Horticulture College and Research Institute, Tamil Nadu Agricultural University (TNAU), Tamil Nadu were used in this study. The study was conducted using plastic pots of 4 kg capacity having a dimension of 25 cm diameter × 20 cm height. Fifteen seeds were broadcast in each pot. After two weeks of germination, five seeds were maintained after establishment, and moist conditions were maintained in the growing media supporting the crop throughout the crop period.

2.2.2 | Treatment structure and Experimental design

The treatment structure comprised different media combinations, which were replicated three times in a completely randomized block design. According to the randomization of treatments, two kg of growing media were filled into each container. The treatment details are as follows T_1 - CP+VC (1:1); T_2 - CP+VC+S (1:1:1); T_3 - CP+VC (2:1); T_4- CP+VC+S (2:1:1); T_5- CP+VC (1:2); T_6 - CP+VC+S (1:2:1) and T_7 - CP alone in which CP refers to Coirpith, VC refers to Vermicompost and S refers to sand (< 2mm). All the substrates were mixed on an equal weight basis.

HIGHLIGHTS

- A growing medium consisting of a 1:1 ratio of coirpith (CP) and vermicompost (VP) is the most effective substrate for Red Amaranthus in soilless culture.
- The CP:VC (1:1) combination produced a 203 % higher fresh weight compared to using coirpith alone.
- Inclusion of sand helps to reduce salinity, while the use of a coirpith-only medium results in a high root-to-shoot ratio, indicating that the plant is under stress.

2.2.3 | Substrate sampling schedule

Sampling was performed destructively at defined crop growth stages to monitor changes in media properties and plant performance. Specifically, pH and electrical conductivity (EC) of the growing media were recorded at four intervals: 0 DAS (before sowing), 10 DAS, 20 DAS, and 30 DAS. These stages were selected to capture the dynamic shifts in substrate chemistry during early establishment and vegetative growth of Red Amaranthus.

2.2.4 | Fertilization for Red Amaranthus in a soilless system

The composition of the fertilizer mixture was worked out according to the recommended fertilizer dose for the fertigation of the Amaranthus crop. The recommended fertigation dose for Amaranthus is 60:30:20 kg N, P_2O_5, and K_2O ha^{-1} (Indurthi et al., 2024). For soilless media, there is no P and K fixation expected due to soil particle adsorption and surface reaction (Elakiya, 2021). Hence, only 50% of P and K doses were adopted, resulting in a modified dose of 60:15:10 kg ha^{-1}. The per-pot requirement was derived by dividing the total requirement by the plant population of 5,00,000 (20 cm × 10 cm spacing), which gives 0.8 g of N, 0.2 g of P_2O_5 and 0.1 g of K_2O. This was adopted in soilless crop experiments, for 42 pots by converting g to kg N, P_2O_5, and K_2O.

The fertilizer requirement for different crop stages was scheduled (Table 1). Accordingly, the calculated quantity of water-soluble fertilizers, viz., Urea, Di Ammonium Phosphate (DAP), and Muriate of Potash (MOP), was worked out, and split doses were given in two split doses, one as basal and the other during 20 DAS. Surface application of a specific fertilizer dose at a specific crop stage was done by mixing the mixture in 4.2 litres of water, and 100 ml was supplied per container. A micronutrient mixture spray was given @ 0.5% percent on 20 DAS.

2.2.5 | Cultural operations and observation

All plant protection measures were carried out periodically to control pests and diseases during crop growth as per recommendations. To prevent microbial contamination, Metarhizium anisopliae was incorporated at 3 g per pot to suppress soil-borne pests and to prevent the coconut grub attack. Neem-based products were initially sprayed in the vegetative stages to control the sucking pests. 0.3 ml Chroanthril (Chlorantraniliprole 18.5% SC) per liter of water was sprayed to control Helicoverpa armigera and ensure to cover the entire foliage.

