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RESEARCH ARTICLE

Production of microgreens under a vertical hydroponic system for nutritional and environmental security

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Abstract

Urban farming systems play a pivotal role in providing fresh, nutritious vegetables to consumers. Microgreens specifically can fit this need. The present study was carried out in the Department of Horticulture, Central University of Tamil Nadu, Thiruvarur, during the period 2023 to 24. To analyse the suitability of microgreens for urban farming, four different microgreens, namely purple radish (*Raphanus sativus*), fenugreek (*Trigonella foenum-graecum*), red amaranth (*Amaranthus tricolor*) and coriander (*Coriandrum sativum*) were grown under a vertical 'A' frame hydroponic system using palmyra fibre waste as root supporting material. The experiment was laid out in a factorial completely randomised block design (FCRD) with different types of containers as a one factor and different nutrient solutions as another factor. Growth parameters (Germination %, length of seedling, yield) and biochemical parameters (carbohydrate, protein, vitamin C, total chlorophyll, carotenoids, total phenol, flavonoids, antioxidants) were documented in all four microgreens. Elemental profiling (29 mineral nutrients) of microgreens samples was done. The results of the experiment indicated that 'protray on plastic tray' as a container performed superiorly. Among the nutrient solutions, vermiwash and seaweed extract gave the best results. The interaction between the type of containers and nutrient solutions showed that the combination of protray on a plastic tray with vermiwash solution and seaweed extract performed best for microgreens species. Improved germination and yield of microgreens in plastic tray containers can be attributed to their superior moisture retention. Vermiwash and seaweed extract enhanced the yield and nutrient content of microgreens, as these are rich in micro, macro nutrients and plant growth-promoting hormones. The carbon sequestering ability of individual microgreens was also recorded. In conclusion, this study underscores the potential of vertical hydroponic systems for microgreens production, offering both nutritional and environmental benefits.

Keywords: carbon sequestration; hydroponic system; microgreens; nutrient profile; palmyra fibre

Introduction

Chronic diseases like cancer, cardiovascular diseases, diabetes, etc., are increasing day by day. One of the major reasons is malnutrition. Vegetables can reduce malnutrition. The Indian Council of Medical Research (ICMR) has recommended that at least 300 g of vegetables must be consumed by an individual per day. Out of this one one-third of the requirement can be met through green leafy vegetables (50 g) and other vegetables (200 g). Though vegetables are referred to as protective foods because they are the treasure of several minerals and vitamins which prevent humans from several diseases, there may be loss of nutrients due to numerous factors like unavailability of storage facilities, inadequate supply and market chain and improper transportation chain system. Hence, growing vegetables in the area of demand will reduce the loss of nutrients. In addition, the scenario of an increasing global population and decreasing land area creates the necessity of growing crops in a minimal area with maximum production in terms of quantity and quality, including nutritional value. This states the importance of cultivating vegetables in small residential vertical hydroponic systems (VHS) to meet daily consumer requirements for nutritious vegetables, especially in urban areas. Microgreens specifically can fit this need. This new class of food, called Microgreens, have been popularised recently, they are also called as the functional food (1). Microgreens are delicate young greens made from vegetable and herb seeds that have two cotyledon leaves, which are developed completely; true leaves may or may not be formed (2). They can be harvested within a period of 7-14 days after germination. Six different microgreens, namely mung bean, lentil, red radish, pearl millet, mustard and red cabbage grown under a 16 hr light and 8 hr dark regime. The ideal temperature for all species ranged between 24 °C and 28 °C, with the best harvest time occurring between 6 and 13 days after sowing (3). Microgreens can serve as a mini package containing important nutrients that can be grown successfully in urban farming systems. The market for microgreens is anticipated to grow annually at 7.6 %, reaching US$17039.744 million in 2025 worldwide (4). Microgreens have rich colour, flavour and texture. They can be grown under sunlight in soil, peat, bark, vermiculite and perlite (5). Microgreens can be consumed along with salads, sandwiches of mature lettuce or celery. Microgreens contain higher concentrations of bioactive components like vitamins, minerals, antioxidants, phenolics, carotenoids, etc. Microgreens are also devoid of anti-nutritional compounds like nitrates. Compared to mature greens, microgreens and baby greens are more recent plant-based functional foods that contain significantly higher levels of phytochemicals (6). Taking advantage of the short duration of the crop, size of edible part, nutritional content, ability to grow in different media, etc, they can be grown under indoor conditions easily in homes of urban areas with limited supply of nutrients and in limited space. Microgreens can be grown hydroponically without soil, using nutrient solution (7). Among the variables influencing a hydroponic system, the nutrient solution used is one of the most crucial in determining crop yield and quality. Hydroponics is one of the best methods for growing vegetables and other plants (8). Standardised guidelines and a test protocol for evaluating hydroponic microgreens production systems were developed (9). The use of optimised nutrient solutions has shown great potential in improving microgreens growth and quality. Half-strength Hoaglands' solution enhances growth and yield in wild leafy and *Brassica* microgreens, while a 25:75 ammonia-to-nitrate ratio boosts beta-carotene and dry matter content (10). Vermiwash application (25 %) promotes greater shoot length in fenugreek (11). Seaweed extract treatments significantly increase phenolic, flavonoid and antioxidant levels in arugula microgreens (12). Because of better production platforms, hydroponic microgreens production could increase both domestically and commercially. In this study, three different nutrient solutions, namely Hoaglands' solution, vermiwash and seaweed extract containing micro and macro nutrients, growth-promoting substances, were used to grow microgreens species. Growing media used in vertical farming should be light in weight, have high moisture-retaining capacity, be easy to handle, be suitable for a hydroponic system and be free from pathogens. Despite the increasing popularity of microgreens cultivation, there is limited research comparing the effectiveness of different nutrient solutions, such as Hoaglands' solution, vermiwash and seaweed extract, on their growth, yield and nutritional quality. The combined influence of nutrient solutions and container types on germination and biochemical composition also remains insufficiently studied. Exploring efficient and sustainable growing systems is essential to optimize microgreens production. The present study aims to address this gap by evaluating microgreens cultivation in vertical hydroponic systems (VHS), which offer a promising approach for urban farming by enabling high productivity, better resource and space utilisation on terraces, balconies and other limited areas. Hence, the objectives of this study were to design a low-cost vertical hydroponic system to produce microgreens and to ascertain nutrients in individual microgreens species. In addition, the carbon sequestering ability of individual microgreens species was also assessed.

