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Research Article

Sustainable Production of Lettuce Using Different Nutrient Solutions and Substrate Mixtures

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Abstract:

Using organic and eco-friendly alternatives, such as soil natural substrates and biofertilizers, helps preserve soil health, reduce chemical dependence, prevent pollution and promote sustainable agriculture practices. This study was carried out at Horticulture Department, Faculty of Agriculture, Tanta University during 2023 and 2024 growing seasons to investigate the effects of various substrate mixtures and nutrient solution sources on the growth, yield, and chemical composition of lettuce, aiming to identify optimal cultivation strategies. The results obtained revealed that sand + vermicompost (8:2) mixture emerged as the unequivocally superior growing medium. It consistently promoted enhanced photosynthetic efficiency (higher chlorophyll), robust vegetative development (greater plant height, increased leaf number and overall biomass), and significantly improved marketable yield (higher fresh and dry weights of lettuce heads). This substrate also demonstrated a remarkable ability to elevate the nutritional quality of lettuce leaves, leading to higher total protein and nitrogen content. Its comprehensive benefits are attributed to its optimal physical properties, sustained nutrient release, and the beneficial microbial activity contributed by vermicompost. The "organic + chemical" nutrient solution generally fostered superior overall vegetative growth and significantly enhanced the nutritional quality (protein and nitrogen content) of lettuce leaves. Collectively, using the combination of sand + vermicompost (8:2) as the substrate in conjunction with an "organic + chemical" nutrient solution could be an excellent substrate for plant development, biomass accumulation, and the nutritional profile of the harvested lettuce.

1. Introduction

Lettuce (*Lactuca sativa* L.) and various other vegetables are fundamental components of healthy diets worldwide, valued for their rich nutritional content, vitamins, and minerals. In Egypt, the cultivation of these crops holds significant economic and dietary importance, contributing substantially to both local consumption and agricultural exports (Saber et al., 2019; Sardo et al., 2024). The increasing demand for high-quality, sustainably produced vegetables drives the search for optimized cultivation practices that enhance productivity while simultaneously minimizing environmental impact.

Soilless farming is a cultivation technique by which crops are grown detached from the soil. Crops are grown in a container filled with several possible growing media with nutrients supplied. Soil substrate culture, a form of soilless cultivation, has emerged as a promising alternative to traditional open-field cultivation (El-Sayed et al., 2016). This method provides a controlled root environment, allowing for precise management of water, nutrients, and aeration, all crucial for optimal plant growth and yield. Among the widely utilized soil substrate materials, Peat moss is highly regarded for its excellent water retention capacity and aeration properties, providing a stable medium for root development (Esraa et al., 2019). Its acidic nature often requires pH adjustment, but its lightweight and sterility make it a popular choice. Vermicompost is a highly effective organic amendment that enriches soil structure, improves water retention, and provides a sustained release of essential nutrients, boosting beneficial microbial activity (Pramanik et al., 2007). It significantly increases lettuce yield, enhances leaf quality, and improves nutrient content (Hashem et al., 2014). Vermiculite is valued for its superior water retention and cation exchange capacity, which are vital for maintaining good aeration and consistent nutrient availability in the substrate. Its inclusion helps create an optimal root environment. Sand, typically washed river sand, is incorporated into substrates primarily to improve drainage and aeration, preventing waterlogging and promoting healthy root respiration (Hassan, 2005).

Optimizing the precise combination and proportion of these different substrate materials significantly influences plant performance, affecting germination rates, vegetative growth, and ultimately, marketable yield. This focus on tailored substrate mixtures aligns with global trends toward sustainable agriculture, aiming to reduce reliance on conventional soil and mitigate environmental risks while ensuring food security and quality through higher yields in controlled environments (Mohamed et al., 2015; Abu-Elela et al., 2018). Vermicompost has expanded its utilization in the form of water extracts commonly referred to as "teas," aqueous extracts. Vermicompost tea is prepared by steeping vermicompost in water with or without aeration to aid in the extraction of nutrients, other metabolites, and microorganisms during vermicomposting. One of the most important benefits of compost tea is improving soil fertility by supplying essential nutrients that can remediation nutritional efficiencies during plants growth (Zaccardelli et al., 2018). Application of vermicompost teas increase plant growth by improving the nutrient status of plants, enhancing beneficial microbial communities (Carpenter-Boggs, 2005).

The effects of organic and in-organic nutrient sources in soilless techniques on the growth and quality parameters of vegetables has been carried out by many researchers (Ortiz, 2020). Phibunwatthanawong and Riddech (2019) found that liquid organic fertilizer had similar growth promotion properties as in-organic fertilizer in the growth of green cos lettuce (*Lactuca sativa* var. longifolia). Also, studies on the effects of organic nutrient sources on field vegetable production had been reported (Aboyeji et al., 2021). Liedl et al. (2004) found that liquid effluent of digested poultry litter appeared to function as well as a commercial hydroponic fertilizer for tomatoes after balancing the forms of N (NO_3/NH_4) and supplementing with Ca $(NO_3)_2$ and $MgSO_4$. One of the major ingredients of soilless cropping is inorganic nutrients. However, the use of inorganic chemical nutrients for agriculture is relatively expensive worldwide (Timsina, 2018).

