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DEVELOPING ENVIRONMENT FRIENDLY GROWING MEDIA FOR SOILLESS CULTIVATION OF SEASONAL VEGETABLES

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Abstract
The pursuit of sustainable agriculture, particularly in arid and semi-arid regions, necessitates alternatives to traditional soil-based cultivation. This study explores the development of environmentally friendly, cost-effective soilless growing media using locally available materials in Tandojam, Sindh, Pakistan. The objective was to identify optimal combinations of biomass, nutrient supplements, and stabilizers for cultivating seasonal vegetables, tomato (Solanum lycopersicum) and okra (Abelmoschus esculentus). Locally sourced materials were categorized into biomass (coco peat, rice husk, wheat straw), supplements (e.g., compost, manure, biochar), and stabilizers (sands, expanded clay, styrofoam). These materials were dried, processed to 2-5 mm size, and mixed in volumetric ratios. Seventy-five media formulations were initially screened under greenhouse conditions. Based on germination rates (>70%) and seedling vigor, 15 treatments were selected for detailed analysis in a Randomized Complete Block Design (RCBD) with three replications. Comprehensive analysis of physico-chemical properties (WHC, porosity, pH, EC, nutrients) and plant growth parameters (germination, plant height, leaf and fruit number) was conducted. Results showed high WHC in banana leaves and coco peat (>82%), with high porosity in wheat straw and styrofoam. Media T32 (60% wheat straw, 20% biochar, 20% expanded clay) showed high vigor in both crops, while coco peat-based media T6 (50% coir, 25% compost, 25% pit sand) and T11 (60% coir, 20% compost, 20% pit sand) consistently achieved superior plant growth. However, bagasse and wheat straw-based media underperformed. Nutrient analysis revealed post-harvest depletion, highlighting the need for fertilization. This study concludes that coir-based media, combined with compost and structural stabilizers, offer a sustainable, low-cost solution for soilless vegetable cultivation in arid climates.

INTRODUCTION

Pakistan's agricultural sector generates a substantial quantity of crop residues from major crops such as rice, wheat, sugarcane, and bananas. These residues, rice husks, bagasse, banana leaves, and wheat straw are often underutilized or improperly disposed of, leading to environmental degradation and missed opportunities for resource recovery (Arias et al., 2023; Dungani et al., 2017; Shitu et al., 2015). Rich in lignocellulosic compounds including cellulose, hemicellulose, and lignin, these agricultural wastes have significant potential to be converted into value-added substrates for soilless cultivation systems (Akram et al., 2020). Utilizing such locally available biomass not only addresses pressing waste management issues but also reduces reliance on imported substrates such as peat and coco peat, which are often costly and scarce in Pakistan (Arias et al., 2023; J. Xiong et al., 2017). Developing sustainable, environment-friendly growing media from these agricultural residues could play a vital role in promoting sustainable agriculture and circular bio economy in the region.

Soilless cultivation, including hydroponics and substrate-based systems, offers distinct advantages over conventional soil-based agriculture. These systems facilitate precise control over water, nutrients, and environmental factors, leading to improved crop yields, efficient water use, and the ability to cultivate vegetables in non-arable or degraded soils (Carrasco, 2022; Carrasco et al., 2022a). Seasonal vegetables, critical to nutrition and food security, face challenges such as discontinuous production, soil salinity, fertility depletion, and the impacts of climate change (Bose & Pal, 2023; Amiri et al., 2023). Soilless cultivation addresses many of these constraints by eliminating dependency on soil quality, reducing water consumption by up to 90%, and enabling year-round production regardless of external climatic stresses (Massa et al., 2020; De Pascale & Rouphael, 2021). However, the success of these systems heavily depends on the choice of substrate, which must provide adequate water retention, aeration, nutrient availability, and support root health.

Traditional substrates such as peat and synthetic materials pose environmental and economic challenges. Peat extraction contributes to the destruction of ecologically important peatlands, releasing stored carbon dioxide and exacerbating climate change (Dhen et al., 2018; Nicese et al., 2024). Synthetic substrates generate significant plastic waste, creating pollution and landfill concerns (Raviv, 2016). Furthermore, the high costs and limited availability of these imported substrates restrict their adoption in Pakistan's agricultural sector (Nicese et al., 2024). This necessitates the exploration and development of alternative substrates derived from renewable, locally available organic wastes such as date-palm residues, co-composted green waste, and lignocellulosic agricultural by-products (Dhen et al., 2018; Xu et al., 2021). These alternatives not only mitigate environmental impacts but also foster economic benefits by reducing dependency on imports and supporting local economies.

Given the potential and challenges, this study focuses on the development and evaluation of sustainable substrates made from agricultural residues for soilless cultivation of seasonal vegetables in Sindh, Pakistan. The study evaluates physical, chemical, and biological properties of various substrates and assesses their impact on crop growth, yield, and quality under controlled conditions. By optimizing locally sourced growing media tailored to regional agro-climatic conditions, this research aims to contribute towards sustainable agricultural practices, efficient resource use, and enhanced food security in the region.

Material and Methods

Experimental Site and Climate Conditions

The study was conducted at Sindh Agriculture University (SAU), Tandojam, Pakistan (25.4255° N, 68.5365° E), in a controlled greenhouse at the Department of Energy and Environment. Tandojam has a hot climate with an average annual temperature of 26.1°C, summer peaks over 40°C, and limited rainfall (~176 mm/year) mainly during July–September. Due to these arid conditions, a greenhouse environment was used to ensure uniform growing conditions, maintaining 25–30°C temperature, 70–80% relative humidity, and a 12-hour light cycle using artificial lighting.

Figure 1: location map of the study area

2.2 Selection and Preparation of Soilless Media

Locally available and cost-effective materials were selected for soilless media based on their physical structure, nutrient value, and sustainability. Materials were categorized as basic biomass (coco peat, rice husk, bagasse, sawdust, banana leaves), nutrient supplements (compost, poultry and cattle manure, biochar, sewage sludge), and stabilizers (e.g., hill sand, desert sand, ceramic pots, Styrofoam) (Table 3.1). All components were sourced within 100 km of the study site. To ensure consistency across treatments, all raw materials were processed in three key stages. First, sun drying was conducted on polyethylene sheets in 5 cm layers, with manual turning twice daily until the materials reached 10-15% moisture, verified using the oven-drying method at 105°C. Next, size reduction was achieved using a 7.5 kW biomass crusher (Model BC-1000) with sequential screening through 10 mm and 5 mm meshes, yielding particles of 2-5 mm; finer particles were discarded to prevent compaction. Finally, the homogenized mixing was carried out using a 100-liter rotary drum mixer. Stabilizers were added first, followed by biomass and then nutrient supplements, mixed at 30 rpm for 10 minutes with an additional 5-minute reverse rotation. Each mixture was prepared in triplicate, using volumetric 10-liter buckets to maintain precise ratios, and homogeneity was verified through random sampling. This multi-step preparation ensured physical uniformity, optimal aeration, and reproducibility in all experimental media treatments.

Table 1: Selection and sourcing of different materials

Sr. No	Material Name	Symbol	Source
		Basic Biomass	
	Coco peat	C	Local coconut processing units
	Sawdust	SW	nearby furniture workshops
	Rice husk	RH	Rice mills in the thatta district
	Wheat straw	WS	After harvesting wheat from nearby area
	Palm peat	PP	Date palm orchards
	Bagasse	Bg	Mehran Sugar mill Tando Allahyar
	Banana leaves	BL	Nearby banana plantations
		Nutrient supplements	
	Cattle manure	CM	Dairy farm, Sindh agriculture university Tandojam
	Poultry manure	PM	Poultry farms in Tando Allahyar district
	Compost	Cp	Prepared on-site using vegetable waste
	Biochar	Bc	Produced in-house using rice husk as feedstock

	Dried municipal sewage sludge	SS	Tandojam Municipal Corporation wastewater drainage outlet
Stabilizers			
	Hill sand	HS	Kirthar Range, Jamshoro district
	Pit sand	PS	Local construction material suppliers in Tandojam
	Desert sand	DS	Thar Desert, Tharparkar district
	Expanded clay	Ec	Local clay pot shops from Tandojam
	Crushed ceramic pots	CP	Pottery shop at Nasarpur
	Waste Styrofoam	Sf	From packaging waste at local electronics stores

2.3 Preparation and Formulation of Soilless Growing Media

A total of 75 soilless media treatments were formulated using locally available biomass, nutrient supplements, and stabilizers to evaluate their suitability for sustainable cultivation. Biomass materials (40-65%) such as coconut coir, rice husk, sawdust, wheat straw, bagasse, and banana leaves served as structural bases. Nutrient supplements (17.5-35%) including compost, poultry manure, biochar, and municipal sewage sludge were added to enhance fertility. Stabilizers (10-47.5%) like sand, expanded clay, and crushed ceramics ensured structural integrity. Treatments T1-T15 tested traditional mixes (coir or rice husk with compost and sand), while T16-T75 explored innovative blends, such as banana leaves with poultry manure and expanded clay. All components were measured volumetrically using calibrated containers and homogenized using a rotary drum mixer. Prepared media were sealed in containers to maintain cleanliness and prevent microbial contamination prior to use.

2.4 Rationale for Treatment Design

The 75 treatments were strategically formulated to evaluate the interplay between biomass types, nutrient content, and physical stability. Drawing from preliminary trials and literature, treatments balanced water retention (from porous biomass), nutrient availability (via organic supplements), and aeration/drainage (through stabilizers). High-stabilizer treatments (T1: 47.5%) promoted drainage, while biomass-heavy mixes (T3: 65%) emphasized moisture retention. Fifteen optimized treatments (Table 3.3) were shortlisted based on screening parameters such as pH (5.8-7.2), EC (0.8–2.3 dS/m), and >70% germination rates. Treatments with imbalanced compositions were excluded. For example, T11 (60% coir, 20% compost, 20% sand) showed ideal physical and nutritional characteristics. Pilot trials further revealed that expanded clay improved root growth in dense biomass mixes, and poultry manure enhanced early seedling Vigor.