Materials and Methods

The experiments were carried out in the Department of Horticulture, School of Life Sciences, Central University of Tamil Nadu, during the period 2023 to 24. Four different microgreens, namely purple radish (*Raphanus sativus*), fenugreek (*Trigonella foenumgraecum*), red amaranth (*Amaranthus tricolor*) and coriander (*Coriandrum sativum*) were grown under an A-frame - vertical hydroponic system (3.05 × 1.83 m with six racks), which was covered using the shade net to provide a congenial microclimate for the production of microgreens. The experiment was laid out in a factorial completely randomised block design (FCRD) with different types of containers as a one factor and different nutrient solutions as another factor. Three different containers, namely C_1- protray on plastic tray (25.4 × 25.4 cm), C_2- areca plate on plastic tray (25.4 × 25.4 cm) and C_3- only areca plate (25.4 × 25.4 cm) and four different solutions viz. N_1- water (control), N_2 - half-strength Hoaglands' solution was prepared by following the composition with some modifications and used at a rate of 8.5 mL L^{-1} (13). N_3-vermiwash and N4-seaweed extract (*Ascophyllum nodosum*) were purchased online and diluted at a concentration of 5 Ml L^{-1} and 2 mL L^{-1}, respectively were used. Palmyra fruit fibre was used as the root supporting material for the production of microgreens. Palmyra fruits were collected from villages in and around the university and dehusked to extract the fibre. For 5-7 days, dehusked portions were soaked in water. Soaked husks were sundried for 10-15 days. Dried husks were pulverised using a pulveriser. As a result, the palm fruit fibre was prepared and stored in bags. The pH of palmyra fruit fibre was estimated to be 6.2 and its EC was determined as 0.634 dS m^{-1}. The moisture content of palmyra fibre, 7-10 % gives optimum production. The spongy characteristics help in proper root oxygenation and water retention. It is easy to handle, lightweight weight and ideal to use as a root supporting material in hydroponics. Seed rate for purple radish was 8 g $tray^{-1}$, for fenugreek 7 g $tray^{-1}$, red amaranth 6 g $tray^{-1}$ and the coriander seed rate used was 7 g $tray^{-1}$. Pre-soaking of seeds in water was done. Palmyra fruit fibre was filled into the containers evenly. Seeds were spread evenly on the substrate. Containers were closed to give darkness for 2 to 3 days at 24 – 27 °C, 100 % RH. The level of water in the hydroponic unit was monitored regularly. After 2-3 days, germinated seeds were exposed to light by opening the containers. The illustration of the experiment is given in the (Fig. 1). Cotyledonary leaves emerged at 6-7 days and this was followed by the emergence of true leaves. First harvesting was done from the 6^{th} day onwards in purple radish microgreens, 8^{th} day in fenugreek microgreens, 7^{th} day in red amaranth microgreens and 14^{th} day in coriander microgreens. After harvesting, the biochemical parameters were studied.