Therefore, the present study aimed to determine 1) the optimal components of different soil substrates (Peat moss, Vermicompost, Vermiculite, and Sand) for maximizing the growth parameters of lettuce, 2) the effect of different substrate cultures on the overall yield and quality characteristics of lettuce, 3) the most suitable soil substrate culture for sustainable and efficient production of lettuce under controlled conditions.

2. Materials and Methods

A pot experiment was carried out at Horticulture Nursery, Faculty of Agriculture, Tanta University for two autumn seasons of 2023 and 2024. The experiment aimed to investigate the use of vermicompost as a substrate amendment in different rates in alternate of peat moss and different nutrient solution sources on the lettuce growth under urban conditions. More or less, the management of urban farming is taken into consideration.

2.1. Plant materials

Lettuce (Romin type) hybrid seeds were sown in polystyrene trays containing peat moss mixed with vermiculite (1:1 v/v) on the 2^{nd} week of October in both cultivated seasons 2023 and 2024. After three weeks (the fourth - fifth true leaf stage), lettuce seedlings transplanted to the investigated substrate treatments in black plastic pots (Volume 5 L) in open system of drainage (one seedling per pot). The pots arranged on black polyethylene (mulch the ground) in 3 rows per bed, the final plant spacing was 20 cm in the row, 30 cm between the rows, and 70 cm in between the beds. Lettuce management practices were in accordance with standard recommendations for commercial growers.

2.2. The Vermicomposting process

The vermicompost provided from Central Lab. For Agricultural Climate (CLAC), Agricultural Research Center (ARC), Egypt. Different Epigiec types of earthworms, *Lumbriscus rubellus* (Red Worm), *Eisenia fetida* (Tiger Worm), *Perionyx excavatus* (Indian Blue) and *Eudrilus eugeniae* (African Night Crawler) (worm diameter: 0.5 – 5 mm and worm length: 10 – 120 mm) were implement in bed vermicomposting system to convert different organic wastes into vermicompost.

Mixing the different raw materials: vegetable and fruit wastes (V. F. W) + shredded paper (Sh. P) in the rate of 2: 2: 1 (v/v), respectively by mixing machine for 7 to 10 days before feeding it to worms with conserve the moisture of mixture in the range of 60 – 70 % to presented pre-composting. The composition of the different urban organic wastes was presented in Table (1). The physical and chemical properties of vermicompost were indicated in Table (2). The physical and chemical properties of vermicompost were estimated by soil, water and environmental research institute, Agriculture Research Center (ARC), Giza, Egypt.

Table 1. The chemical composition (%) of the different urban organic wastes.

Raw material	V. F. W	Sh. P	The mix
C/N ratio	62.60	166.81	78.18
N	0.34	0.016	0.78
P	0.19	0.01	0.31
K	0.64	0.00	0.73
Ca	0.81	0.20	0.81
Mg	0.43	0.01	0.59

Table 2. Physical and chemical properties of vermicompost.

Components	Value	Components	Value
B.D (Kg/m^3)	715	P %	1.27
O. M %	33.22	K %	0.59
C/N ratio	1:12.27	Fe (ppm)	802
pH	8.17	Mn (ppm)	143
EC (dS/m)	6.67	Zn (ppm)	37.0
N %	1.57	Cu (ppm)	14.0
N-NH_4 (ppm)	65	Pb (ppm)	9.0
N-NO_3 (ppm)	81		

2.3. Substrate system materials

Top-roof ground covered with black polyethylene 80 micron to protect the ground from the drainage solution. Pots of different substrates arranged in 3 rows / bed and placed in open drainage system. Sand was primarily washed with running tap water to get rid of the undesirable salts for twice then with diluted nitric acid to confirm salinity remove, then with running tap water to wash nitric acid compounds from the sand before use it as a grown substrate.

Table 3. The physical and chemical properties of different substrates.

Substrate	Physical			Chemical		
	B.D (Kg/L)	T.P.S (%)	W.H.C	A.P (%)	pH (1:10)	EC (dsm^{-1})
Peat: Vermiculite (1:1)	0.71	69.50	55.0	14.5	6.8	0.78
Sand: Vermicompost (9:1)	1.57	42.0	21.0	21.0	7.3	1.32
Sand: Vermicompost (8:2)	1.44	44.0	24.5	19.5	7.4	1.62
Sand: Peat (1:1)	0.89	60.1	43.2	16.9	6.9	0.35
Sand: Peat (2:1)	1.14	59.4	47.6	12	7.15	0.57

Bulk density (B.D), Total poor space (T.P.S), Water holding capacity (W.H.C), Air porosity (A.P), Organic matter (O.M).

The chemical and physical properties of soil and vermicompost in both seasons are presented in Table (1) and (2). After sand was getting dry, it mixed with different vermicompost and/or peat moss in different proportions depending on the different treatments under the investigation. The different rates of these mixes depend on the volume of each compound.