Table 2: Optimized Treatments Selected Based on Preliminary Performance in Germination and Structural Stability

Treatment	Biomass	Nutrient Supplement	Stabilizer	Performance Basis (Best)
T1	C 40 % (1880 m^3)	Cp 30 % (1410 cm^3)	PS 30% (1410 cm^3)	**09**
T2	RH 40 % (1880 cm^3)	Cp 30 % (1410 cm^3)	PS 30% (1410 cm^3)	**12**
T3	SD 40 % (1880 cm^3)	Cp 30 % (1410 cm^3)	PS 30% (1410 cm^3)	**05**
T4	WS 40 % (1880 cm^3)	Cp 30 % (1410 cm^3)	PS 30% (1410 cm^3)	**14**
T5	Bg 40 % (1880 cm^3)	Cp 30 % (1410 cm^3)	PS 30% (1410 cm^3)	**15**

T6	C 50 % ($2350\ m^3$)	Cp 25 % ($1175\ cm^3$)	PS 25% ($1175\ cm^3$)	**02**
T7	RH 50 % ($2350\ cm^3$)	Cp 25 % ($1175\ cm^3$)	PS 25% ($1175\ cm^3$)	**04**
T8	SD 50 % ($2350\ cm^3$)	Cp 25 % ($1175\ cm^3$)	PS 25% ($1175\ cm^3$)	**03**
T9	WS 50 % ($2350\ cm^3$)	Cp 25 % ($1175\ cm^3$)	PS 25% ($1175\ cm^3$)	**10**
T10	Bg 50 % ($2350\ cm^3$)	Cp 25 % ($1175\ cm^3$)	PS 25% ($1175\ cm^3$)	**13**
T11	C 60% ($2820\ cm^3$)	Cp 20% ($940\ cm^3$)	PS 20% ($940\ cm^3$)	**01**
T12	RH 60% ($2820\ cm^3$)	Cp 20% ($940\ cm^3$)	PS 20% ($940\ cm^3$)	**11**
T13	SD 60% ($2820\ cm^3$)	Cp 20% ($940\ cm^3$)	PS 20% ($940\ cm^3$)	**08**
T14	WH 60 % ($2820\ cm^3$)	Cp 20% ($940\ cm^3$)	PS 20% ($940\ cm^3$)	**06**
T15	Bg 60% ($2820\ cm^3$)	Cp 20% ($940\ cm^3$)	PS 20% ($940\ cm^3$)	**07**

The final 15 treatments retained for detailed analysis (Figure 3.2) represented the most promising combinations for seasonal vegetable cultivation, aligning with the study's goal of identifying locally sustainable, high-performance media.

Figure 2: layout of different compositions of growing media in pots

Optimization of the growing media involved evaluating 75 treatments based on germination rate, structure, water retention, nutrient content, and root growth. Treatments not meeting performance standards were discarded, and promising ones were shortlisted for further trials. Economic viability was assessed by calculating costs of materials, labor, and scalability, with locally sourced inputs reducing expenses. The final selections were compared with conventional soil and commercial peat mixes to ensure cost-effectiveness and market potential.

2.5 Experimental Design

The study was conducted in two phases to evaluate 75 growing media formulations. Phase-I involved germination tests in trays to select the top 15 treatments based on seedling Vigor and germination rates (>70%). Phase-II used a Randomized Complete Block Design (RCBD) with three replications per treatment (45 pots total) in a controlled greenhouse environment at Sindh Agriculture University (Figure 3.3). Tomato and okra seeds were sterilized, pre-treated, and sown at specified depths, with growth monitored under standard temperature, humidity, and light conditions. A control incubation experiment assessed nutrient stability and microbial activity over 90 days using moist, ventilated samples of the selected media.

Figure 3: Treatment pots in greenhouse facility

2.6 Physico-Chemical Properties of Soilless Growing Media

The physical properties of soilless growing media include **bulk density**, measured by drying media in core rings using the following formula,

$$\rho b = \frac{W_b - W_r}{(\pi h d^2/4)}$$

where ρb is the bulk density g/cm^3; Wb is the weight of media and core ring after oven dried (g); Wr is the weight of the core ring (g); h is the height of the core (cm); and d is the core diameter (cm). **Particle density** determined using the pycnometer method involving water displacement; and total porosity can be calculated using the following formula.

$$\rho_s = \frac{\rho_w \times M_s}{M_{dw}}$$

Where ρ is the particle density; ρ_w is the density of water (g/cm); M_s is the mass of oven dried media (g); and M_{dw} is the mass of water displaced by media (g). Particle size distribution is analysed by sieving and shaking the media through different mesh sizes to determine particle fractions by following formula. The media was shacked for 10 min and media left in each sieve was calculated using the formula.

$$Percent\ passing = Percent\ arriving - Percent\ retained$$

Water holding capacity is gravimetrically measured by saturating a sample, draining, and weighing retained water relative to dry weight. The WHC was calculated using the formula:

$$WHC = \frac{M_w}{M_s} \times 100$$

Where WHC is the water holding capacity; M_w is the mass of water retained in the sample (g); and M_s is the mass of oven dried sample (g).

Chemically, **pH and electrical conductivity** are measured in a water suspension to assess media acidity and salinity. Organic carbon content is determined by acid digestion and titration using the Walkley-Black method. Essential nutrients like calcium, magnesium, phosphorus, potassium, manganese, iron, zinc, and copper are quantified by acid digestion of dried media samples followed by analysis using Atomic Absorption Spectroscopy, Flame Photometry, or UV-Vis spectrophotometry, ensuring optimal nutrient availability for plant growth. The percentage WB carbon is given by the formula:

$$Organic\ carbon\ cotent\ (\%) = M \times \frac{(V_1 - V_2)}{W} \times 0.3 \times$$

Where M is molarity of $FeSO_4$, V_1 is volume (mL) of $FeSO_4$ required in blank titration, V_2 is volume (mL) of $FeSO_4$ required in actual titration, W is weight (g) of oven dried sample and CF is correction factor.

2.7 Nutrient Content Analysis

Sodium was determined using the Mehlich-1 extraction method by shaking 2 g of air-dried media with 0.05 N HCl and 0.025 N H_2SO_4 at a 1:10 ratio, filtering, and analyzing with AAS or ICP-OES; sodium concentration was calculated using the following formula:

$$Na = \frac{C \times V}{M}$$

Where C is sodium concentration (mg/L), V is extraction solution volume (L), and M is dry sample mass (kg).

Phosphorus was assessed by digesting 1 g of dried media using the same acid mix, followed by UV-Vis spectrophotometric analysis at 880 nm with results computed using the following formula:

$$CP = \frac{(Asample - Ablank) \times Vfinal \times DF)}{\epsilon \times b \times W}$$

Where, CP is Phosphorus concentration in the sample (mg/kg), A sample is Absorbance of the sample solution, A blank is Absorbance of the blank solution, V final is Final volume of the digested sample solution (mL), DF is Dilution factor (if any), ϵ is Molar absorptivity ($L \cdot mol^{-1} \cdot cm^{-1}$), b is Path length of the cuvette (cm) and W is Weight of the media sample (g).

Potassium was determined similarly through acid digestion, filtration, and analysis by Flame Photometry, and its concentration was calculated using the following formula:

$$CK = \frac{(R\ sample - R\ blank) \times Vfinal \times DF}{(R\ standard \times W}$$

Where CK is Potassium concentration in the sample (mg/kg), *R sample* is Reading of the sample solution from the flame photometer, R blank is Reading of the blank solution, *V final* is Final volume of the digested sample solution (mL), *DF* is Dilution factor (if applicable), *R standard* is Reading of the potassium standard solution and *W* is Weight of the media sample (g).

Nitrogen was analyzed using the Dumas dry combustion method via a LECO CNS 2000 analyzer by combusting 0.5 g of the media sample at 1000°C in oxygen, and nitrogen content was calculated using the following formula:

$$N(\%) = \frac{M}{m} \times 100$$

Where m is the mass of nitrogen detected (g) and M is the total sample mass (g).

2.8 Plant Growth analysis

Plant growth parameters were systematically analysed to assess the performance of seasonal vegetables cultivated in different soilless growing media. Weekly measurements were conducted for plant height, number of leaves, branches, and fruits, while a separate seed germination test was also carried out for each medium. Plant height was measured from the base of the stem to the tip of the highest leaf or terminal bud using a measuring tape, ensuring consistency in timing to reduce diurnal effects. The number of leaves, including true leaves and cotyledons, was counted weekly, with careful tracking of newly emerged foliage. Similarly, the number of branches was recorded weekly by identifying lateral shoots originating from the main stem, and the number of fruits, both mature and developing, was counted to evaluate productivity. All plants were grown in labelled containers arranged in a randomized block design to minimize environmental variability, and data were consistently recorded for statistical analysis.

2.9 Statistical Analysis

To assess the significance and interactions of various treatments, an analysis of variance (ANOVA) was employed. Additionally, the means were compared using the Tukey post-hoc test, considering a significance level of $P<0.05$ to determine statistical significance. All statistical analyses were conducted using Prism GraphPad software version 5.1.

Results

Physicochemical Characteristics of Biomass, Nutrient Supplements, and Stabilizers

Table 3 presents the physicochemical properties of biomass materials including bulk density, WHC, pH, EC, and porosity. Coco peat and palm peat showed high WHC and low bulk density, ideal for moisture retention. Rice husk, bagasse, and wheat straw exhibited moderate WHC and high porosity, while sawdust and tree bark had lower WHC.

Table 3: Physio chemical properties of different biomass

Material	Bulk Density (g/cm³)	WHC (%)	pH	EC (dS/m)	Porosity (%)
Coco Peat/Coir	0.2	82.93	6	1.6	69.3
Palm Peat	0.14	85	6	1.8	60
Rice Husk	0.19	70	6.3	1.5	72
Saw Dust	0.22	60	4.8	1	50
Tree Bark	0.23	55	5.3	0.8	60
Bagasse	0.18	70	6.3	1.5	65
Banana Leaves	0.16	85	5.8	1	75
Wheat Straw	0.16	70	6.5	1.2	80

Table 4 shows nutrient supplements where municipal sludge and poultry manure had high WHC and EC, indicating high nutrient content. Cattle manure and compost provided moderate WHC and EC, while biochar had low WHC but high porosity and pH, enhancing aeration.