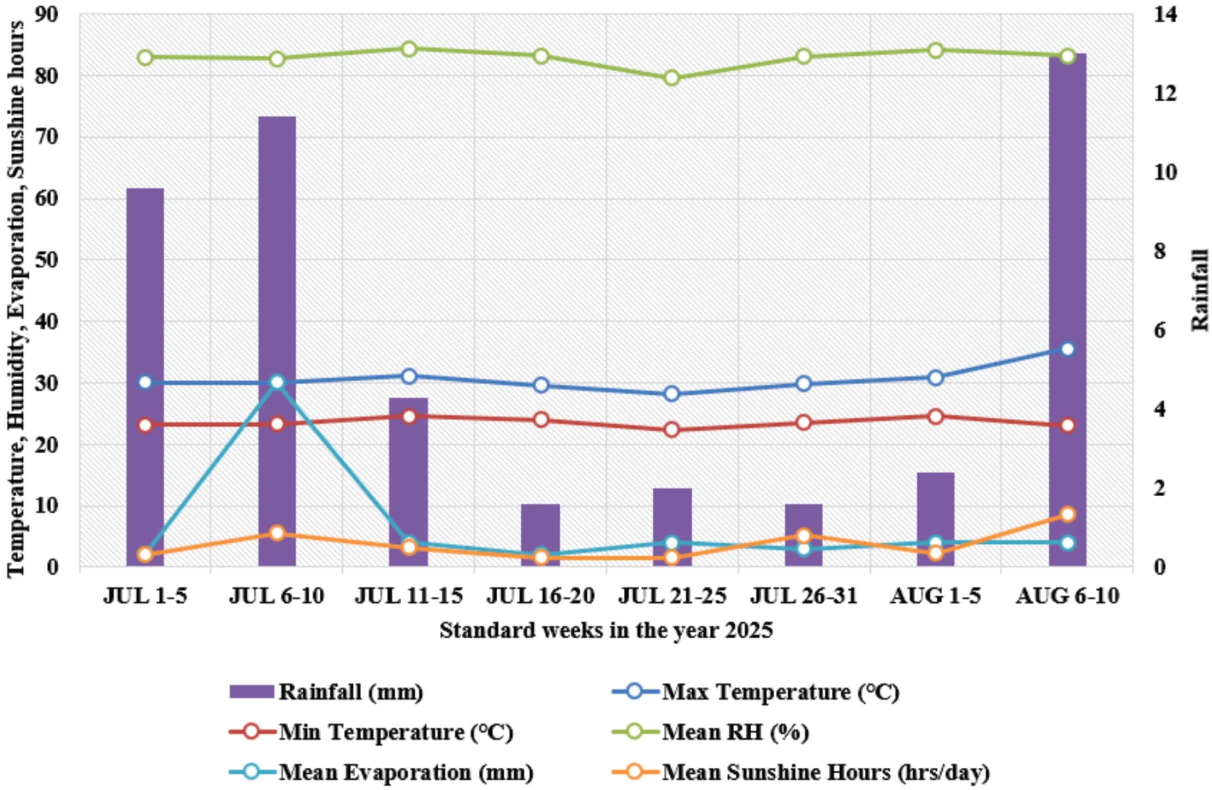

FIGURE 1 Weather prevailed during the cropping period (July – August 2025) (VIA, Pollachi)

Source: The weather data were collected from the meteorological observatory of Vanavarayar Institute of Agriculture, Pollachi

TABLE 1 Fertilizer dose applied for Red Amaranthus in soilless experiment

1. Recommended dose of fertilizers			
Nutrients →	N	P_2O_5	K_2O
Recommended Fertilizer for Fertigation - for 5,00,000 plants/ hectare	60 kg	30 kg	20 kg
Recommended Fertilizer for each pot (5 plants/pot)	0.60 g	0.30 g	0.20 g
Recommended Fertilizer for 42 pots	25.2	12.6	8.4
2. Fertilizer sources and day of applications			
Fertilizer application day (Days after sowing -DAS	Fertilizer used g for 42 pots		
	Urea	DAP	MOP
Basal dose	27.5	14	7
20 DAS	27.5	0	0
Total	55	14	7

DAP - Diammonium phosphate (18-46-0), MOP - Muriate of potash (0-0-60), No. of pots used in pot experiment – 42, *Method of application of fertilizers:* Surface application on growing media in each pot (calculated quantity of fertilisers were mixed in 4.2 litres of water and applied at the rate of 100 ml per pot)

2.3 | Calculation of Nutrient Uptake & Nutrient Use Efficiencies

Total nitrogen (N), phosphorus (P), and potassium (K) contents in oven-dried plant samples were determined using standard procedures (Piper, 1966; Jackson, 1973). These values were used to compute nutrient uptake and fertilizer use efficiencies.

Nutrient uptake: Nutrient uptake was calculated by multiplying the nutrient concentration (%) by the dry matter yield and expressed as grams per pot.

$$\text{Nutrient uptake} = \frac{\text{Nutrient content } (\%) \times \text{Total dry matter yield } (\text{g pot}^{-1})}{100} \quad (1)$$

Response ratio: It is the increase in yield per unit quantity of nutrient applied, which is calculated by using the formula

$$\text{Response ratio} = \frac{(\text{Yield in fertilized pot} - \text{Yield in unfertilized pot})}{\text{Quantity of applied nutrient}} \quad (2)$$

Physiological efficiency: It is the increase in yield per unit quantity of nutrient utilized by plant (total uptake), which is calculated by using the formula.

$$\text{Physiological efficiency} = \frac{(\text{Yield in fertilized pot} - \text{Yield in unfertilized pot})}{\text{Quantity of absorbed nutrient}} \quad (3)$$

Apparent nutrient recovery: Recovery of added fertilizer nutrient is calculated separately for N, P, and K. Apparent nutrient recovery (ANR) is an obvious measure of fertilizer use efficiency and expressed in percentage (Mengel *et al*., 2006; Jalpa *et al*., 2020).

$$\text{ANR } (\%) = \frac{(\text{Nutrient uptake in fertilized pot} - \text{Nutrient uptake in unfertilized pot})}{\text{Quantity of applied nutrient}} \times 100 \quad (4)$$

2.4 | Statistical Analysis

The data on growth and yield parameters of Red Amaranthus, along with nutrient uptake and efficiency, were analyzed statistically using analysis of variance (ANOVA) and continued with Duncan's Multiple Range Test (DMRT) if the results showed significant differences.

3 | RESULTS AND DISCUSSION

3.1 | Initial characteristics of particulate organic substrates/inorganic materials

Raw coirpith exhibited (Table 2) the lowest bulk density (0.118 Mg m^{-3}) while vermicompost (0.592 Mg m^{-3}) recorded the highest bulk density. The pH of the coirpith (6.49) was slightly acidic, while that of vermicompost was near neutral (7.46). The EC of raw coirpith recorded the highest 4.53 dS m^{-1}, and for vermicompost, the EC recorded was 1.86 dS m^{-1}, respectively. Similar to EC, TDS was highest for raw coirpith (2296 mg L^{-1}) and low with 886 mg L^{-1} for vermicompost. While comparing the substrates, the highest carbon (33.84 %) and widest C/N ratio (52.9) was found in coirpith. A moderate organic C of 16.62 per cent and a moderate C/N ratio (25.1) were recorded for vermicompost.

With respect to total nutrient content, the highest N was noticed for vermicompost (11.265 g kg^{-1}), whereas coirpith recorded a total N of 2.821 g kg^{-1}. In case of total P, high content was found in vermicompost (5.065 g kg^{-1}) and lowest was found in coirpith (0.193 g kg^{-1}). High total K was recorded in coirpith (2.324 g kg^{-1}) followed by vermicompost (1.162 g kg^{-1}).