Table (3) presented the physical and chemical properties of different sand mixtures with vermicompost, and peat moss. Each plastic pot (6 L capacity) filled with 5 L of different substrates depending on the treatment. Each pot has bottom holes to drain the surplus of the nutrient solution. The different substrate mixtures were modified to the required volume on the second season. Lettuce plants irrigated manually depending on the season water requirements that are calculated by Central Laboratory for Agricultural Climate (CLAC), Agricultural Research Center, Egypt

2.4. Nutrient solution sources

1 - The chemical nutrient solution used in the experiment was provided by CLAC that adapted from Cooper, (1979) and modified by Abul-Soud et al. (2016).

2 Vermicompost-tea (Vermi-tea) was prepared by soaking 10 kg of vermicompost in water tank (50 L) for 12 - 24 hours (aerobic extract) to have the concentrated source of organic nutrient solutions. Filtration of vermicompost tea was not necessary regarding the manual irrigation.

3. Chemical + Vermi-tea, first: vermicompost tea was added to water tank (50 L) regarding the greater amount of vermin-tea to reach 500 ppm then chemical nutrient solution implemented to get the required level of 1000 ppm.

The EC of the different nutrient solutions were adjusted by using EC meters to the required level (1000 ppm). The chemical composition of different nutrient solutions is illustrated in Table (4).

2.5. The study treatments

Two factors were investigated under the current study as follows:

First factor: Substrates mixtures

A. Peat moss: vermiculite (1:1 v/v) (control) (SM1)
B. Sand : vermicompost (9:1 v/v) (SM2)
C. Sand : vermicompost (8:2 v/v) (SM3)
D. Sand : peat moss (1:1 v/v) (SM4)
E. Sand : peat moss (2:1 v/v) (SM5)

Second factor: nutrient solution source

1. Vermicompost-tea (VCT)
2. Chemical nutrient solution (CF)
3. Chemical+vermicompost-tea nutrient solution (CF+VCT)

2.6. Experimental design

A factorial experiment in a randomized complete block design was conducted, with two factors. The experiment contained 15 treatments; each treatment was replicated three times (9 plants / replicate).

2.7. Measurements

2.7.1. Vegetative growth and yield parameters

After 8 weeks from the transplanting date, three samples from each replicate were randomly collected to evaluate the following growth and yield parameters of lettuce:

Plant height (cm), number of leaves, plant fresh and dry weight (g), (dry matter were determined after oven-drying the samples of the lettuce at 70 ºC for 48 hours).

2.7.2 Chemical analysis of lettuce plants

Total chlorophyll content was measured by Minolta chlorophyll meter SPAD-502 according to Yadava (1986). Total protein was estimated using the micro-Kjeldahl method, with a nitrogen-to-protein conversion factor of 6.25 (Jones, 1931). Mineral analysis (N, P and K), plant samples of each replicate were dried at 70o C in an air forced oven for 48 h. and dried plants were digested in H_2SO_4 according to the method described by Allen (1974) and N, P and K contents were estimated in the acid digested solution. Total nitrogen was determined by micro Kjeldahl method according to the procedure described by Black et al. (1965). Phosphorus content was determined using spectrophotometer according to Watanabe and Olsen (1965). Potassium content was determined photo-metrically using Flame photometer as described by Chapman and Pratt (1961).

2.8 Statistical analysis

Analysis of data was performed using SAS (Statistical Analysis System) program for statistical analysis. The differences among means for all traits were tested for significance at 5 % level according to Waller and Duncan (1969).

Table 4. The chemical composition of different sources of nutrient solutions.

Nutrient source	Macronutrients (ppm)					Micronutrients (ppm)					
	N	P	K	Ca	Mg	Fe	Mn	Zn	B	Cu	Mo
Chemical.	140	40	240	150	48	3.0	0.8	0.4	0.5	0.25	0.02
Vermi-tea	103	12	190	90	34	4.25	1.50	0.26	0.31	0.20	.025
Chemical +Vermi-tea	122	27	165	120	41	3.6	1.2	0.30	0.35	0.20	0.02

3. Results and discussion

3.1. Growth and yield

The fertilizers solution types of chemicals, compost tea, and their interaction gave a significant impact on the plant height, leaf length, and number of leaves/plants, (Tables 5). The tallest lettuce plants and leaves (36.4 and 36.2 cm, and 16.0, and 15.8 cm for plant height and leaf length for both seasons, respectively) were obtained in those plants treated with a mixture of CF +VCT, followed by CF treatment alone (34.2 and 33.6 cm, for plant height and 15.0 and 14.8 cm for leaf length, respectively), for both seasons. In the same Table, the effect of different substrates mixture on the growth traits showed that SM3 gave the tallest plants but SM2 gave the shortest plants. The lettuce plants cultured in SM3 which received CF+VCT exhibited the tallest plants (42.8 and 42. 6 cm for the two seasons, respectively), and highest leaf length (18.8 and 18.7 cm for the two seasons, respectively).