Table 4: Physio chemical properties of nutrient supplement

Nutrient Supplement	Bulk Density (g/cm³)	WHC (%)	pH	EC (dS/m)	Porosity (%)
Cattle Manure	1	62.5	8	3	62.5
Sludge (Municipal)	1.1	85	7.2	4.25	60
Compost	0.7	55	7	2.5	65
Poultry Manure	0.89	75	7.5	3.75	65
Biochar	0.6	40	8	1.25	67.5

Table 5 includes stabilizers; expanded clay and crushed ceramic pots offered good WHC and porosity, whereas pit sand, hill sand, and desert sand had low WHC and EC, suitable for soil structure. Styrofoam, with the lowest density and WHC, was effective for aeration.

Table 5: Physio chemical properties of Stabilizer

Stabilizer	Bulk Density (g/cm³)	WHC (%)	pH	EC (dS/m)	Porosity (%)
Pit Sand	1.5	20	7	0.2	40
Expanded Clay	0.35	45	7.5	1	72.5
Styrofoam	0.02	10	5.5	0.05	87.5
Hill Sand	1.6	25	6.5	0.2	42.5
Desert Sand	1.3	15	7	0.1	50
Crushed Ceramic Pots	1	32.5	7.8	0.35	60

3.2 Physical properties of best-performing media

3.2.1 Bulk density

Figure 4 shows bulk density variations of soilless media at 40%, 50%, and 60% biomass. At 40%, coir had the highest bulk density (0.78 g/cm³), followed by bagasse (0.72 g/cm³), with rice husk, sawdust, and wheat straw showing intermediate values. At 50%, coir again led (~0.76 g/cm³), followed by bagasse and rice husk. At 60%, bulk density decreased across all media, becoming more uniform (~0.68–0.70

g/cm³). Significant differences ($p < 0.05$) were observed at 40% and 50%, but not at 60%, indicating that higher biomass levels result in more uniform bulk density.

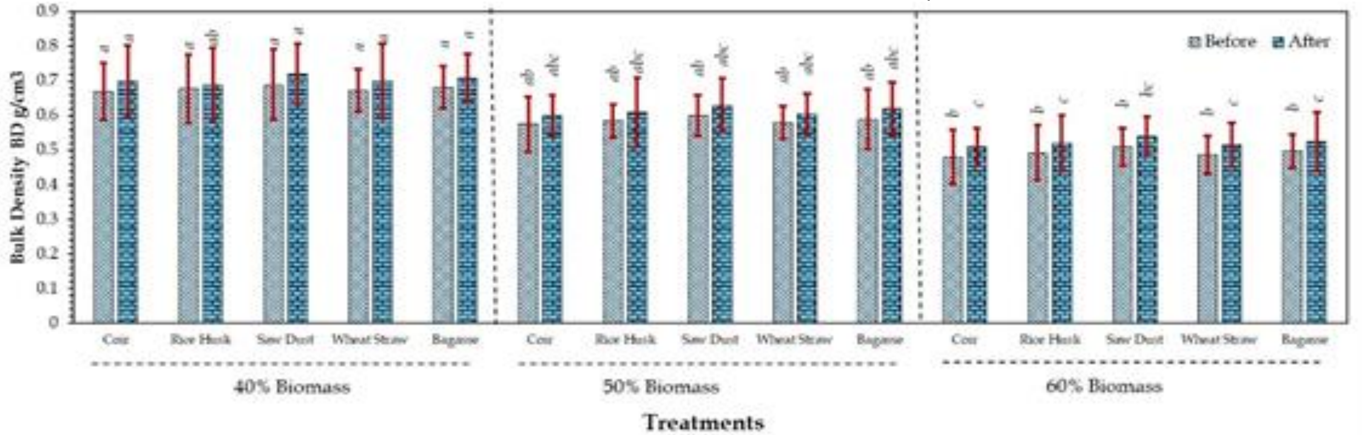

Figure 4: Bulk Density (g/cm³) of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.2.2 Total Porosity

Figure 5 illustrates porosity of coir, rice husk, sawdust, wheat straw, and bagasse at 40%, 50%, and 60% biomass. Porosity ranged from 70% to 80%, with coir and rice husk slightly higher (77-79%) than others (74-77%). No significant differences ($p > 0.05$) were observed among treatments, indicating all media maintained effective porosity for aeration and water infiltration, enhancing soil structure uniformly.

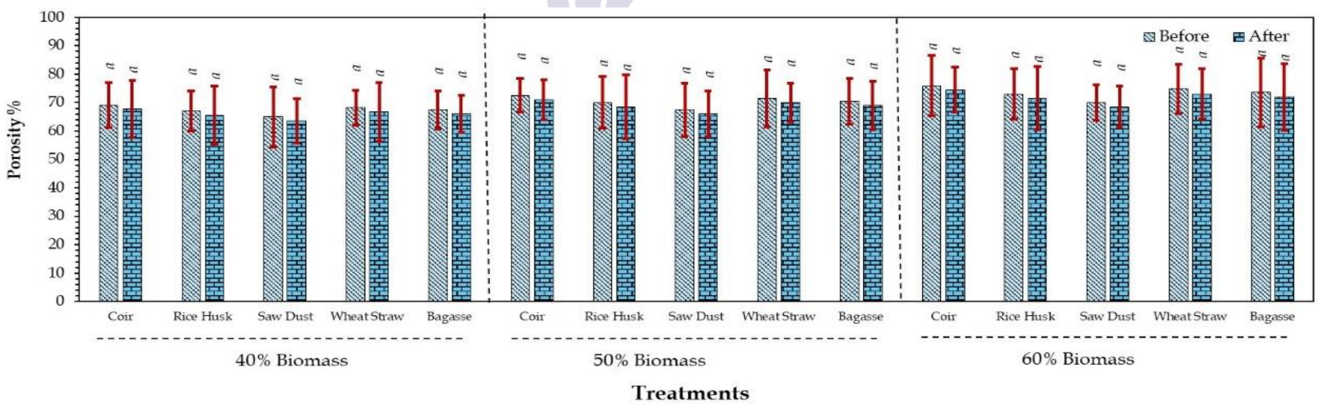

Figure 5: Total porosity (%) of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.2.3 Water Holding Capacity

Figure 6 shows WHC (%) of different substrates at 40%, 50%, and 60% biomass. Coir consistently had the highest WHC (75-85%), followed by rice husk and sawdust (65-80%). Bagasse showed the lowest (45-50%), with wheat straw also lower at 60% biomass. Statistical analysis ($p < 0.05$) confirmed significant differences, with coir and rice husk offering superior water retention across all levels.

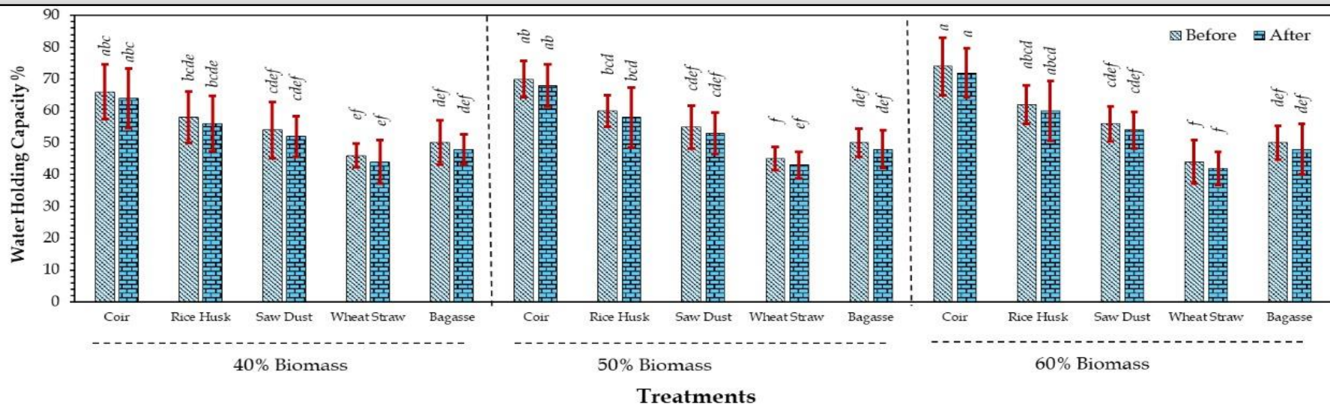

Figure 6: Water holding capacity (%) of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.2.4 Relationship between Bulk Density, Porosity, and Water Holding Capacity

Figure 7 illustrates the interaction between bulk density (0.40-0.90 g/cm³), porosity (40-100%), and WHC across different biomass types and levels. Coir showed higher bulk density with moderate porosity and strong WHC. Sawdust exhibited low bulk density and variable porosity with stable WHC. Rice husk, wheat straw, and bagasse showed intermediate values. WHC generally increased with bulk density in coir and rice husk, while wheat straw and bagasse showed a negative trend. Sawdust maintained consistent WHC regardless of bulk density.

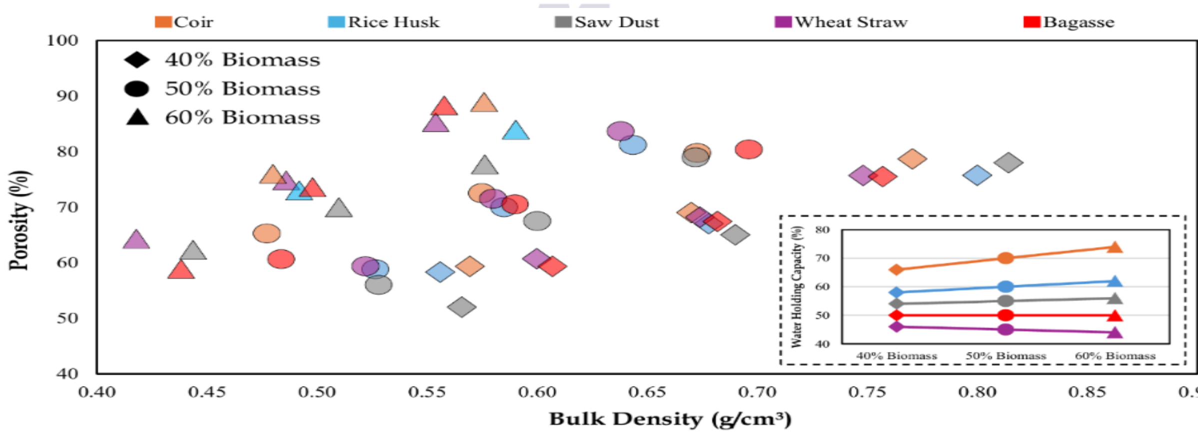

Figure 7: Relationship between bulk density and porosity in soilless growing media composed of different biomass materials at 40%, 50%, and 60% biomass levels.