3.2 | Physico-chemical properties of growing media in crop stages

Electrical conductivity decreased with crop growth stages from 2.41 to 1.07 dS m^{-1} (*Fig.* 2). The observed reduction in electrical conductivity (EC) in treatments containing sand might be due to dilution in the quantity of organic materials, which are the sources of salts. This dilution effect lowered the overall salt concentration in the growing medium, thereby mitigating salinity stress and improving plant performance. These results are in line with the findings of Elakiya (2021). When comparing the treatment mean values, the treatment containing coirpith alone registered slightly acidic pH throughout the crop growth stages (*Fig.* 3). The mean pH was found to rise from slightly acidic (6.42) to a near neutral state (7.34) with advancement in crop growth stages. Treatments incorporating sand demonstrated a reduction in salinity, underscoring its functional role in substrate optimization.

3.3 | Effect of media combination on Growth Parameters of Red Amaranthus

Significant differences were observed in the growth attributes of Red Amaranthus due to the effect of combinations of growing media. The plant height, number of leaves per plant, leaf length, leaf breadth, and leaf area were recorded (Table 3) for growth parameters.

3.3.1 | Effect of media combination on plant height and leaf count

Plants grown in the media consisting of coirpith: vermicompost (1:1) attained the highest mean plant height (25.8 cm) followed closely by coirpith: vermicompost (2:1) (22.5 cm). These treatments consistently outperformed others, highlighting the synergistic effect of vermicompost with lightweight porous media. The lowest plant height was observed in coirpith (11.5 cm). Media enriched with vermicompost consistently outperformed coirpith alone, reaffirming the role of vermicompost as a nutrient-dense amendment rich in microbial activity. Similar results were obtained while optimizing soilless media for Red Amaranthus where cocopeat-vermicompost showed significantly higher growth and yield than cocopeat alone. Vermicompost enhanced nutrient availability and root development (Shetty *et al*., 2024).

Apart from providing mineral nutrients, vermicompost contributes to the biological fertility of growing media by adding beneficial microbes. Vermicompost contains residues of mucus excreted through the digestive canal of earthworms that would stimulate antagonism and competition between diverse microbial populations, resulting in the production of favourable antibiotics and hormones boosting plant growth. Mucus accelerating and enhancing decomposition of organic matter composing stabilized humic substances, which release plant available nutrients at high levels (Atiyeh *et al*., 2000) and embody water-soluble phytohormonal elements

(Edwards *et al*., 2004) have been reported.

Coirpith is highly resistant to biological degradation, hence it could render physical support stablyto the plant roots for several months. On average, coirpith is composed of 75–80 % coir dust and 20–25 % short fibre (Stewart-Wade, 2020). Coirpith dust is highly hydrophilic, having increased wettability, structural stability, total porosity and air content, total water-holding capacity, and reduced bulk density (Shara *et al*., 2017).

As an inert physical particle, sand may have aided in increasing the porosity of the media. The particle sizes of sand expressed significantly different results in porosity. However, sand addition in growing media decreased the proportion of other organic constituents in growing media (Elakiya, 2021). This would have reduced the contribution of nutrients to the plant growth, and hence the yield would have declined in the treatments where the sand was a part of the growing media.

TABLE 2 Physical properties, chemical composition and nutrient content of substrates used for media preparation

Physical properties and chemical composition				
S.No	Parameter	Unit	Coirpith	Vermi compost
1	Bulk density	Mg m^{-3}	0.118	0.592
2	Carbon	%	33.84	16.62
3	TDS (1:5 dilution)	mg L^{-1}	2296	886
4	pH (1:5 dilution)	pH	6.49	7.46
5	EC (1:5 dilution)	dS m^{-1}	4.53	1.86
6	C/N Ratio		52.9	25.1
Nutrient Composition				
S.No	Nutrients	Unit	Coirpith	Vermi compost
7	Total N	g kg^{-1}	2.821	11.265
8	Total P	g kg^{-1}	0.193	5.065
9	Total K	g kg^{-1}	2.324	1.162

TABLE 3 Effect of media composition on vegetative parameters of Red Amaranthus at harvest stage

Treatment	Plant height (cm)	Number of leaves $plant^{-1}$	Leaf length (cm)	Leaf breadth(cm)	Leaf area (cm^2)	Stem grith (cm)
CP+VC (1:1)	25.8 a	10 a	10.5 a	8.1 a	63.79 a	2.8 a
CP+VC+S (1:1:1)	21.7 b	7 c	6.7 c	6.2 c	31.16 d	1.2 e
CP+VC (2:1)	22.5 b	8 b	7.8 b	7.4 b	43.29 b	2.2 b
CP+VC+S (2:1:1)	22.1 b	8 b	7.1 c	7.4 b	39.41 c	1.9 c
CP+VC (1:2)	21.3 b	7 c	6.8 c	6.5 c	33.15 d	1.4 d
CP+VC+S (1:2:1)	20.2 c	6 d	6.5 c	6.2 c	30.23 d	1.1 e
CP alone	11.5 d	6 d	4.2 d	2.2 d	6.93 e	0.8 f
Sed±	0.730	0.401	0.330	0.163	1.566	0.026
CD (P=0.05)	1.566*	0.859*	0.708*	0.349*	3.358*	0.057*

**CP - Coirpith, VC – Vermicompost, S - Sand <2 mm.*
Note: In 'Treatments' column, the values in parenthesis indicate ratio of substrates
**Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)*

3.3.2 | Effect of media combination on leaf length, width and area

Leaf width, leaf length, and leaf area are direct indications of plant growth. While comparing the performance of different growing media, leaf length, leaf breadth, and leaf area of Red Amaranthus exhibited significant differences. The leaf length ranged from 4.2 to 10.5 cm, leaf breadth ranged from 2.2 to 8.1 cm, and leaf area ranged from 6.93 to 63.79 cm^2. Treatment with equal proportions of coirpith and vermicompost, especially when paired together in a 1:1 ratio, showed increased leaf counts per plant (10). The lowest number of leaves per plant in CP alone (6) highlights the inadequacy of coirpith as a stand-alone medium.