The highest number of leaves per plant was observed in plants grown in the SM3. Treated plants with a mixture of CF+ VCT gave the highest value followed by a CF treatment, while VCT treatment gave the lowest value in this respect. Regarding the interaction, the highest leaves number per plant was given by lettuce plants of SM3 and CF+VCT treatment in both seasons (Table 5).

The results in Table 6 revealed that the mixture substrate of SM3 gave the heaviest fresh weights followed by SM2 treatment. On the other hand, SM1 substrate gave the lowest weight in both seasons. The data regarding application of a nutrient solution of CF+VCT had the highest value of fresh and plant dry weight, followed by CF treatment. VCT treatment was found to be less effective compared to other treatments for weight analysis. The lettuce plants grown in SM3 which received CF+VCT exhibited the heaviest fresh and dry weights for the two seasons. Litterick et al. (2004) found that using organic compost can improve the physical, chemical and biological properties of growing medium. Replacement of peat with moderate amounts of vermicompost produces beneficial effects on plant growth due to the increase on the bulk density of the growing media and decrease total porosity and amount of readily available water in the soil. In soilless lettuce farming, both vermicompost tea and chemical fertilizers can positively impact plant growth and biomass yield, in different effects. Vermicompost tea enhances important aspects of lettuce quality, e.g. antioxidant properties and nutrient content, while chemical fertilizers may promote faster growth and higher yields in the initial stages. Chemical fertilizers can result in higher initial yields compared to organic treatments (Abdel-Haleem et al., 2022).

Using vermicompost tea aqueous extract has been found to increase plant health, crop production, and nutritional quality (Gamaley et al., 2001; Pant et al., 2013). Though the tea's content organic acids, and plant growth regulators have a favorable influence on early root formation and plant growth (Edwards et al., 2006; Pant et al., 2012). Compost tea contains live microorganisms that may boost nutrient absorption and plant development (Scheuerell and Mahaffee, 2002; Hargreaves et al., 2008). Additionally, vermicompost tea contains more nitrate, which is the more easily absorbed type of nitrogen for plants and releases nutrients rapidly (Manivannan et al., 2009; Mupondi et al., 2010). The most raise in the number of leaves per plant consequently plant weight was obtained in CF+VCT treatment in both seasons. Liquid organic fertilizers boost plant production, microbial communities in the soil, and mineral nutrient quality of the plants. Also, it has a high concentration of beneficial bacteria, which has been shown to improve plant growth by increasing soil fertility and mineral concentration in plant tissue (Fritz, 2012).

3.2. Chemical Composition

Data presented in Table 7 showed the effect of different nutrient solutions on total chlorophyll content and protein in lettuce leaves grown under different mixtures of substrates. For total chlorophyll and protein content, the results indicated that their values increased when lettuce plants received CF+VCT fertilization as compared with the other treatments. Generally, CF+VCT had the highest chlorophyll (36.14- 34.3%) and protein (11.8 %) value followed by CF, in both seasons.

Table 5. Effect of different substrate mixtures, nutrient solution sources, and their interaction on plant height (cm), average leaf length (cm), and number of leaves/plant of lettuce during 2023and 2024 seasons.