3.3 Chemical properties of Optimized soilless growing media

3.3.1 Electrical Conductivity (EC)

Figure 8 shows EC values of soilless media before and after plant growth. Initial EC varied significantly (F=3.01, p=0.0063), with W40 (40% Wheat Husk) showing the highest (2.73 dS/m) and S60 (60% Sawdust) the lowest (1.52 dS/m), indicating biomass impact on salinity. Post-growth, EC differences were not significant (F=1.08, p=0.4181), suggesting convergence due to plant uptake. However, W40 remained highest (2.55 dS/m) and S60 lowest (1.83 dS/m), showing continued influence of biomass type.

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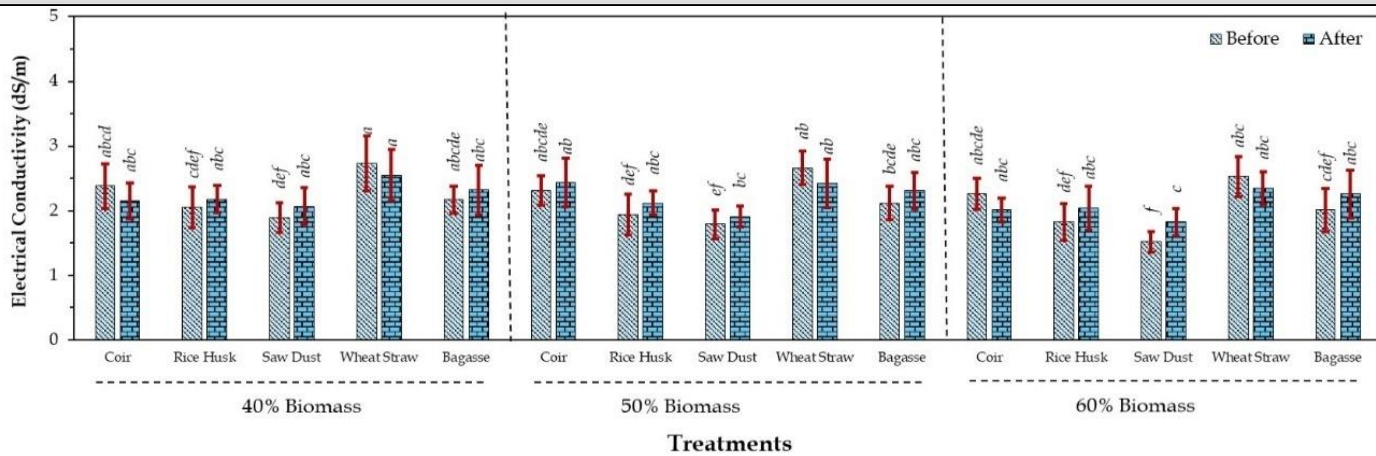

Figure 8: Electrical Conductivity of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.3.2 pH Level

Figure 9 shows pH levels of soilless media before and after the experiment. Initially, pH ranged from 5.53 to 6.52 with no significant differences, indicating slightly acidic and uniform conditions. The highest pH (6.52) was in 60% sawdust; the lowest (5.53) in 40% wheat husk. After the experiment, pH changes were minimal and still not significant. Most treatments showed a slight decrease, likely due to root exudates or microbial activity, with 60% sawdust remaining highest (6.27) and 50% coir lowest (5.61).

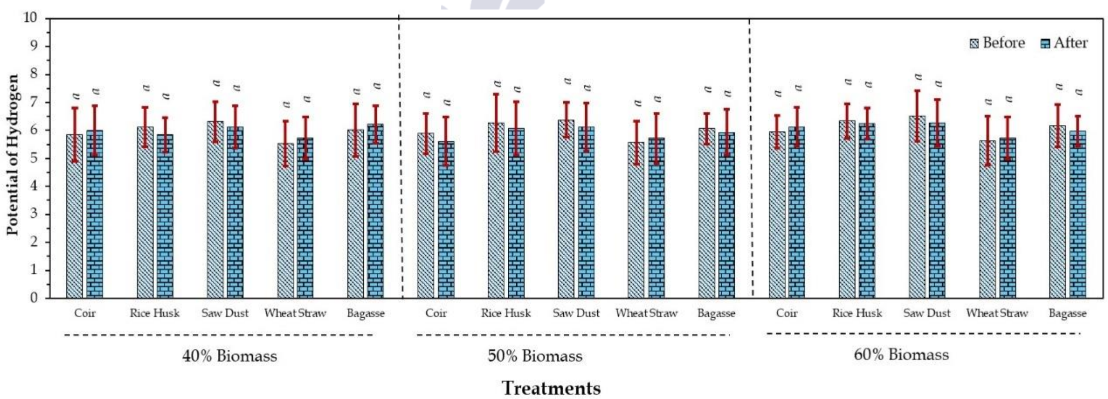

Figure 9: Electrical Conductivity of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4 Nutrient Content

3.4.1 Sodium (Na)

Figure 10 presents sodium concentrations in soilless growing media used for seasonal vegetables, before and after the pot experiment. ANOVA results showed significant treatment effects both before ($F(14,28) = 12.36$, $p < 0.0001$) and after ($F(14,28) = 15.29$, $p < 0.0001$) the experiment. Initially, Bagasse 50% (B50) had the highest sodium level (117.50 ppm), and Wheat Husk 40% (W40) the lowest (38.07 ppm). Post-experiment, B50 remained highest (104.30 ppm), while W40 still had the lowest (31.40 ppm), indicating a consistent sodium retention pattern across treatments.

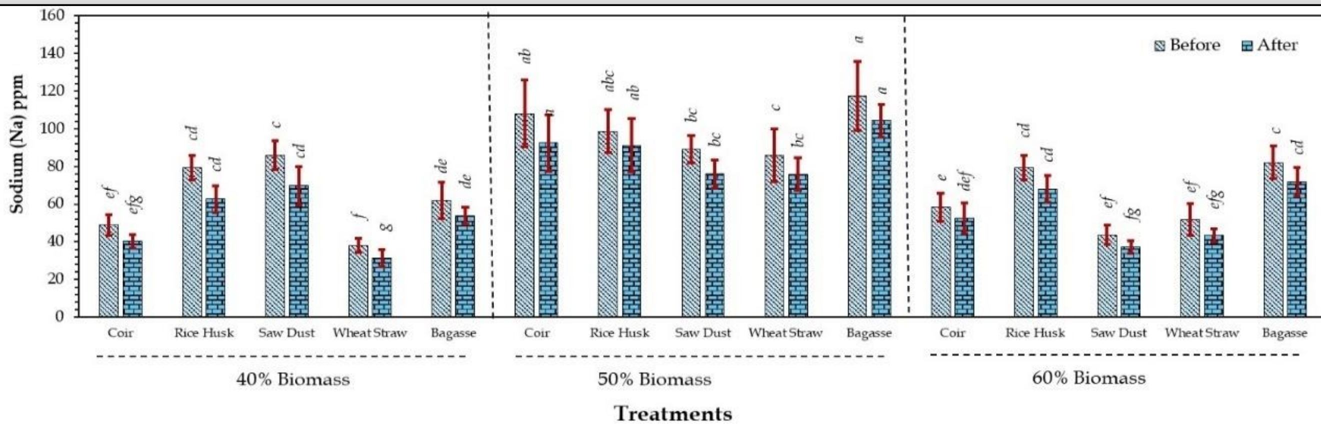

Figure 10: Sodium concentration of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments ($P < 0.05$).

3.4.2 Phosphorus (P)

Phosphorus concentrations varied significantly across treatments, with Bagasse 50% (B50) showing the highest levels both before (47.000 ppm) and after (43.100 ppm) the experiment, while Wheat Husk 40% (W40) consistently had the lowest (9.400 ppm before, 7.100 ppm after). ANOVA confirmed significant differences ($p < 0.0001$) at both stages, indicating consistent phosphorus availability patterns among treatments (Figure 11).

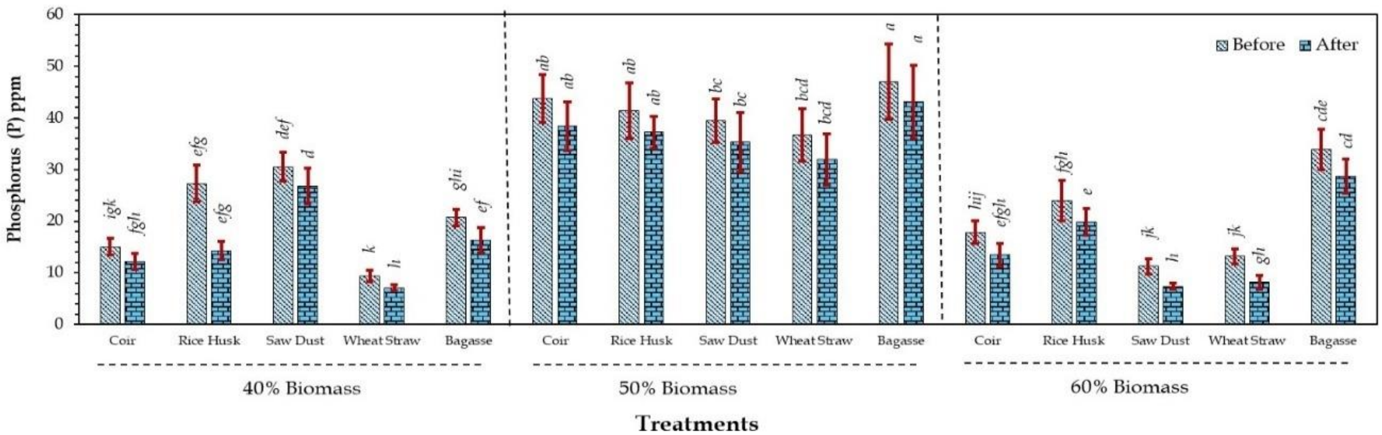

Figure 11: Phosphorus concentration of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments ($P < 0.05$).

3.4.3 Potassium (K)

Potassium levels varied significantly across treatments, with Bagasse 50% (B50) showing the highest concentrations before (45.120 ppm) and after (39.200 ppm) the experiment, and Wheat Husk 40% (W40) the lowest (8.460 ppm before, 6.503 ppm after). ANOVA confirmed significant differences ($p < 0.0001$), and reductions in K levels post-experiment indicate plant uptake during growth (Figure 12).