Maximum leaf area (63.79 cm^2) was recorded in CP+VC (1:1), followed by CP+VC (2:1) (43.29 cm^2), which were significantly different from each other. The synergistic effect of organic matter in vermicompost and the porosity of coirpith would have likely enhanced photosynthetic surface development. Reduced leaf area in CP+VC (2:1) and CP+VC+S (2:1:1) showed that excessive coirpith might have hindered leaf expansion due to poor aeration and waterlogging. Amaranthus, being a fast-growing leafy vegetable, would have suffered from reduced chlorophyll content and stunted growth under such nutrient-deficient conditions (Epelde *et al*., 2018; Borthakur *et al*., 2025). In the combination, CP+VC (1:2) and CP+VC+S (1:2:1), high doses of vermicompost might have raised pH, affecting nutrient solubility and microbial dynamics. Excessive vermicompost can lead to nutrient imbalances, especially elevated salts or ammonia, which may inhibit germination and seedling growth, causing phytotoxicity risks (Ceritoglu *et al*., 2021).

3.3.3 | Effect of media combination on stem girth

The highest stem girth (2.8 cm) was recorded in the CP + VC (1:1) treatment, indicating that a balanced mix of coir pith and vermicompost creates a favorable medium for stem development. Vermicompost enriched the substrate with nutrients and beneficial microbes, while coir pith would have improved aeration and water retention. In the treatment CP + VC + S (1:1:1), stem girth dropped sharply to 1.2 cm. The inclusion of sand (S) in the growing medium consistently led to reduced stem girth across all ratios. Sand would have diluted the nutrient concentration and reduced organic content, thereby limiting growth.

CP + VC (2:1) showed a moderate stem girth (2.2 cm), suggesting that increasing coir pith slightly would have reduced nutrient density but still supported decent growth. CP + VC (1:2) resulted in lower stem girth (1.4 cm), possibly due to excessive vermicompost leading to nutrient imbalance or compaction, which hindered root expansion and nutrient uptake. The lowest stem girth (0.8 cm) was observed with coir pith alone, underscoring its limited nutritive value when not supplemented with vermicompost. Though coir pith improved anchoring of the plant, it lacked the essential nutrients required for robust stem development.

3.4 | Root parameters of Red Amaranthus

3.4.1 | Root length

Root length (Table 4) exhibited a significant influence of various growing media and varied from 10.6 to 15.8 cm. The growing media comprising coirpith: vermicompost (1:1) recorded the maximum root length (15.8 cm), followed by the media combination coirpith: vermicompost in the ratio 2:1 (14.7 cm). The treatment with coirpith alone showed restricted root development (10.6 cm), indicating its limitations in sustaining healthy root architecture.

Coirpith and vermicompost media combinations would have favored better root elongation, likely due to a balanced moisture profile, root-zone porosity, and bioactive compounds from vermicompost. An optimal root-zone environment facilitates more profound and more extensive root systems and improved root architecture, which enhances nutrient and water uptake, which is critical for overall plant vigor and biomass accumulation. Similar findings were reported by Madhusree and Madhumita (2021), where media containing coirpith and vermicompost in balanced ratios significantly improved root traits in ornamental species.

3.4.2 | Root to Shoot ratio

The Root-to-Shoot Ratio serves as a valuable diagnostic tool in soilless cultivation systems. It can be used as an early indicator of substrate performance and plant stress, enabling growers to make timely adjustments to the growing medium. The media combinations were observed to have a significant effect on the root-to-shoot ratio of Red Amaranthus. Lower root-to-shoot ratios (0.59–0.61) were observed in all combinations involving VC and/or sand, indicating greater shoot biomass relative to root biomass. A lower root-to-shoot ratio is often desirable for leafy crops like Amaranthus, as it indicates efficient nutrient uptake and allocation to edible biomass. CP alone resulted in the highest ratio (0.83), indicating more root biomass relative to shoot biomass, which could often be in response to stress conditions such as nutrient deficiency or salinity. This imbalance suggests the plant is struggling to acquire sufficient resources, which can negatively impact shoot growth and overall yield. Under nutrient deficiency or drought, the root-to-shoot ratio often increases, reflecting adaptive investment in root growth for resource acquisition (Peng *et al*., 2019).

3.5 | Effect of media combination on Yield of Red Amaranthus

The highest fresh weight (61.52 g pot^{-1}) and dry weight (17.42 g pot^{-1}) were recorded in the treatment with coirpith + vermicompost (1:1), indicating optimal nutrient availability and balanced physical structure, which was a significant difference from all other combinations. The next best performance was observed in CP + VC (2:1), with a fresh weight of 43.97 g pot^{-1} and dry weight of 11.57 g pot^{-1}, suggesting that increasing coirpith slightly reduced nutrient density but still supported biomass accumulation. The lowest yield was recorded in coirpith alone, with a fresh weight of 20.32 g pot^{-1} and dry weight of 5.60 g pot^{-1}, confirming its inadequacy as a standalone medium. The lack of nutrients and microbial activity in coirpith likely restricted plant growth and biomass accumulation. (Table 5; *Fig.* 4).

Plant growth is dependent on the rate of accumulation of dry matter. Total dry matter production is the integral of crop growth rate over the entire growing period and is related to assimilatory surface area, leaf area, duration, other growth attributes, and yield (Yoshida, 1972). The dry matter accumulation influences the economic yield on one hand, while production of drymatter is dependent upon adequate supply of plant nutrients (Maghfoer *et al*., 2015).