Treatment details

Factor 1 (Type of container)		Factor 2 (Type of nutrient solution)	
C_1	Protray on a plastic tray	N_1	Control (tap water)
C_2	Areca plate on a plastic tray	N_2	Hoaglands' solution
C_3	Only areca plate	N_3	Vermiwash solution
		N_4	Seaweed extract

Replication: 2

Estimation procedures for growth and biochemical parameters

Seed germination percentage was determined using the formula in Equation 1.

Germination percentage = Number of seeds germinated/Total number of seeds sown × 100 (Eqn. 1)

The result was expressed as a percentage. Length of the seedling at the harvest stage was measured using a measuring scale. The average of 5 seedlings was recorded and expressed in cm.Yield per tray was calculated using a precision balance after harvesting and expressed in g $tray^{-1}$. Total chlorophyll and carotenoid contents were calculated by using the formula (14). Carbohydrate content was tested through the anthrone method (15). Protein estimation was carried out by Lowrys' method (16). Vitamin C, total phenols, flavonoids and antioxidant content were measured using standard methods (17, 18).

Estimation of mineral nutrients

The best-performing treatment combination was identified in each crop using growth and biochemical data. Those samples were

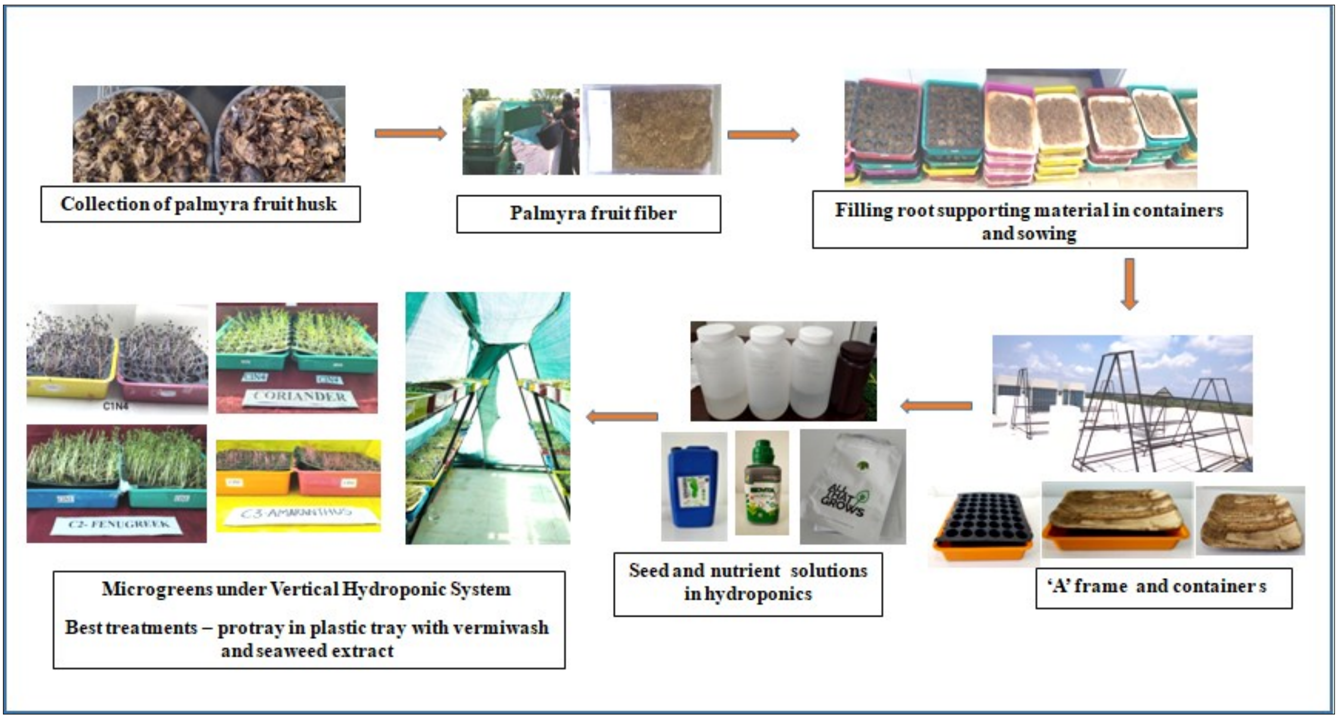


Fig. 1. Vertical hydroponic system for microgreens production.

digested using diacid HNO_3 and $HClO_4$ (9:4) and analysed for elemental profiling. Elemental profiling of microgreens samples was done using ICPMS (Inductively coupled plasma mass spectrometry), Thermo Scientific™ Icap™ RQ.