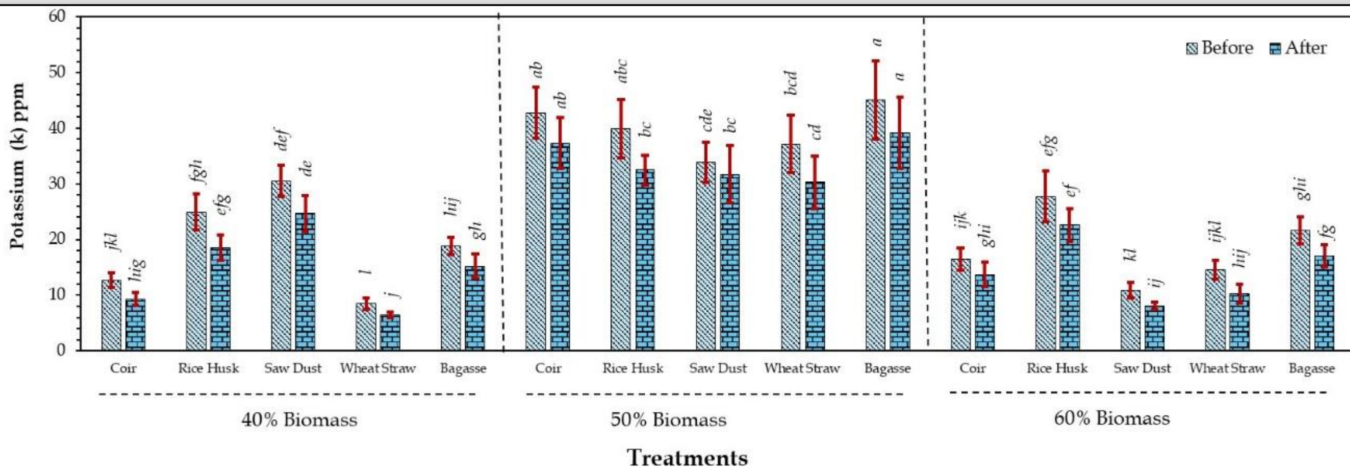

Figure 12: Potassium content of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4.4 Nitrogen (N)

Figure 13 illustrates significant differences in nitrogen (N) concentrations across treatments before (F = 10.01, p < 0.0001) and after (F = 12.15, p < 0.0001) the pot experiment. The C40 treatment (40% Coco peat/coir) had the highest nitrogen levels both before (564.00 ppm) and after (512.00 ppm), while R60 (60% Rice Husk) had the lowest (235.00 ppm before, 189.00 ppm after). Results indicate that biomass type significantly affects nitrogen retention, with coco peat enhancing and rice husk reducing nitrogen availability.

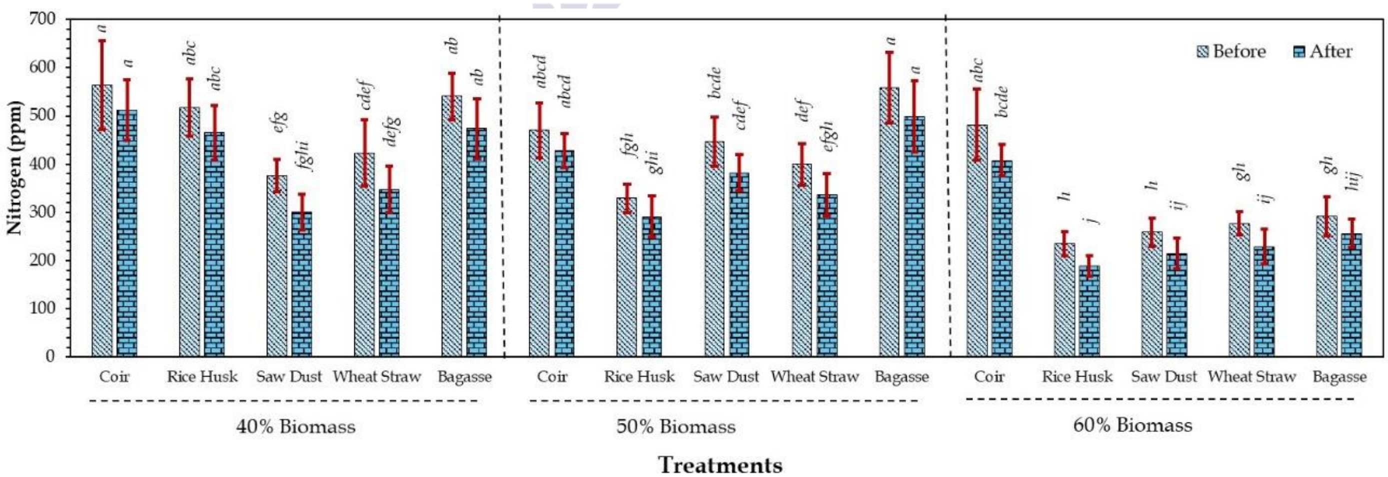

Figure 13 Nitrogen content of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4.5 Cation Exchange Capacity (CEC)

Figure 14 presents the impact of different soilless growing media on Cation Exchange Capacity (CEC) before and after the pot experiment. ANOVA results showed significant differences among treatments both before (F(14,28) = 14.05, p < 0.0001) and after planting (F(14,28) = 19.67, p < 0.0001). Initially, the C60 treatment (60% Coco peat/coir) had the highest CEC (15.600), while S60 (60% Saw Dust) had the lowest (5.500). After planting, W60 (60% Wheat Husk) had the highest CEC (12.700), and S50 (50% Saw Dust) the lowest (3.103). Overall, CEC values declined after plant growth across all treatments.

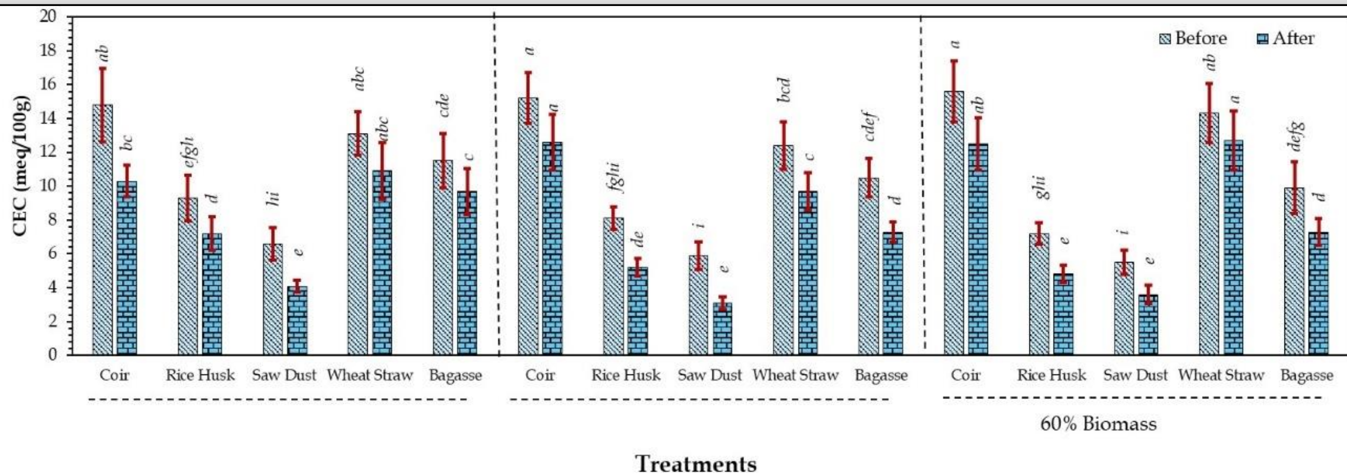

Figure 14: Cation Exchange Capacity of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4.6 Organic Carbon (OC)

Figure 15 illustrates the variation in Organic Carbon (OC) content across different soilless growing media before and after the pot experiment. ANOVA results showed significant treatment effects both before ($F = 9.45$, $p < 0.0001$) and after planting ($F = 14.84$, $p < 0.0001$). Initially, the C50 treatment (50% Coco peat/coir) recorded the highest OC value (1880.0 ppm), while W50 (50% Wheat Husk) had the lowest (846.0 ppm). After the experiment, the highest OC was in C40 (40% Coco peat/coir) at 1583.0 ppm, and the lowest was in R60 (60% Rice Husk) at 644.0 ppm.

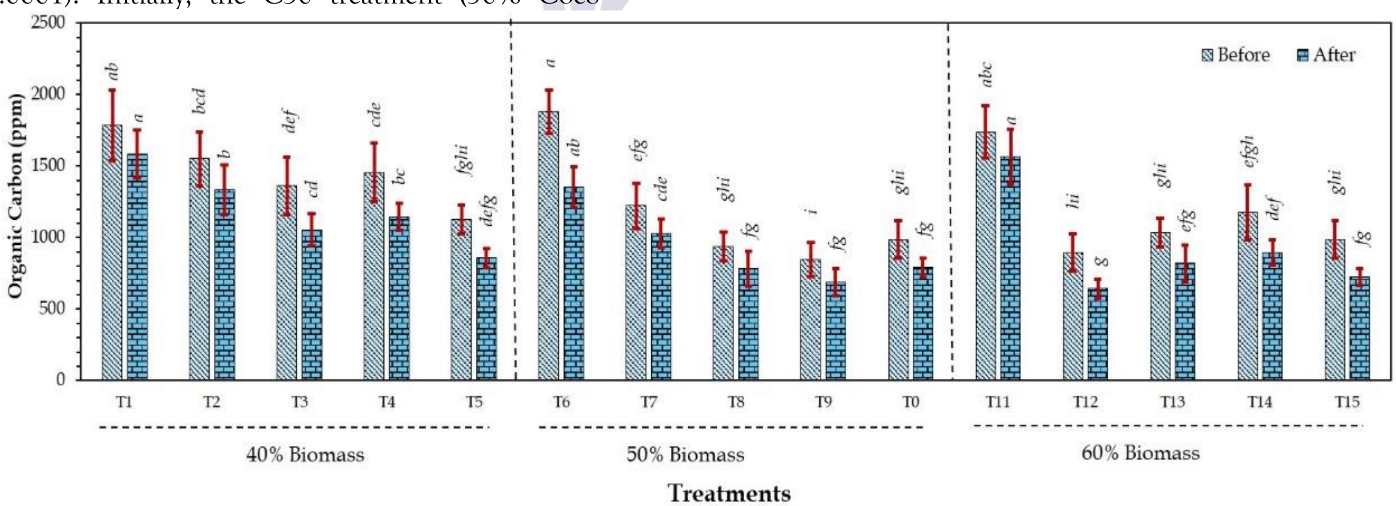

Figure16: Organic carbon content of soilless growing media at different biomass levels (40%, 50%, 60%) Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4.7 Carbon/Nitrogen Ratio (C/N)

Figure 17 presents the effect of soilless growing media on the Carbon/Nitrogen (C/N) ratio of various biomass-based substrates. Before planting, ANOVA showed a significant treatment effect ($F = 8.28$, $p < 0.0001$), with the highest C/N ratio in W60 (60% Wheat Husk) at 4.24 and the lowest in B50 (50% Bagasse) at 1.76. After the pot experiment, the treatment effect became non-significant ($F = 0.65$, $p = 0.7994$), with C50 and R60 showing the highest mean C/N ratio (1.39), and C60 (60% Coco peat/coir) the lowest (1.11). This decline suggests plant activity influenced nutrient dynamics in the media.