Treatment		Plant height (cm)		Average leaf length (cm)		Number of leaves/plant	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
Substrate							
Peat: Vermiculite (1:1)		31.6±1.2^{cd}	31.3±1.4^{cd}	13.92±0.48^{c}	13.76±0.54^{cd}	18.36±0.33^{cd}	18.05±0.42^{c}
Sand: Vermicompost (9:1)		36.6±1.0^{b}	36.3±1.1^{b}	16.05±0.45^{b}	15.92±0.48^{b}	21.51±0.56^{b}	21.34±0.61^{b}
Sand: Vermicompost (8:2)		40.1±1.1^{a}	39.7±1.3^{a}	17.63±0.44^{a}	17.46±0.49^{a}	22.67±0.61^{a}	22.43±0.63^{a}
Sand: Peat (1:1)		29.5±0.8^{d}	29.2±0.9^{d}	12.95±0.32^{d}	12.84±0.35^{d}	17.56±0.45^{d}	17.10±0.31^{d}
Sand: Peat (2:1)		32.4±0.9^{c}	32.2±1.0^{c}	14.27±0.35^{c}	14.13±0.40^{c}	18.75±0.22^{c}	18.45±0.29^{c}
Solution							
VCT		31.6±1.0^{c}	31.4±1.1^{b}	13.90±0.44^{c}	13.82±0.46^{c}	18.71±0.45^{c}	18.58±0.48^{c}
CF		34.2±1.1^{b}	33.6±1.2^{b}	15.03±0.50^{b}	14.76±0.50^{b}	19.68±0.55^{b}	19.45±0.59^{b}
CF+VCT		36.4±1.3^{a}	36.2±1.4^{a}	15.95±0.54^{a}	15.88±0.58^{a}	20.91±0.71^{a}	20.39±0.77^{a}
Substrate× Solution							
Peat: Vermiculite (1:1)	VCT	29.7±1.3^{a}	29.2±2.5^{a}	13.19±0.51^{a}	12.93±0.93^{a}	18.24±0.42^{f}	17.87±1.06^{fg}
	CF	32.0±1.9^{a}	31.5±1.0^{a}	14.08±0.87^{a}	13.81±0.34^{a}	18.00±0.47^{f}	18.27±0.94^{ef}
	CF+VCT	33.0±2.9^{a}	33.2±3.4^{a}	14.48±1.16^{a}	14.54±1.36^{a}	18.85±0.87^{ef}	17.99±0.26^{f}
Sand: Vermicompost (9:1)	VCT	33.6±1.5^{a}	33.7±1.1^{a}	14.69±0.61^{a}	14.76±0.43^{a}	19.76±0.66^{de}	19.87±0.48^{de}
	CF	36.5±0.7^{a}	35.9±2.2^{a}	16.04±0.37^{a}	15.75±0.87^{a}	21.59±0.34^{c}	21.22±1.29^{cd}
	CF+VCT	39.7±0.4^{a}	39.3±1.1^{a}	17.41±0.30^{a}	17.24±0.47^{a}	23.18±0.56^{b}	22.93±0.45^{ab}
Sand: Vermicompost (8:2)	VCT	37.2±1.0^{a}	37.0±1.5^{a}	16.40±0.29^{a}	16.29±0.53^{a}	20.94±0.25^{cd}	20.76±0.42^{cd}
	CF	40.3±1.5^{a}	39.6±1.8^{a}	17.72±0.73^{a}	17.39±0.68^{a}	22.32±0.54^{bc}	21.93±0.78^{bc}
	CF+VCT	42.8±1.6^{a}	42.6±2.3^{a}	18.76±0.52^{a}	18.69±0.85^{a}	24.74±0.66^{a}	24.61±0.20^{a}
Sand: Peat (1:1)	VCT	27.2±0.9^{a}	27.2±0.8^{a}	11.96±0.31^{a}	11.94±0.28^{a}	16.23±0.20^{g}	16.20±0.19^{g}
	CF	29.5±0.8^{a}	29.0±1.5^{a}	12.98±0.42^{a}	12.75±0.60^{a}	17.65±0.81^{fg}	17.30±0.59^{fg}
	CF+VCT	31.7±0.5^{a}	29.0±1.5^{a}	13.91±0.10^{a}	13.82±0.42^{a}	18.80±0.28^{ef}	17.79±0.36^{fg}
Sand: Peat (2:1)	VCT	30.1±0.8^{a}	30.0±1.2^{a}	13.28±0.23^{a}	13.19±0.43^{a}	18.39±0.31^{ef}	18.22±0.27^{ef}
	CF	32.6±1.2^{a}	32.1±1.5^{a}	14.34±0.59^{a}	14.08±0.55^{a}	18.86±0.45^{ef}	18.54±0.83^{ef}
	CF+VCT	34.6±1.3^{a}	34.5±1.9^{a}	15.19±0.42^{a}	15.13±0.69^{a}	19.00±0.42^{ef}	18.60±0.46^{ef}
p-value							
Substrate		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Solution		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Substrate × Solution		0.9939^{ns}	0.9998^{ns}	0.9767^{ns}	0.9992^{ns}	0.0312*	0.0473*

VCT = Vermicompost-tea; CF = Chemical nutrient solution; Data (means ± SE) *, **, and *** indicate, differences at $p \le 0.05$, 0.01, and ≤0.001 probability levels, and "ns" indicates a non-significant difference. Mean values sharing the same lower-case letter for substrate, soluation, and their interactions in the same column are not significantly different at $p \le 0.05$ from Duncan's test.

Table 6. Effect of different substrate mixtures, nutrient solution sources, and their interaction on plant fresh weight (g), and plant dry weight (g) of lettuce during 2023and 2024 seasons.