Estimation procedure to evaluate the carbon sequestration of individual microgreens species

For evaluating the carbon sequestration ability of individual microgreens, an experiment was designed to grow microgreens with four treatments. A container set-up was made by placing the treatment trays into the black containers of area 0.1539 m^2 and volume of 0.0446 m^3 as shown in the (Fig. 2).

Treatment details to evaluate carbon sequestration (Replication: 4)	
T_0	Protray on a plastic tray with water
T_1	Protray on a plastic tray with Hoaglands' solution
T_2	Protray on a plastic tray with vermiwash solution
T_3	Protray on a plastic tray with seaweed extract.

For evaluating the carbon sequestration ability of microgreens species, CO_2 % was measured using the F-950 Felix Three gas analyser, USA. The plastic trays were placed into the black containers. The container lid was sealed. A small hole was made on top of the lid to insert the syringe of the gas analyser. The initial reading was taken once the container was closed and the final reading was taken at 12 hr intervals, both morning and evening, to calculate the CO_2 production by the microgreens setup during dark and light conditions. After every 48 hr, ventilation was given for 1 hr. The reading was noted before and after ventilation. The reading taken once the black container was sealed was taken as the initial CO_2 % concentration and the reading taken before opening the black container was taken as the final CO_2 % concentration. Variation between initial and final reading was calculated to interpret the carbon sequestering ability of microgreens. The data obtained from all four microgreens were analysed graphically.

Fig. 2. Container setup to measure the real-time CO_2 %.

Statistical data analysis

The effect of different containers, nutrient solutions on the growth and biochemical parameters of microgreens was analysed in a two-way analysis of variance (ANOVA) using 'Agris' software at 5 % level of significance.

Results and Discussion

Influence of treatments on growth parameters of microgreens

The analysis showed a significant difference among the treatments for all the growth parameters (Fig. 3-5). Protray on plastic tray with seaweed extract (C_1N_4) showed the best effect on germination percentage, length of seedling at harvest stage, yield of purple radish and coriander microgreens. Protray on plastic tray with vermiwash solution (C_1N_3) showed the maximum germination percentage, length of seedling at harvest stage, yield in fenugreek and red amaranth microgreens. Better germination and yield of microgreens in protray on plastic tray container is due to its ability to retain moisture and provide conducive conditions for growth. The presence of Phenyl Acetic Acid (PAA) and other compounds in the seaweed extract might have an effect on the vegetative growth (19). Vermiwash containing the growth-promoting substances such as auxins, gibberellins, cytokinins, micronutrients, vitamins and amino acids have influenced the growth of microgreens (20).

Influence of treatments on biochemical parameters of microgreens

The analysis showed a significant difference among the treatments for all the biochemical parameters (Tables 1-4).

Total chlorophyll content

The treatment combinations areca plate with vermiwash spray (C_3N_3) showed the maximum chlorophyll content in purple radish microgreens (0.344 mg g^{-1}), which was at par with the treatment combination (C_2N_4) areca plate on plastic tray with seaweed extract (0.321 mg g^{-1}). The total chlorophyll content of coriander microgreens was also high (0.221 mg g^{-1}) in the treatment combination (C_3N_3) areca plate with vermiwash spray. Red amaranth microgreens grown in an Areca plate with Hoaglands' solution (C_3N_2) exhibited increased chlorophyll content (0.204 mg g^{-1}), which was at par with the treatment combination (C_1N_3) protray on plastic tray with vermiwash (0.198 mg g^{-1}). The chlorophyll content of fenugreek microgreens (mg g^{-1}) was significantly high in