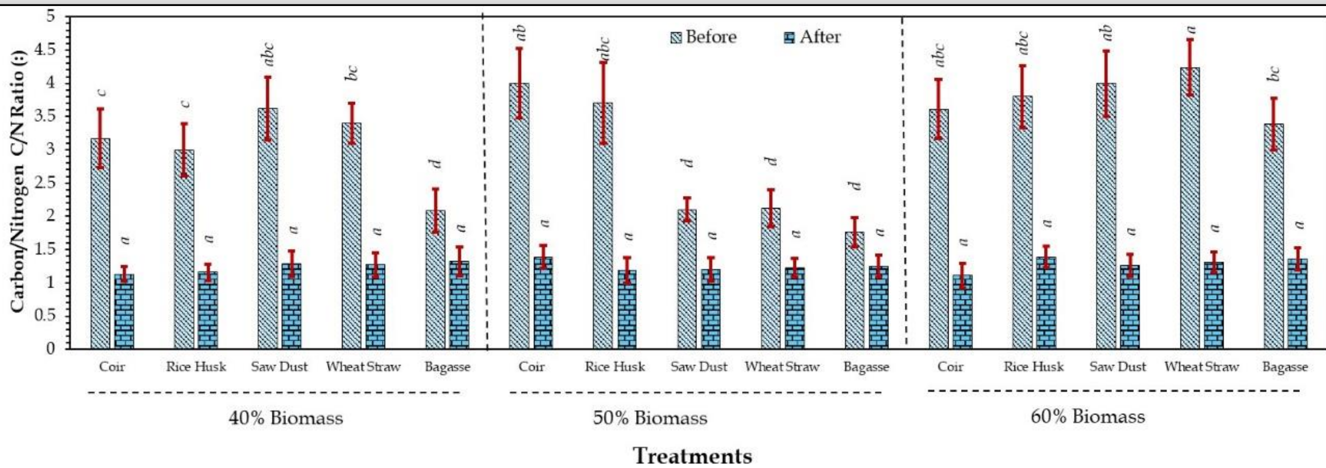

Figure 17: Carbon/Nitrogen ratio of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

3.4.8 Organic Matter % (OM)

Figure 18 illustrates the variation in Organic Matter (OM) content across different soilless media. Before the pot experiment, ANOVA showed significant differences among treatments (p = 0.0001), with the highest OM in C60 (48.000%) and the lowest in R60 (27.000%). After the experiment, C60 remained highest (45.000%) and R60 lowest (23.000%). The overall reduction in OM suggests decomposition occurred during plant growth.

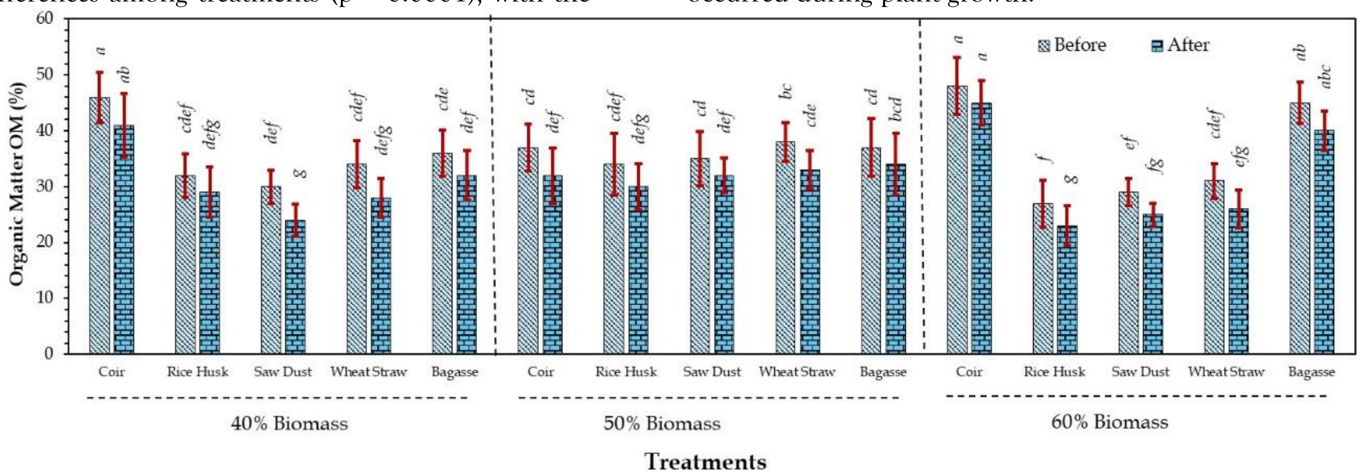

Figure 18: Organic Matter of soilless growing media at different biomass levels (40%, 50%, 60%). Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

4.5 Plant growth parameters

4.5.1 Plant height

Figure 19 highlights how plant height evolved during the crop cycle under different soilless media. Early growth (Week 1) showed minor height differences across treatments in both seasons. As the crop progressed, coir-based media (T6 and T11) led to markedly higher plant heights up to 100.5 cm and 116.3 cm by Week 16 demonstrating a significant advantage in vegetative growth. Bagasse treatments showed the lowest plant height consistently. ANOVA confirmed that 60% coir biomass treatments significantly enhanced plant height over time.

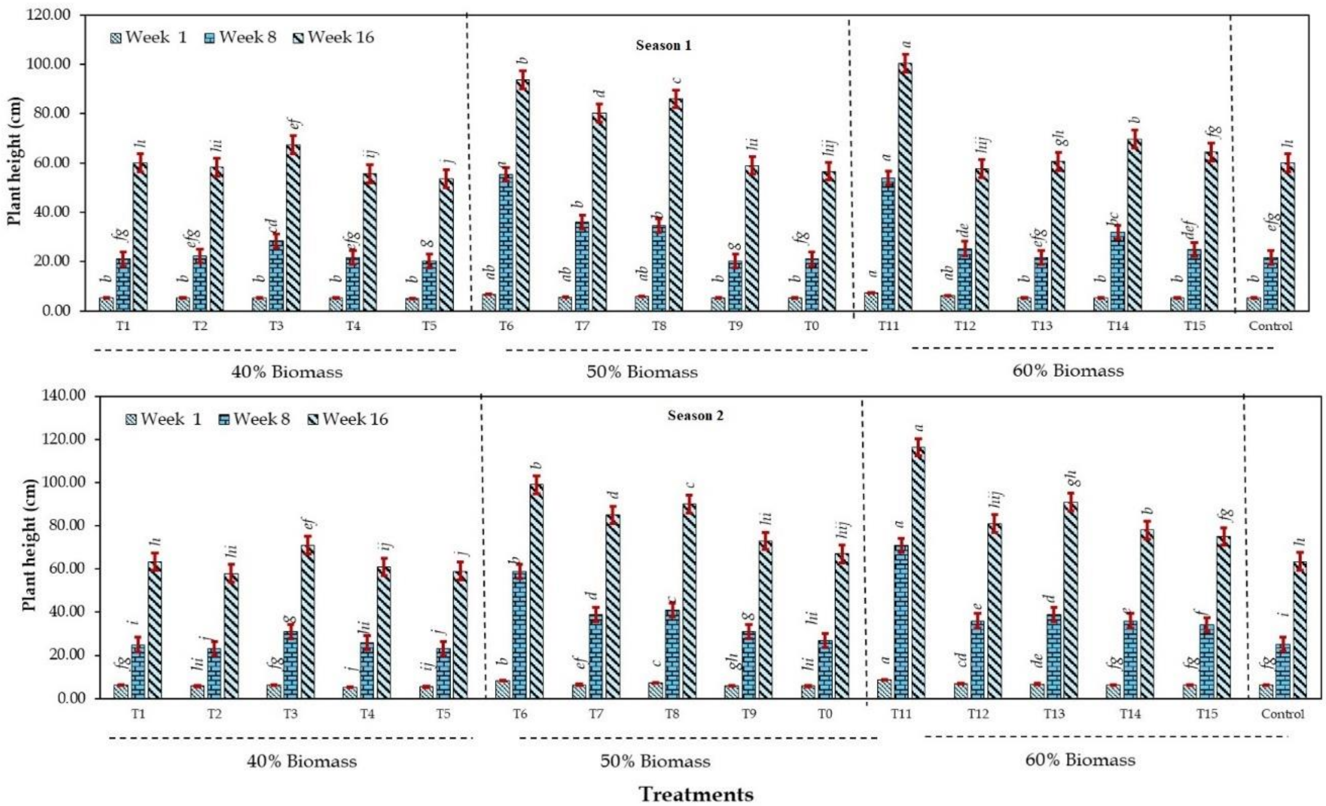

Figure 19: Two-season progression of plant height across different biomass treatments of soilless growing media. Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

4.5.2 Steam thickness (mm)

Figure 20 illustrates how stem thickness, an indicator of plant structural strength, varies with soilless media composition. Early measurements in Week 1 showed minimal differences among treatments. By Week 8, coir-based treatments (T6 and T11) had notably thicker stems (3.4-3.8 mm), indicating enhanced structural growth. By Week 16, coir treatments led with the greatest stem thickness (up to 9.5 mm), followed closely by sawdust (T8) and rice husk (T7). Bagasse and wheat straw treatments consistently had the lowest stem thickness throughout both seasons. Statistical analysis confirmed that coir-based media, particularly at 50% and 60% biomass levels, significantly promoted stronger stem development over time.