In the present study, the growth and yield parameters were exceptionally high in growing media containing coirpith: vermicompost in the ratio of 1:1 followed by coirpith: vermicompost in the ratio 2:1. The increased dry matter under the above treatment might be mainly due to early vigour shown by the crop which was due to the availability of plant nutrients at adequate level along with sufficient moisture for early development of plant parts and roots, which might have enhanced more uptake of nutrients. This result aligns with the findings of Ramesh

(2014), who evaluated multiple media combinations for Amaranthus tricolor, where treatments with coir pith and vermicompost in a 1:1 ratio, when supplemented with organic nutrition, showed superior growth, yield, and cooking quality. Uma and Malathi (2009) reported that humic materials and other plant growth-influencing substances, such as plant growth hormones produced by microorganisms during vermicomposting, increased the growth and yield of amaranthus.

The results on the yield parameters of red amaranthus distinctly indicated the importance of combining proper fertilization with the correct composition of growing media to achieve higher production. Sande et al. (2024) observed that the combined application of vermicompost at 25% and inorganic fertilizers at 75–100% of the recommended dose yielded optimal results for biomass accumulation.

3.6 | Effect of media combination on Nutrient uptake of Red Amaranthus

The effect of composition of growing media on uptake of macronutrients by Red Amaranthus was estimated at final harvest stage. Among the growing media experimented, the highest amount of total N uptake (0.190 g pot^{-1}), total P uptake (0.085 g pot^{-1}) and total K uptake (0.160 g pot^{-1}) were observed in the growing media comprising coirpith: vermicompost in equal proportions (T_1) which was followed by growing media having coirpith: vermicompost in 2:1 proportions (T_3) (*Fig.* 5). This enhanced uptake in the CP:VC (1:1) treatment may be attributed to the balanced nutrient profile and improved root-zone conditions provided by the coir pith and vermicompost blend, which facilitated optimal nutrient absorption.

Efficient use of fertilizer nutrients is necessary for optimum growth and yield, for which making continuous availability of nutrients in the growing media is essential. During the vegetative stage, the plant vigorously absorbs nutrients to build up the plant framework, and the excess nutrients are stored within the plant and translocated to the fruit at later stages for further development (Pfluger and Mengel, 1972). Plant analysis serves as an elegant tool for understanding the growth and physiology of plants at various growth stages.

The fresh weight of Red Amaranthus raised with the growing media of coirpith: vermicompost in equal proportion recorded the highest value of nutrient content of N, P, K, and corresponding nutrient uptake. Several studies indicated that the application of organic manure along with inorganic fertilizers enhanced the mobility of nutrients around the root zone. Even though all the growing media were fertilized with a uniform dose of fertilizer solution periodically, the integrated effect of growing media with coirpith: vermicompost was reflected well in nutrient content and uptake significantly (*Fig. 6*).

TABLE 4 Effect of media composition on root length and root and shoot ratio of Red Amaranthus at harvest stage

T.No.	Root length (cm)	Root: Shoot ratio
CP+VC (1:1)	15.8 a	0.61 b
CP+VC+S (1:1:1)	12.8 c	060 b
CP+VC (2:1)	14.7 b	0.60 b
CP+VC+S (2:1:1)	13.3 c	0.59 b
CP+VC (1:2)	13.1 c	0.59 b
CP+VC+S (1:2:1)	12.1 d	0.60 b
CP alone	9.6 e	0.83 a
Sed±	0.380	0.013
CD(P=0.05)	0.815*	0.029*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

TABLE 5 Effect of media composition on yield parameters of Red Amaranthus at harvest stage

T.No.	Fresh Weight g pot^{-1}	Dry Weight g pot^{-1}
CP+VC (1:1)	61.52 a	17.42 a
CP+VC+S (1:1:1)	34.74 d	10.11 c
CP+VC (2:1)	43.97 b	11.57 b
CP+VC+S (2:1:1)	39.32 c	10.33 c
CP+VC (1:2)	36.14 d	10.15 c
CP+VC+S (1:2:1)	32.23 e	9.42 d
CP alone	20.32 f	5.60 e
Sed±	0.903	0.180
CD(P=0.05)	1.936*	0.387*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

Vermicompost, which contains nutrients such as nitrates, available P, K, Ca, and Mg, and has a large specific surface area for nutrient retention, would enhance nutrient uptake. Apart from providing mineral nutrients, particularly N and K, vermicompost also contributes to the biological fertility of soil and enhances decomposition of organic matter, composing stabilized humic substances , which would increase quick dissolution and mobility of immobile P as soluble P. Uma & Malathi (2009) also reported enhanced nutrient uptake and biomass in Amaranthus when vermicompost was used as a soil supplement. The present studies corroborate to the findings of . Yadav *et al*. (2022) demonstrated that integrated nutrient management involving vermicompost and biofertilizers significantly increased leaf number, fresh and dry weight, and nutrient uptake in *Amaranthus tricolor*. Patel *et al*. (2019) also reported that vermicompost combined with Azotobacter and PSB enhanced nitrogen and phosphorus availability, leading to higher grain and stalk yield in *Amaranthus hypochondriacus.*

TABLE 6 Effect of treatments on nutient use efficiency at harvest stage

Treatments	Response ratio (g yield g^{-1} nutrient applied)			Physiological efficiency (g yield g^{-1} nutrient absorbed)			Apparent Nutrient Recovery (%)		
	N	P	K	N	P	K	N	P	K
CP+VC (1:1)	3.046 a	13.374 a	20.507 a	323 e	725 e	383 d	5.411 a	10.587 a	30.700 a
CP+VC+S (1:1:1)	1.720 d	7.552 d	11.580 d	459 c	996 c	419 c	3.703 d	7.500 d	27.367 c
CP+VC (2:1)	2.177 b	9.559 b	14.657 b	413 d	862 d	426 c	4.559 b	9.587 b	29.733 b
CP+VC+S (2:1:1)	1.947 c	8.548 c	13.107 c	452 c	984 c	452 b	4.173 c	8.413 c	28.067 c
CP+VC (1:2)	1.789 d	7.857 d	12.047 d	454 c	1096 b	430 c	3.886 d	7.065 d	27.633 c
CP+VC+S (1:2:1)	1.596 e	7.007 e	10.743 e	487 b	1063 b	421 c	3.480 e	7.000 d	27.067 d
CP alone	1.006 f	4.417 f	6.773 f	584 a	1202 a	603 a	3.074 f	6.565 e	20.067 e
Sed±	0.057	0.1507	0.3021	11.75	20.85	10.22	0.0863	0.2035	0.5016
CD(P=0.05)	0.123*	0.3233*	0.6480*	25.21*	44.73*	21.92*	0.1849*	0.4365*	1.0757*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