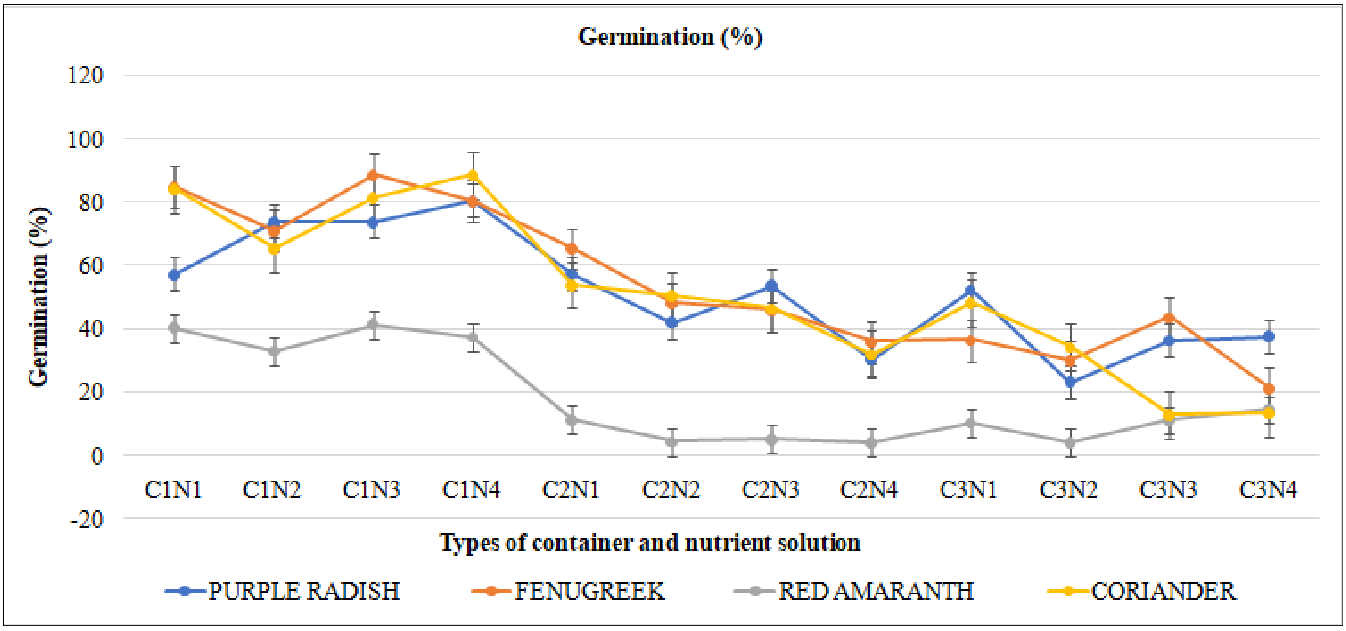


Fig. 3. Germination percentage of microgreens species.