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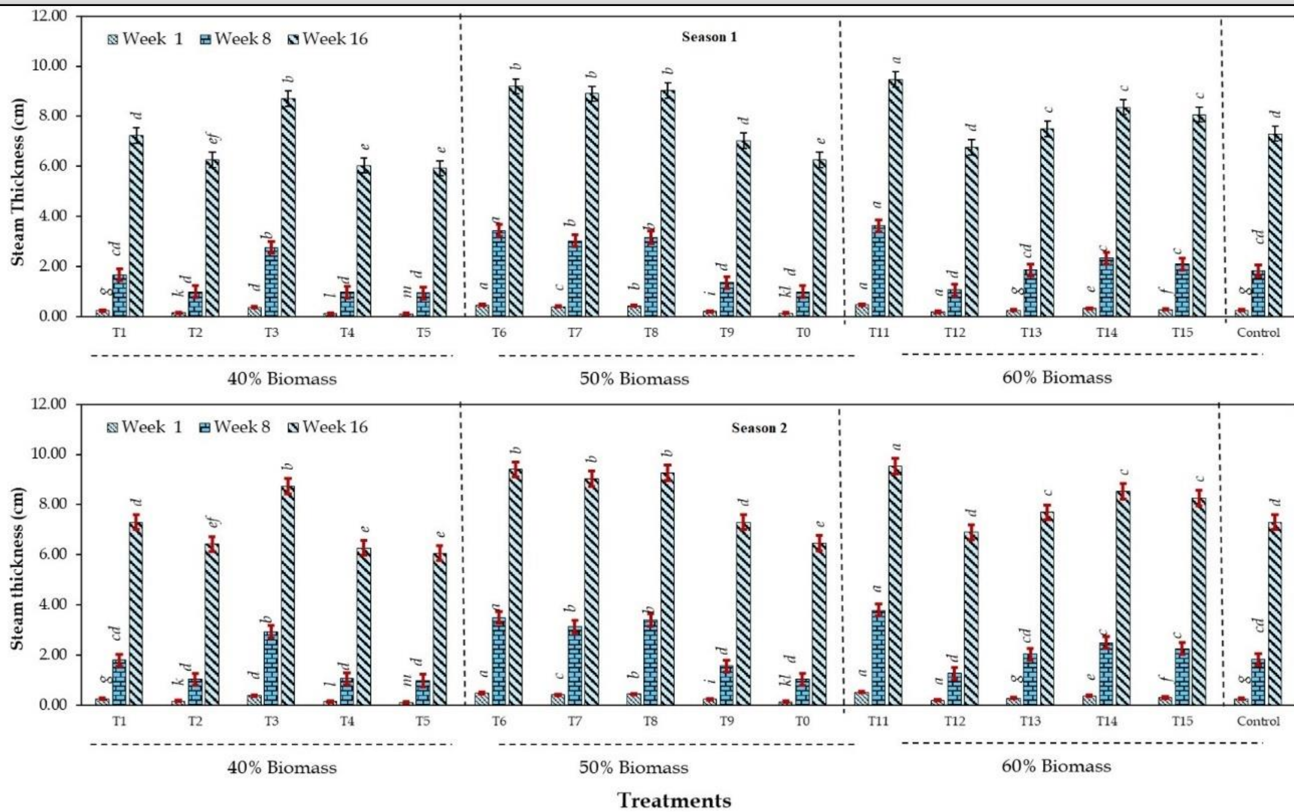

Figure 20: Two-season progression of stem thickness across different biomass treatments of soilless growing media.

Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

4.5.3 Number of leaves

Figure 21 shows the effect of soilless media on leaf production. At Week 1, leaf numbers were similar across treatments, with coir treatments (T6, T11) having a slight edge. By Week 8, coir media significantly increased leaf count (78–86 leaves), outperforming other treatments. By Week 16, coir treatments-maintained superiority with 122–130 leaves, while rice husk (T7) and sawdust (T8) followed with moderate leaf counts (102–108). Bagasse and wheat straw treatments had the lowest leaf numbers (33–71). Statistical analysis confirmed the coir's significant positive effect on leaf production, emphasizing media composition's role in enhancing photosynthetic capacity.

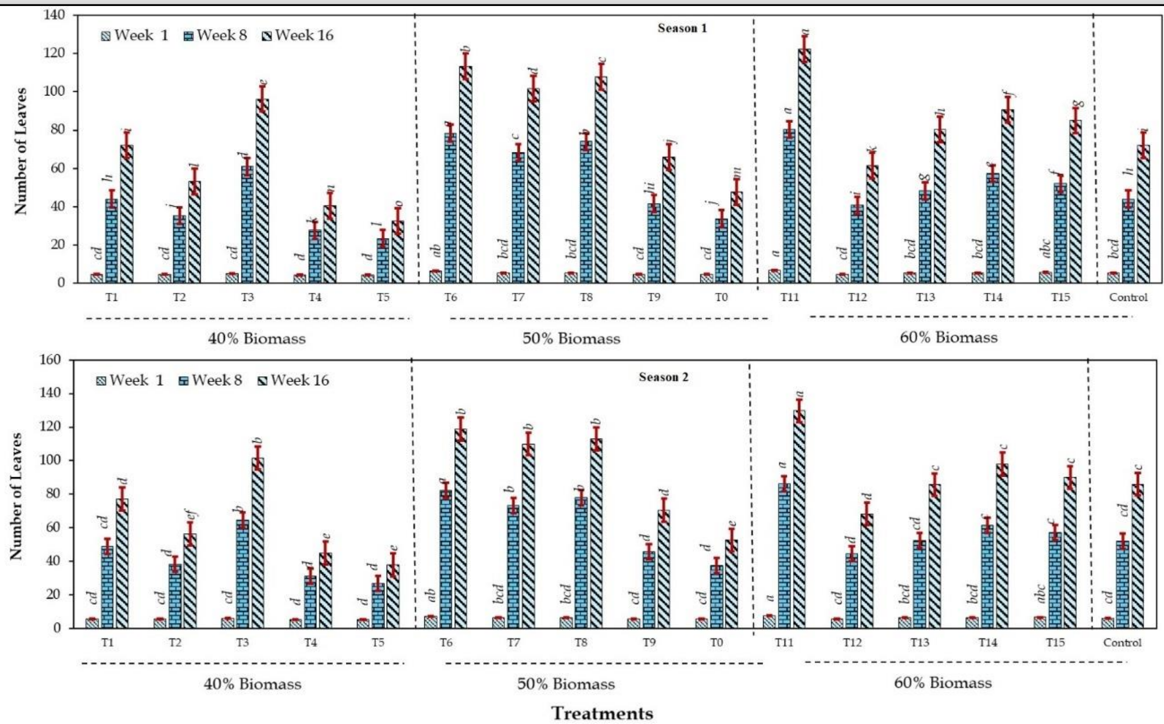

Figure 21 Two-season analysis of number of leaves across different biomass treatments of soilless growing media. Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

4.5.4 Number of flowers

Figure 22 illustrates the effect of soilless media on flower production. No flowers were observed at Weeks 1 and 8 in any treatment, reflecting early vegetative growth stages. By Week 16, coir-based treatments (T6 and T11) showed significantly higher flower counts, with T6 producing 51 and 56 flowers, and T11 producing 53 flowers in the first and second seasons, respectively. Rice husk (T7) and sawdust (T8) also performed well, with 46-51 flowers, while moderate flowering occurred in treatments T9 and T10 (28–38 flowers). Control treatment produced 39-40 flowers, and bagasse and wheat straw treatments had the lowest flower numbers. Statistical analysis confirmed that coir media significantly enhanced reproductive development, emphasizing substrate composition’s key role in flower production and potential fruit yield.

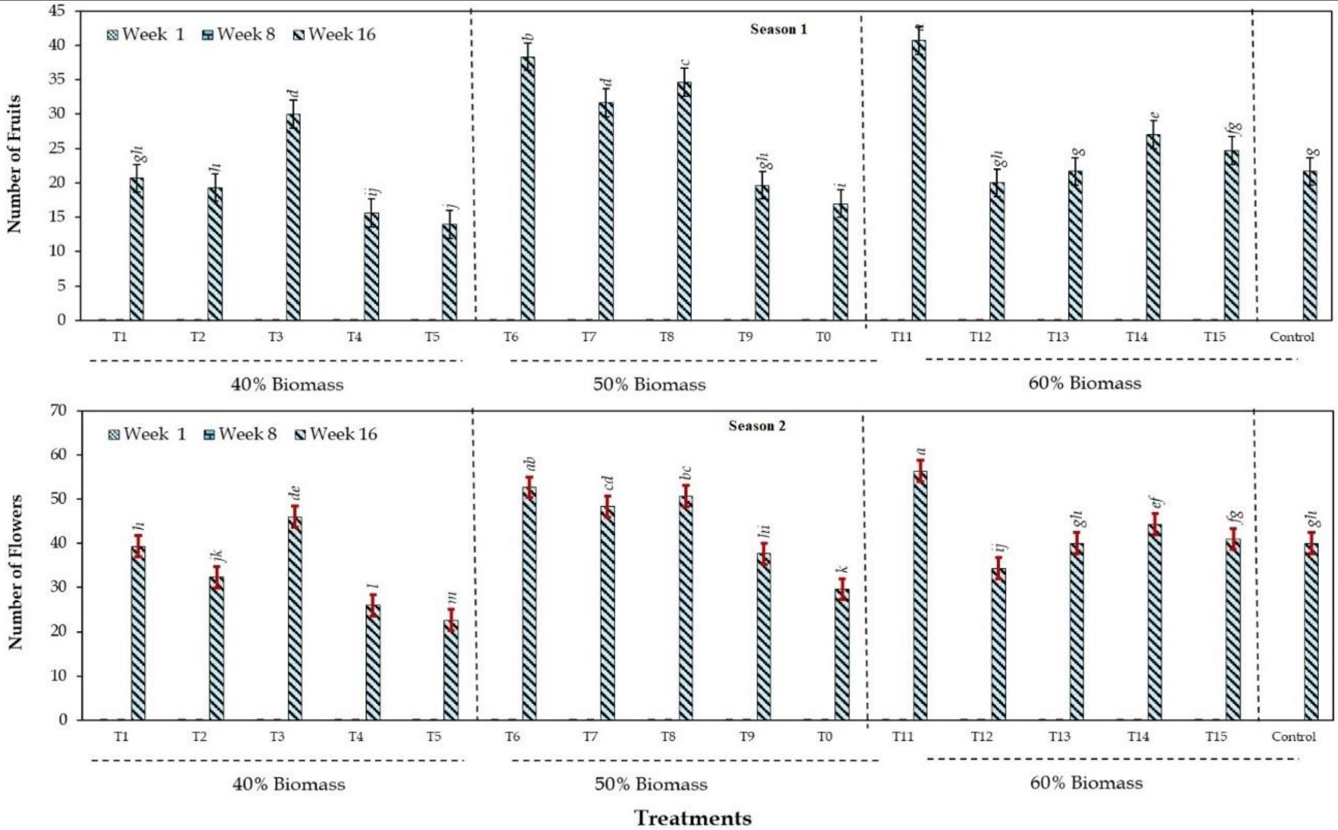

Figure 22: Two-season analysis of number of flowers across different biomass treatments of soilless growing media. Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