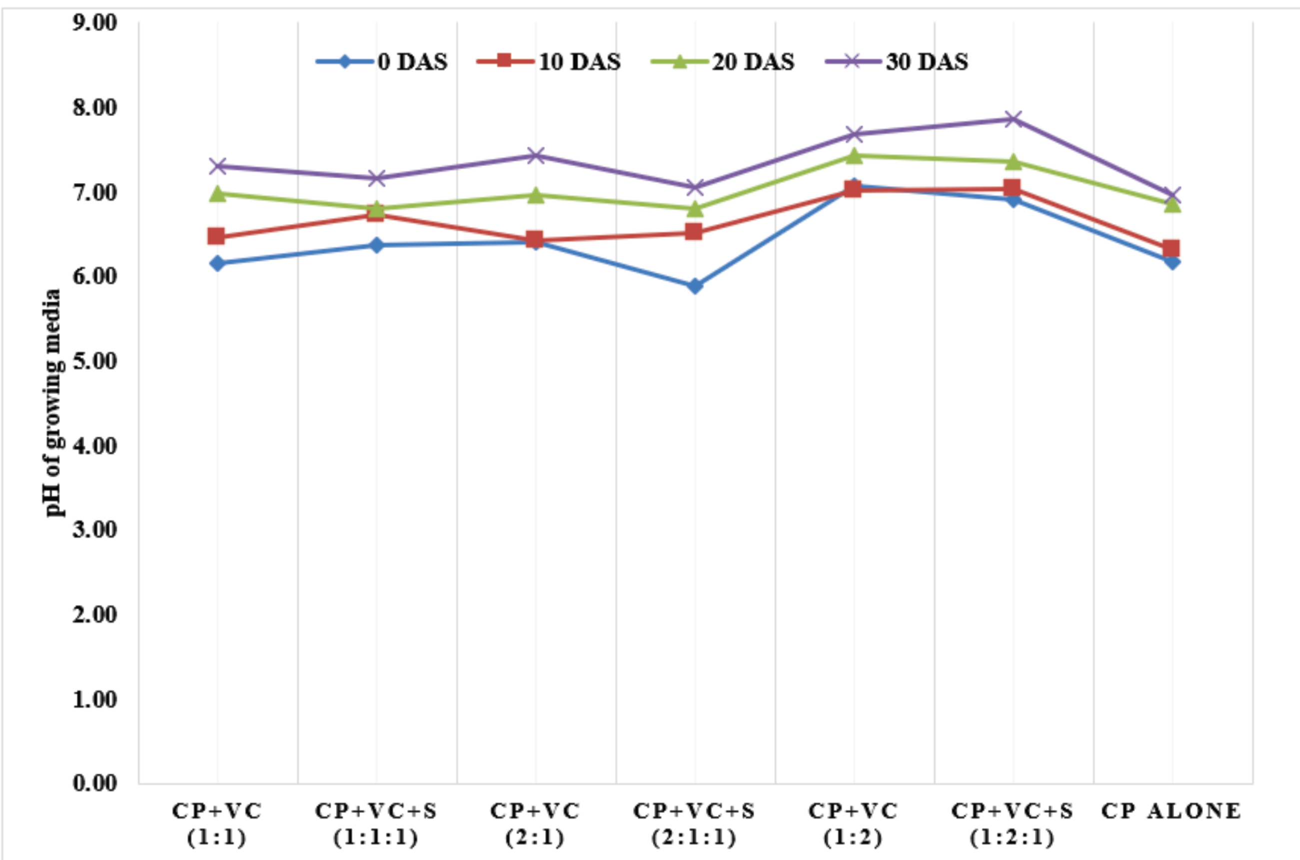

FIGURE 2 Changes in reaction state (pH) of growing media during crop growth stages