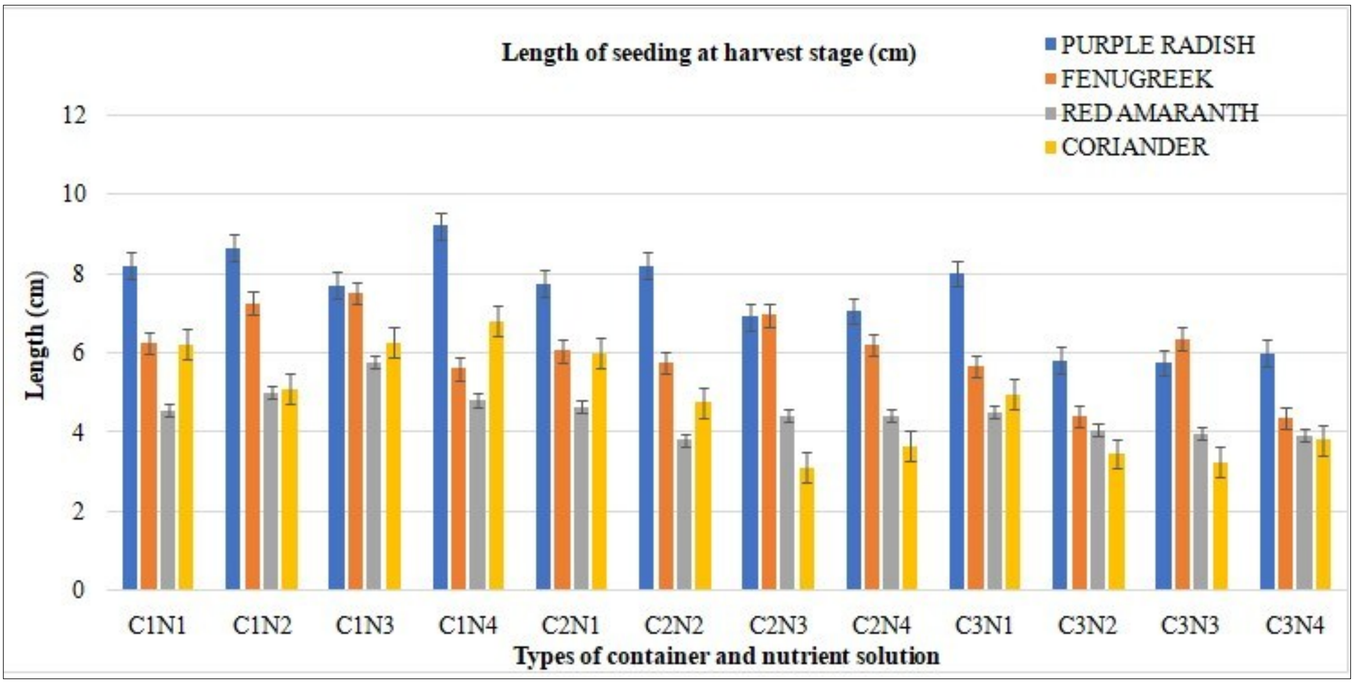


Fig. 4. Length of seedling at harvest stage in the treatment combinations.

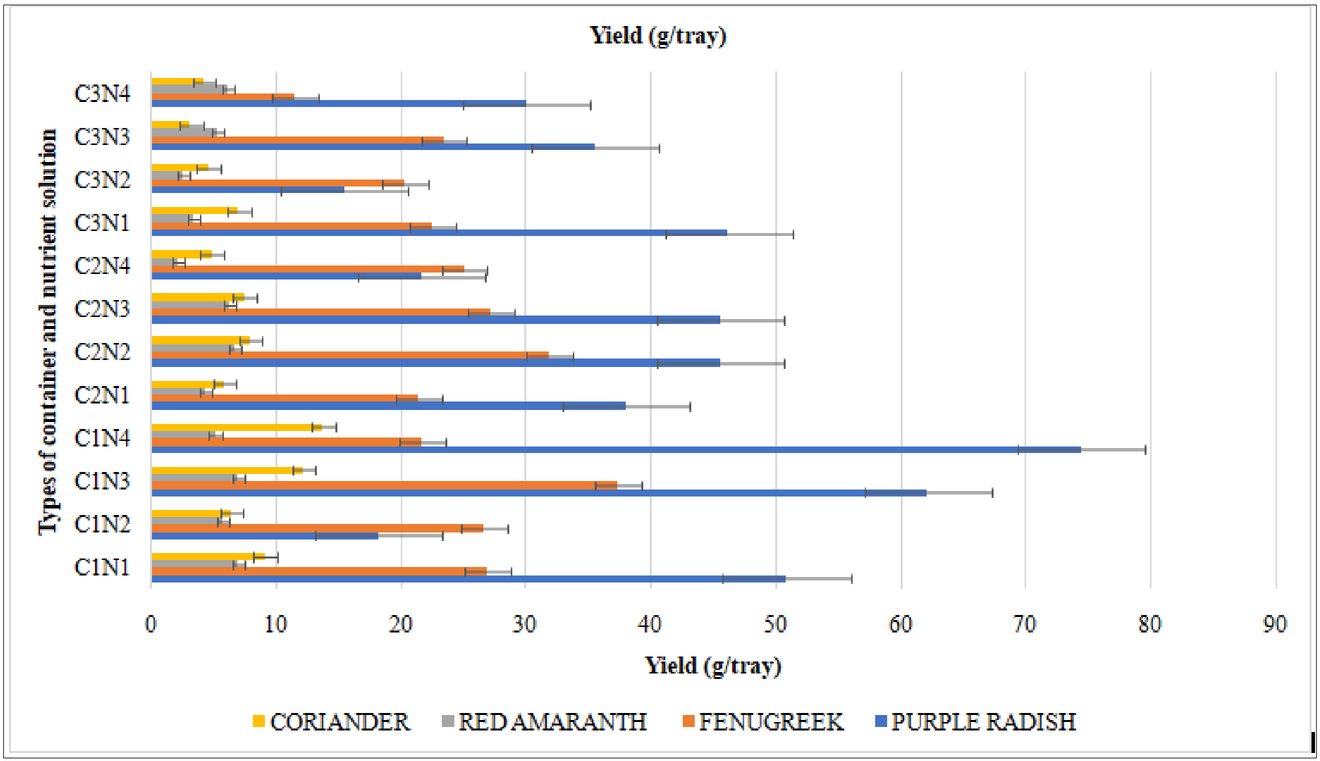


Fig. 5. Yield of microgreens species.