4.5.5 Number of fruits

Figure 23 presents the influence of soilless growing media on fruit production. No fruits were observed at Weeks 1 and 8 in either season, consistent with the typical delay in fruiting following flowering. By Week 16, significant differences emerged among treatments. Coir-based media (T6 and T11) produced the highest fruit counts, with 41 and 38 fruits in the first season and 42 and 37 in the second season, respectively, demonstrating a strong positive effect on fruit set and development. Rice husk (T7) and sawdust (T8) showed moderate fruit production (32-36 fruits), outperforming wheat straw (T9) and bagasse (T10), which had the lowest yields (17-22 fruits). The control treatment yielded moderately (22 fruits), while treatments T12, T14, and T15 produced the fewest fruits (16-28). Statistical analysis confirmed that coir treatments significantly enhanced fruit production, emphasizing the importance of substrate composition for optimizing crop yield and economic returns.

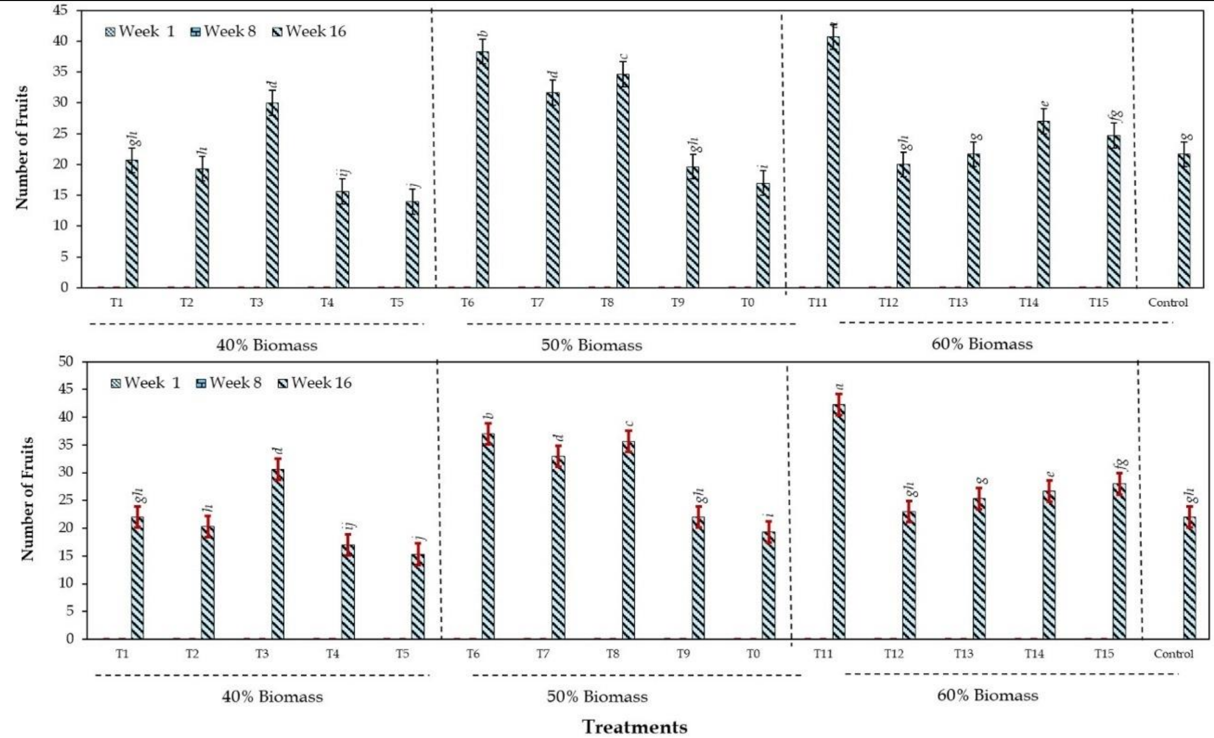

Figure 23: Two-season progression of the number of fruits across different biomass treatments of soilless growing media. Different letters within each treatment indicate significant difference among the treatments (P < 0.05).

5. Discussion

This study evaluated the efficacy of various soilless growing media compositions for seasonal vegetable cultivation, focusing on their physicochemical properties and influence on plant growth. The findings reveal distinct differences among biomass types, nutrient supplements, and stabilizers, offering insights to optimize soilless media formulations. The bulk density and porosity of the media were critical determinants of root environment quality. Coir-based media consistently exhibited favorable bulk densities (0.68–0.70 g/cm³) at higher biomass concentrations (60%), supporting optimal root penetration and aeration. These results align with prior research indicating that ideal soilless substrates maintain bulk densities between 0.40 and 0.80 g/cm³ to balance root growth and moisture retention (WALLACH, 2008a; Rus et al., 2023). Porosity ranged from 70% to 80%, with coir and rice husk demonstrating higher values conducive to enhanced aeration and drainage (Suhaimi et al., 2024). The fibrous structure of coir and the lightweight, porous nature of rice husk contributed significantly to these properties, promoting root health by preventing anaerobic conditions (Abellan-Garcia et al., 2023). Water holding capacity (WHC) further distinguished coir as a superior medium, reaching up to 85% at 60% biomass levels. This high WHC ensures sustained moisture availability essential for nutrient uptake and growth (Jana & Boxi, 2020). Rice husk also showed commendable WHC (70–80%), while bagasse and wheat straw had lower retention capacities, limiting their standalone efficacy for moisture management (Banitalebi et al., 2019b). Although high WHC is beneficial, excessive moisture can reduce aeration, emphasizing the need for media blends (Banitalebi et al., 2019b). Incorporating materials like rice husk or perlite with coir may optimize the balance between water retention and aeration.

The pH of all media was within the optimal range (5.5–6.5) for vegetable crops, facilitating nutrient availability (Schober et al., 2023). Slight pH declines observed by post-experiment are typical, likely driven by root exudates and microbial activity (Zaccheo et al., 2021). Electrical conductivity (EC) values varied from 1.5 to 2.7 dS/m, with wheat husk-based media exhibiting the highest EC. While these levels are generally acceptable, elevated EC warrants monitoring to avoid salt stress, particularly in sensitive species (J. Zhang et al., 2024).

Coir-based media showed enhanced cation exchange capacity (CEC), indicating improved nutrient retention and supply stability, crucial for reducing leaching and maintaining plant nutrient availability (Jana & Boxi, 2020). The observed reduction in CEC after cultivation reflects nutrient uptake and leaching losses, highlighting the dynamic nature of nutrient cycling in soilless systems. Stabilizers such as expanded clay and styrofoam exhibited distinct effects on media properties. Expanded clay improved water retention and soil structure, suitable for sandy soils requiring enhanced moisture conservation (Jiang et al., 2020). Styrofoam, characterized by low bulk density and minimal WHC, enhanced aeration, beneficial for preventing compaction in denser soils. Thus, stabilizer selection should be tailored to soil texture and crop-specific needs.

Coir-based media consistently promoted superior plant height and stem thickness, achieving heights between 100.5 and 116.3 cm and stem diameters of 9.3 to 9.5 mm by Week 16. These outcomes stem from coir's balanced physical and chemical attributes, including optimal moisture retention, nutrient content, and aeration, which support vigorous root and shoot development (Schober et al., 2023; Machado et al., 2021). Enhanced water availability in coir media likely mitigated drought stress effects, while good aeration prevented root diseases, corroborating findings by Dewi et al. (2020). The positive impact of coir on reproductive parameters further emphasizes its suitability for supporting full plant life cycles, consistent with studies linking substrate quality to improved flowering and fruiting (Gao et al., 2023; Feng et al., 2024). Overall, coir emerged as the most effective biomass component, owing to its superior water retention, aeration, nutrient balance, and CEC. Rice husk and sawdust exhibited moderate performance and represent viable alternatives where coir availability or cost is prohibitive, especially in blends that enhance media properties synergistically (Banitalebi et al., 2019b). Bagasse and wheat straw showed lower performance, likely due to inferior water retention and structural properties, though their conversion into biochar may improve their suitability (Tsai et al., 2023).

Conclusions

This research successfully developed, optimized, and evaluated environmentally friendly soilless growing media for seasonal vegetable cultivation using locally available materials in Tandojam, Sindh, Pakistan. A total of 75 initial media compositions derived from local biomass, nutrient supplements, and stabilizers were characterized, revealing significant variability in physico-chemical properties that influenced media performance. Through rigorous screening and greenhouse trials, 15 superior formulations were identified, with coco peat/coir-based media specifically treatments T6 (50% coco peat/coir, 25% compost, 25% pit sand) and T11 (60% coco peat/coir, 20% compost, 20% pit sand) demonstrating optimal water holding capacity, porosity, pH stability, and nutrient supply. These media significantly enhanced vegetative growth and reproductive yield of tomato and okra compared to other substrates. However, nutrient depletion during cultivation indicates the need for external fertilization to maintain productivity. Overall, this study highlights the potential of locally sourced biomass to produce cost-effective, sustainable soilless media that improve vegetable growth and yield under regional conditions. It is recommended from this study that future work should focus on developing tailored nutrient management strategies to ensure sustained crop productivity with these optimized media.

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