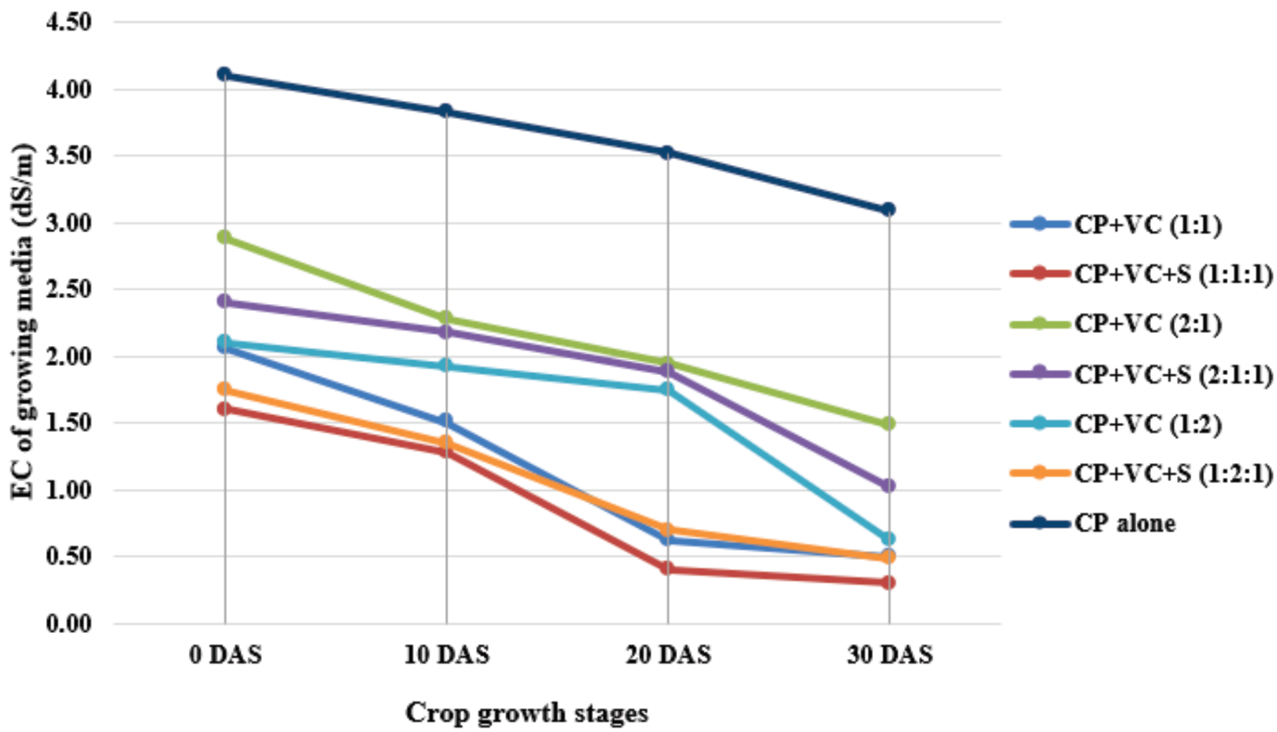

FIGURE 3 Changes in salinity (EC) of growing media during crop growth stages

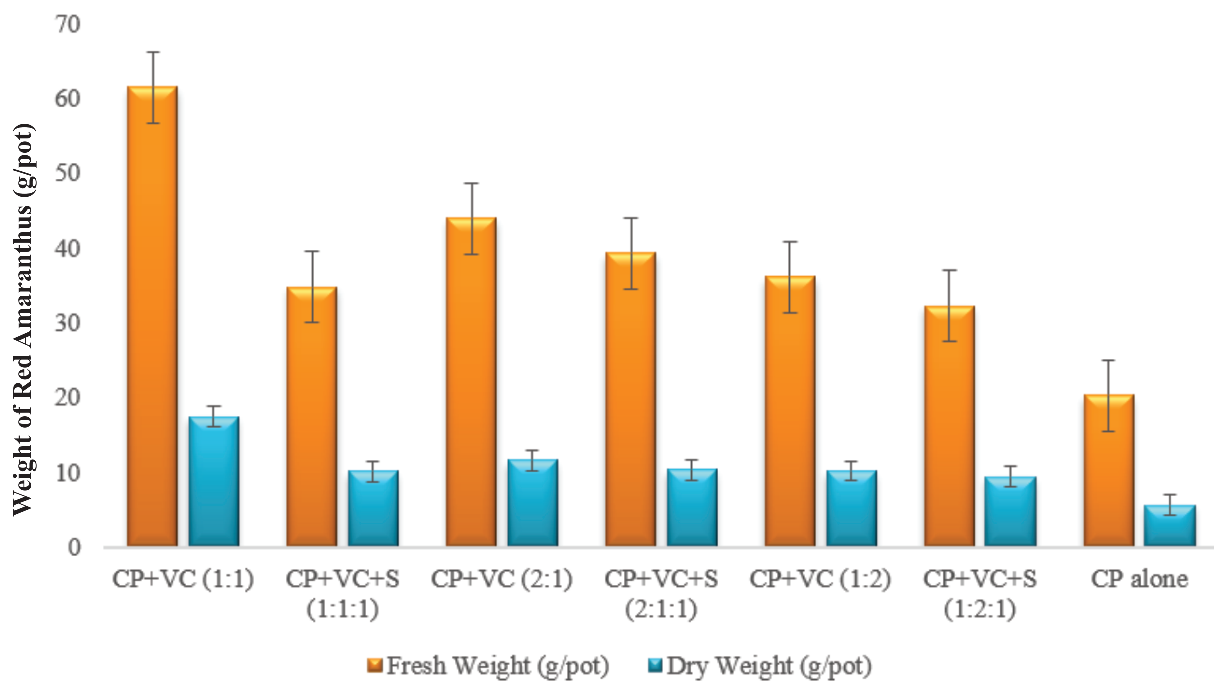

FIGURE 4 Effect of media combination on fresh weight and dry weight of Red Amaranthus