Table 1. Effect of types of container and nutrient solution on biochemical parameters of purple radish microgreens

Treatments		Carbohydrate (g 100 g^{-1})	Protein (g 100 g^{-1})	Chlorophyll (mg g^{-1})	Carotenoid (mg g^{-1})	Vitamin C (mg 100 g^{-1})	Total flavonoids (mg g^{-1})	Total phenol (mg g^{-1})	Total antioxidant (mg g^{-1})
C_1		3.23	2.39	0.195	2.957	219.1	35.7	43.7	189.7
C_2		3.90	2.43	0.234	2.871	233.6	38.2	32.3	195.9
C_3		2.54	2.01	0.238	2.492	245.0	44.0	48.4	196.3
N_1		3.30	2.45	0.199	2.087	127.0	39.0	32.7	196.7
N_2		3.55	1.77	0.200	2.588	219.3	36.0	35.6	186.6
N_3		2.72	1.97	0.224	2.512	251.7	33.8	45.1	194.6
N_4		3.32	2.92	0.267	3.904	332.3	48.3	52.4	197.9
C_1N_1		3.50	3.10	0.182	2.792	200.0	29.5	39.0	185.8
C_1N_2		3.15	1.55	0.166	2.648	131.5	25.6	16.6	176.0
C_1N_3		2.45	0.90	0.166	2.470	75.0	32.4	43.9	190.4
C_1N_4		3.80	4.00	0.265	3.915	470.0	55.2	75.3	206.8
C_2N_1		3.20	2.70	0.294	1.927	131.0	45.9	28.7	202.9
C_2N_2		4.20	1.95	0.162	2.515	227.5	30.3	32.8	189.6
C_2N_3		4.70	2.25	0.161	2.409	476.0	36.3	33.1	190.0
C_2N_4		3.50	2.80	0.321	4.629	100.0	40.3	34.4	201.0
C_3N_1		3.20	1.55	0.120	1.542	50.0	41.8	30.5	201.5
C_3N_2		3.30	1.80	0.273	2.603	299.0	52.1	57.5	194.3
C_3N_3		1.00	2.75	0.344	2.655	204.0	32.8	58.2	203.5
C_3N_4		2.65	1.95	0.214	3.167	427.0	49.5	47.3	185.9
Grand mean		3.22	2.28	0.222	2.773	232.6	39.3	41.4	194.0
C	**SED**	0.17	0.14	0.014	0.117	2.2	0.2	2.0	1.7
	CD at 5 %	0.38	0.30	0.030	0.255	4.8	0.4	4.2	3.7
N	**SED**	0.20	0.16	0.015	0.135	2.5	0.2	2.3	1.9
	CD at 5 %	0.44	0.34	0.035	0.295	5.5	0.5	4.9	4.2
C × N	**SED**	0.35	0.27	0.028	0.234	4.4	0.4	3.9	3.4
	CD at 5 %	0.76	0.59	0.060	0.511	9.6	0.9	8.5	7.3

Table 2. Effect of types of container and nutrient solution on biochemical parameters of fenugreek microgreens

Treatments		Carbohydrate (g 100 g^{-1})	Protein (g 100 g^{-1})	Chlorophyll (mg g^{-1})	Carotenoid (mg g^{-1})	Vitamin C (mg 100 g^{-1})	Total flavonoids (mg g^{-1})	Total phenol (mg g^{-1})	Total antioxidant (mg g^{-1})
C_1		1.60	1.50	0.141	2.268	30.3	45.7	25.6	64.3
C_2		1.34	1.59	0.094	1.763	16.1	42.6	27.9	66.9
C_3		1.91	1.73	0.119	2.002	25.8	44.8	27.5	62.0
N_1		1.10	1.57	0.084	1.533	17.8	34.0	23.0	51.0
N_2		1.38	1.40	0.116	2.040	15.3	44.1	27.3	69.3
N_3		2.28	1.82	0.134	2.158	33.4	51.4	28.5	68.7
N_4		1.70	1.63	0.139	2.312	29.9	48.1	29.3	68.6
C_1N_1		1.30	1.40	0.120	2.217	16.7	42.4	22.9	59.1
C_1N_2		0.75	1.15	0.107	1.795	18.8	35.3	23.3	55.2
C_1N_3		2.75	1.85	0.170	2.503	71.1	67.4	33.4	82.1
C_1N_4		1.60	1.60	0.169	2.558	14.6	37.7	22.8	60.6
C_2N_1		0.90	1.70	0.045	1.073	20.8	31.1	25.4	49.0
C_2N_2		1.45	1.35	0.096	1.796	12.5	42.6	27.3	78.3
C_2N_3		1.30	2.05	0.086	1.636	12.5	37.9	24.8	55.9
C_2N_4		1.70	1.25	0.151	2.546	18.8	58.9	34.1	84.3
C_3N_1		1.10	1.60	0.087	1.310	15.9	28.5	20.6	44.7
C_3N_2		1.95	1.70	0.145	2.528	14.6	54.3	31.3	74.4
C_3N_3		2.80	1.55	0.146	2.336	16.7	48.8	27.2	68.2
C_3N_4		1.80	2.05	0.099	1.833	56.3	47.7	31.0	60.8
Grand mean		1.6167	1.6042	0.118	2.011	24.1	44.4	27.0	64.4
C	**SED**	0.11	0.09	0.005	0.079	2.5	1.2	0.3	1.9
	CD at 5 %	0.25	0.19	0.012	0.172	5.4	2.5	0.6	4.1
N	**SED**	0.13	0.10	0.006	0.091	2.9	1.3	0.3	2.2
	CD at 5 %	0.29	0.22	0.013	0.198	6.2	2.9	0.7	4.7
C × N	**SED**	0.23	0.17	0.011	0.158	4.9	2.3	0.6	3.7
	CD at 5 %	0.50	0.38	0.023	0.344	10.7	5.1	1.2	8.2