Treatment		**Plant fresh weight (g)**		**Plant dry weight (g)**	
		1st season	**2nd season**	**1st season**	**2nd season**
Substrate					
Peat: Vermiculite (1:1)		287.54±5.07^{c}	274.19±4.73^{cd}	36.37±0.76^{bc}	35.72±0.75^{bc}
Sand: Vermicompost (9:1)		333.48±8.72^{b}	330.87±9.45^{b}	44.73±1.44^{a}	44.05±1.44^{a}
Sand: Vermicompost (8:2)		351.47±9.48^{a}	347.82±9.72^{a}	46.38±1.44^{a}	45.35±1.32^{a}
Sand: Peat (1:1)		272.28±6.97^{d}	267.33±5.55^{d}	34.71±1.03^{c}	34.37±1.01^{c}
Sand: Peat (2:1)		294.15±4.14^{c}	282.86±3.26^{c}	37.26±0.68^{b}	36.45±0.54^{b}
Solution					
VCT		290.19±6.99^{c}	286.63±7.32^{c}	37.24±1.09^{c}	36.97±1.10^{c}
CF		306.81±8.22^{b}	297.33±9.44^{b}	39.95±1.23^{b}	38.98±1.24^{b}
CF+VCT		326.35±10.71^{a}	317.89±11.48^{a}	42.48±1.81^{a}	41.62±1.69^{a}
Substrate× Solution					
Peat: Vermiculite (1:1)	VCT	283.09±7.14^{f}	269.52±10.90^{fg}	35.38±1.53^{gh}	34.55±1.56^{de}
	CF	287.26±7.53^{ef}	272.00±9.07^{fg}	36.62±1.74^{g}	35.69±1.05^{d}
	CF+VCT	292.28±13.42^{ef}	281.04±5.51^{f}	37.11±0.86^{fg}	36.93±1.37^{d}
Sand: Vermicompost (9:1)	VCT	306.32±10.16^{de}	308.03±7.38^{de}	40.89±1.37^{def}	41.12±0.99^{c}
	CF	334.70±5.31^{c}	329.01±19.99^{cd}	43.44±0.59^{cd}	42.70±2.57^{bc}
	CF+VCT	359.43±8.62^{b}	355.57±7.02^{b}	49.86±1.19^{ab}	48.33±1.75^{a}
Sand: Vermicompost (8:2)	VCT	324.75±3.81^{cd}	321.92±6.44^{cd}	41.77±0.99^{de}	41.37±0.43^{c}
	CF	346.05±8.38^{bc}	340.0±12.14^{bc}	46.50±0.80^{bc}	45.06±1.52^{b}
	CF+VCT	383.61±10.23^{a}	381.55±3.12^{a}	50.86±1.64^{a}	49.63±1.16^{a}
Sand: Peat (1:1)	VCT	251.69±3.09^{g}	251.16±2.89^{g}	31.92±1.30^{h}	31.85±1.24^{e}
	CF	273.67±12.58^{f}	268.18±9.13^{fg}	35.85±1.00^{g}	35.20±1.47^{d}
	CF+VCT	291.47±4.29^{ef}	282.65±5.43^{f}	36.36±2.06^{g}	36.07±1.86^{d}
Sand: Peat (2:1)	VCT	285.12±4.86^{ef}	282.53±4.22^{f}	36.25±1.16^{g}	35.95±1.44^{d}
	CF	292.36±6.91^{ef}	277.46±7.14^{f}	37.34±1.64^{fg}	36.27±0.53^{d}
	CF+VCT	304.97±5.80^{de}	288.58±5.25^{ef}	38.19±0.78^{efg}	37.13±0.62^{d}
p-value					
Substrate		<0.001***	<0.001***	<0.001***	<0.001***
Solution		<0.001***	<0.001***	<0.001***	<0.001***
Substrate × Solution		0.0455*	0.0424*	0.0446*	0.0418*

VCT = Vermicompost-tea; CF = Chemical nutrient solution; Data (means ± SE) *, **, and *** indicate, differences at $p \leq 0.05$, 0.01, and ≤0.001 probability levels, and "ns" indicates a non-significant difference. Mean values sharing the same lower-case letter for substrate, soluation, and their interactions in the same column are not significantly different at $p \leq 0.05$ from Duncan's test.

Table 7. Effect of different substrate mixtures, nutrient solution sources, and their interaction on total chlorophyll content (mg/100 g FW), and protein (%) of lettuce during 2023 and 2024 seasons.

Treatment		Total chlorophyll content (mg/100 g FW)		Protein (%)	
Substrate		**1st season**	**2nd season**	**1st season**	**2nd season**
Peat: Vermiculite (1:1)		32.26±0.80bc	29.53±0.37cd	10.39±0.18c	9.79±0.23b
Sand: Vermicompost (9:1)		36.89±1.19a	36.56±1.08b	12.05±0.31b	12.59±0.54a
Sand: Vermicompost (8:2)		36.94±1.78a	38.67±1.08a	12.70±0.34a	12.80±0.45a
Sand: Peat (1:1)		30.25±0.98c	28.67±0.38d	9.84±0.25d	9.60±0.20b
Sand: Peat (2:1)		32.77±0.73b	30.61±0.28c	10.63±0.15c	9.83±0.28b
Solution					
VCT		32.46±0.86b	31.38±0.85c	10.48±0.25c	10.08±0.31c
CF		32.86±0.86b	32.66±1.05b	11.09±0.30b	10.81±0.38b
CF+VCT		36.14±1.33a	34.38±1.50a	11.79±0.39a	11.88±0.57a
Substrate× Solution					
Peat: Vermiculite (1:1)	VCT	32.53±1.91de	28.86±0.65ef	10.22±0.26h	9.18±0.29f
	CF	31.95±1.38def	29.42±0.52ef	10.38±0.27fgh	10.03±0.49ef
	CF+VCT	32.31±1.43de	30.33±0.62ef	10.56±0.49fgh	10.17±0.23def
Sand: Vermicompost (9:1)	VCT	33.61±0.73cde	33.81±0.70d	11.07±0.37ef	11.13±0.27cd
	CF	37.21±1.29bc	36.48±1.54cd	12.09±0.19cd	12.30±0.84b
	CF+VCT	39.84±2.25ab	39.38±1.83b	12.99±0.30b	14.35±0.22a
Sand: Vermicompost (8:2)	VCT	36.15±1.43bcd	36.05±0.59cd	11.73±0.14de	11.63±0.24bc
	CF	32.17±1.76def	37.73±0.70bc	12.51±0.30bc	12.29±0.44b
	CF+VCT	42.51±2.36a	42.24±1.68a	13.86±0.36 a	14.48±0.10a
Sand: Peat (1:1)	VCT	27.98±0.38f	27.87±0.45f	9.09±0.11i	9.08±0.11f
	CF	30.47±2.06ef	28.78±0.87ef	9.89±0.45h	9.69±0.33ef
	CF+VCT	32.29±1.53de	29.35±0.47ef	10.53±0.15fgh	10.04±0.34ef
Sand: Peat (2:1)	VCT	32.05±1.30def	30.33±0.32ef	10.30±0.17gh	9.38±0.51ef
	CF	32.51±1.37de	30.88±0.39e	10.56±0.25fgh	9.76±0.46ef
	CF+VCT	33.76±1.45cde	30.61±0.79e	11.02±0.21efg	10.36±0.51de
p-value					
Substrate		<0.001***	<0.001***	<0.001***	<0.001***
Solution		<0.001***	<0.001***	<0.001***	<0.001***
Substrate × Solution		0.0235*	0.0402*	0.0448*	0.0164*