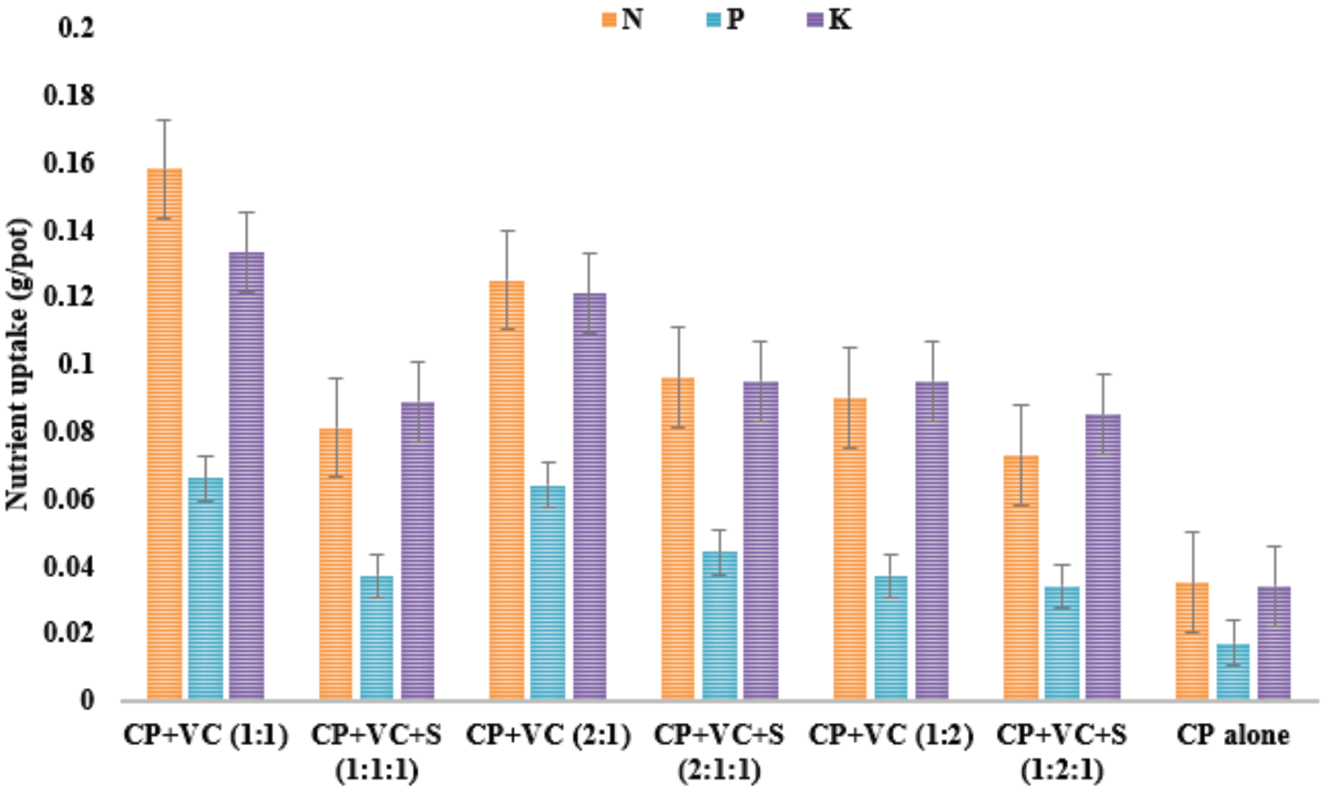

FIGURE 5 Effect of media combination on nutrient uptake of Red Amaranthus

FIGURE 6 Pot culture experiment with Red Amaranthus at 30 DAS

3.7 | Effect of media combination on Nutrient use efficiency

Based on the yield and nutrient uptake estimated for Red Amaranthus in growing media, the nutrient use efficiencies were computed in terms of response ratio, apparent nutrient recovery, and physiological efficiency for the applied N, P, and K nutrients (Table 6).

3.7.1 | Request Ratio (RR)

The coirpith and vermicompost (1:1) treatment recorded the highest RR values across all nutrients (N: 3.046, P: 13.374, K: 20.507), indicating a robust yield response per unit of nutrient applied. This aligns with previous findings that vermicompost enhances nutrient availability and microbial activity, thereby improving crop performance (Singh *et al*., 2020). In contrast, treatments incorporating sand (e.g., CP+VC+S in a 1:2:1 ratio) showed diminished RR values, which indicated that sand might have diluted nutrient concentration unfavorably for nutrient uptake.

3.7.2 | Apparent Nutrient Recovery (ANR)

CP+VC (1:1) again led in ANR for all nutrients, with potassium showing the highest recovery (K: 30.700%). This reflected that the coirpith and vermicompost combination in equal parts improved root uptake and reduced nutrient losses, likely due to better moisture retention, and microbial interactions facilitated by the compost blend (Singh *et al*., 2020; Sathiyavathi *et al*., 2023). Treatments with sand consistently showed lower ANR, suggesting that sand may reduce nutrient retention or impede root access to nutrients. However, the differences were not drastic, indicating that sand can still be a useful amendment when appropriately balanced.

3.7.3 | Physiological Efficiency (PE)

The CP-alone treatment exhibited the highest PE, particularly for phosphorus (P: 1202 g yield/g nutrient absorbed) and potassium (K: 1016 g/g). Although CP alone recorded the highest physiological efficiency, this value can be interpreted with caution due to its low absolute N uptake. The inflated PE may reflect limited nutrient acquisition rather than actual efficiency in biomass conversion. Coirpith's slow-release properties may synchronize nutrient availability with crop demand, enhancing internal nutrient utilization (Mahanta, 2017). Treatments incorporating vermicompost (VC), especially CP+VC (1:1), demonstrated balanced PE values alongside higher nutrient uptake, indicating more effective nutrient assimilation, reinforcing the role of organic matter in improving nutrient assimilation and metabolic efficiency (Sathiyavathi *et al*., 2023).

4 | CONCLUSIONS

In this study, the performance of various organic substrate combinations—mainly coirpith (CP), vermicompost (VC), and sand (S)—as growing media for Red Amaranthus in soilless cultivation is analyzed. Based on growth, yield, and nutrient use efficiency, it was found that all media supported healthy growth of Red Amaranthus despite the salinity present. The combination of coirpith and vermicompost in equal parts (1:1) emerged as the best growing medium for Red Amaranthus in soilless systems, as it strikes a good balance between physical support, nutrient supply from vermicompost, and enhanced aeration and water retention from coirpith, offering a model for sustainable urban farming. Therefore, these results provide a validated approach for optimizing soilless substrates, with implications for urban food security, resource efficiency, and sustainable production of leafy vegetables.

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CONFLICT OF INTEREST

Authors declare that there are no conflicts of interest in any form that could have influenced the research presented in this paper.

DATA AVAILABILITY STATEMENT

The data used in this study are available from the links provided in this manuscript or upon request from the authors.

AUTHOR'S CONTRIBUTION

This research work conducted by PR, SS, DRK and IA.; NE: Conceptualization, methodology, data curation, formal analysis, investigation, manuscript writing and supervision.

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