VCT = Vermicompost-tea; CF = Chemical nutrient solution; Data (means ± SE) *, **, and *** indicate, differences at p ≤ 0.05, 0.01, and ≤0.001 probability levels, and "ns" indicates a non-significant difference. Mean values sharing the same lower-case letter for substrate, solution, and their interactions in the same column are not significantly different at p ≤ 0.05 from Duncan's test.

While VCT treatment was the lowest in both seasons. In the same Table, it is clear from all substrate's mixture that, SM3 gave the highest chlorophyll and protein content but SM4 gave the lowest values in this regard. The lettuce plants cultured in SM3 exhibited the highest chlorophyll and protein content in both seasons. Total chlorophyll content was achieved maximum reading by SM-plants with CF+VCT as compared to other treatments. Vermicompost tea includes micronutrients and a variety of plant growth stimulants, enzymes, useful bacteria, and mycorrhizae that stimulate physiological process including photosynthesis process (Gupta, 2005). As a result, enhanced nutrient availability, improved soil physical characteristics, and increased activity of microorganisms with greater amounts of organics may have aided in raising plant height, number of leaves, leaf area, and leaf area index. (Reddy and Reddy, 2005).

All types of fertilization amendments applicated consistently increased total N, P and K contents per plant (Table 8). The highest values of N, P, and K % values were obtained by CF+VCT treatment followed by CF treatment, while the lowest values were observed in lettuce treated by VCT. The highest content of nutrients was noticed by lettuce plants grown in SM3 which received CF+VCT application. The lower nitrogen content in lettuce plants treated with VCT may be due to the slower and less predictable mineralization rates of organic nitrogen, which might not always match the plant's demand, leading to transient deficiencies (Hao and Chang, 2003).

Table 8. Effect of different substrate mixtures, nutrient solution sources, and their interaction on nitrogen (%), phosphorus (%), and potassium (%) of lettuce during 2021 and 2022 seasons.

Treatment		Nitrogen (%)		Phosphorus (%)		Potassium (%)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
Substrate							
Peat: Vermiculite (1:1)		1.66±0.03^{c}	1.57±0.04^{b}	0.614±0.020^{c}	0.606±0.016^{c}	1.072±0.034^{c}	1.058±0.031^{c}
Sand: Vermicompost (9:1)		1.93±0.05^{b}	2.02±0.09^{a}	0.701±0.022^{b}	0.695±0.021^{b}	1.226±0.038^{b}	1.215±0.036^{b}
Sand: Vermicompost (8:2)		2.03±0.05^{a}	2.05±0.07^{a}	0.773±0.018^{a}	0.765±0.016^{a}	1.351±0.032^{a}	1.337±0.030^{a}
Sand: Peat (1:1)		1.57±0.04^{d}	1.54±0.03^{b}	0.567±0.015^{d}	0.562±0.014^{d}	0.991±0.025^{d}	0.982±0.024^{d}
Sand: Peat (2:1)		1.70±0.02^{c}	1.57±0.05^{b}	0.626±0.015^{c}	0.620±0.013^{c}	1.094±0.026^{c}	1.082±0.025^{c}
Solution							
VCT		1.68±0.04^{c}	1.61±0.05^{c}	0.613±0.019^{c}	0.608±0.018^{c}	1.070±0.033^{c}	1.062±0.033^{c}
CF		1.77±0.05^{b}	1.73±0.06^{b}	0.660±0.024^{b}	0.646±0.020^{b}	1.152±0.041^{b}	1.129±0.036^{b}
CF+VCT		1.89±0.06^{a}	1.90±0.09^{a}	0.697±0.023^{a}	0.694±0.023^{a}	1.218±0.040^{a}	1.213±0.041^{a}
Substrate× Solution							
Peat: Vermiculite (1:1)	VCT	1.64±0.04^{h}	1.46±0.05^{f}	0.594±0.028^{a}	0.579±0.023^{a}	1.032± 0.045^{a}	1.008±0.046^{a}
	CF	1.66±0.04^{fgh}	1.61±0.08^{ef}	0.618±0.046^{a}	0.605±0.005^{a}	1.080±0.077^{a}	1.058±0.012^{a}
	CF+VCT	1.69±0.08^{fgh}	1.63±0.04^{def}	0.631±0.037^{a}	0.633±0.044^{a}	1.103±0.070^{a}	1.108±0.083^{a}
Sand: Vermicompost (9:1)	VCT	1.77±0.06^{ef}	1.78±0.04^{cd}	0.638±0.021^{a}	0.641±0.016^{a}	1.116±0.039^{a}	1.123±0.028^{a}
	CF	1.94±0.03^{cd}	1.97±0.13^{b}	0.704±0.026^{a}	0.690±0.030^{a}	1.229±0.042^{a}	1.205±0.055^{a}
	CF+VCT	2.07±0.05^{b}	2.30±0.04^{a}	0.762±0.029^{a}	0.754±0.028^{a}	1.332±0.045^{a}	1.318±0.044^{a}
Sand: Vermicompost (8:2)	VCT	1.88±0.02^{de}	1.86±0.04^{bc}	0.724±0.004^{a}	0.718±0.008^{a}	1.263±0.005^{a}	1.253±0.020^{a}
	CF	2.00±0.05^{bc}	1.97±0.07^{b}	0.777±0.042^{a}	0.762±0.020^{a}	1.358±0.069^{a}	1.331±0.038^{a}
	CF+VCT	2.22±0.06^{a}	2.32±0.01^{a}	0.819±0.006^{a}	0.816±0.020^{a}	1.432±0.015^{a}	1.427±0.040^{a}
Sand: Peat (1:1)	VCT	1.46±0.02^{i}	1.45±0.02^{f}	0.524±0.007^{a}	0.523±0.006^{a}	0.915±0.014^{a}	0.914±0.013^{a}
	CF	1.58±0.07^{h}	1.55±0.05^{ef}	0.570±0.026^{a}	0.558±0.019^{a}	0.995±0.042^{a}	0.976±0.036^{a}
	CF+VCT	1.68±0.02^{fgh}	1.61±0.05^{ef}	0.608±0.010^{a}	0.604±0.013^{a}	1.063±0.012^{a}	1.055±0.023^{a}
Sand: Peat (2:1)	VCT	1.65±0.03^{gh}	1.50±0.08^{ef}	0.586±0.003^{a}	0.581±0.007^{a}	1.023±0.004^{a}	1.014±0.016^{a}
	CF	1.69±0.04^{fgh}	1.56±0.07^{ef}	0.629±0.034^{a}	0.617±0.016^{a}	1.099± 0.056^{a}	1.077±0.031^{a}
	CF+VCT	1.76±0.03^{efg}	1.66±0.08^{de}	0.663±0.005^{a}	0.661±0.016^{a}	1.160±0.012^{a}	1.155±0.033^{a}
p-value							
Substrate		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Solution		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Substrate × Solution		0.0448*	0.0164*	0.8740^{ns}	0.9545^{ns}	0.8911^{ns}	0.9773^{ns}

VCT = Vermicompost-tea; CF = Chemical nutrient solution; Data (means ± SE) *, **, and *** indicate, differences at $p \leq 0.05$, 0.01, and ≤0.001 probability levels, and "ns" indicates a non-significant difference. Mean values sharing the same lower-case letter for substrate, solutions, and their interactions in the same column are not significantly different at $p \leq 0.05$ from Duncan's test.

Conclusion and Recommendations

This study promotes the linkages between sustainable agriculture practices and specific Sustainable Development Goals (SDGs), examining the potential of eco-friendly soil substrates and biofertilizers to improve the soil health, reduce dependence on mineral fertilizers and pollution, and conserve water resources, which reflects on the preservation of natural resources and the reduction of environmental pollution. For Balanced High Yield and Superior Nutritional Quality: The most effective strategy is to utilize a Sand + Vermicompost (8:2) substrate in conjunction with an "Organic + Chemical" nutrient solution. This combination provides a holistic benefit, ensuring robust growth, significant biomass accumulation, and enhanced nutritional value in the harvested leaves. For Maximizing Marketable Plant Weight: If the primary objective is to achieve the highest possible marketable plant weight, the use of a Sand + Vermicompost (8:2) substrate combined with a "Chemical" nutrient solution is specifically advised. This precise nutrient delivery system, paired with the optimal substrate, is crucial during the critical head-filling phase to maximize yield.

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