Table 3. Effect of types of container and nutrient solution on biochemical parameters of red amaranth microgreens

Treatments		Carbohydrate (g 100 g^{-1})	Protein (g 100 g^{-1})	Chlorophyll (mg g^{-1})	Carotenoid (mg g^{-1})	Vitamin C (mg 100 g^{-1})	Total flavonoids (mg g^{-1})	Total phenol (mg g^{-1})	Total antioxidant (mg g^{-1})
C_1		1.10	0.93	0.105	2.947	87.5	19.7	18.9	139.0
C_2		0.98	0.99	0.109	3.882	79.3	19.1	21.7	164.3
C_3		0.59	1.09	0.116	3.967	77.8	19.9	24.3	177.9
N_1		0.77	0.61	0.073	2.805	41.2	17.0	17.8	145.7
N_2		0.90	0.87	0.124	4.171	93.0	22.4	25.0	178.4
N_3		1.01	1.25	0.145	4.220	102.5	19.7	20.8	143.7
N_4		0.88	1.28	0.098	3.201	89.3	19.1	23.0	173.7
C_1N_1		0.87	0.68	0.071	2.718	39.5	12.7	15.4	135.7
C_1N_2		0.80	0.73	0.080	2.732	96.0	17.9	16.9	132.0
C_1N_3		1.61	1.42	0.198	3.694	112.5	28.0	25.4	137.7
C_1N_4		1.11	0.89	0.072	2.645	102.0	20.1	18.0	150.6
C_2N_1		0.81	0.50	0.082	3.044	24.0	19.8	19.8	155.7
C_2N_2		1.06	0.97	0.088	3.701	109.0	21.6	27.4	198.8
C_2N_3		1.18	0.95	0.093	4.010	108.0	12.0	14.7	120.3
C_2N_4		0.87	1.54	0.173	4.776	76.0	22.9	24.9	182.3
C_3N_1		0.63	0.63	0.065	2.652	60.0	18.7	18.3	145.7
C_3N_2		0.83	0.91	0.204	6.079	74.0	27.7	30.8	204.4
C_3N_3		0.25	1.39	0.145	4.955	87.0	19.0	22.3	173.2
C_3N_4		0.66	1.42	0.050	2.183	90.0	14.2	25.9	188.1
Grand mean		0.89	1.00	0.110	3.599	81.5	19.6	21.7	160.4
C	**SED**	0.04	0.01	0.003	0.007	0.4	0.6	0.1	0.9
	CD at 5 %	0.09	0.03	0.007	0.015	0.9	1.2	0.2	1.9
N	**SED**	0.05	0.02	0.004	0.008	0.5	0.6	0.1	1.0
	CD at 5 %	0.11	0.03	0.009	0.017	1.1	1.4	0.2	2.2
C × N	**SED**	0.08	0.03	0.007	0.014	0.9	1.1	0.1	1.7
	CD at 5 %	0.18	0.06	0.015	0.030	1.9	2.4	0.3	3.7

Table 4. Effect of types of container and nutrient solution on biochemical parameters of coriander microgreens

Treatments		Carbohydrate ($g\ 100\ g^{-1}$)	Protein ($g\ 100\ g^{-1}$)	Chlorophyll ($mg\ g^{-1}$)	Carotenoid ($mg\ g^{-1}$)	Vitamin C ($mg\ 100\ g^{-1}$)	Total flavonoids ($mg\ g^{-1}$)	Total phenol ($mg\ g^{-1}$)	Total antioxidant ($mg\ g^{-1}$)
C_1		0.70	2.60	0.120	2.414	64.1	32.4	36.7	151.7
C_2		0.53	1.28	0.175	2.770	57.6	28.9	34.7	197.6
C_3		0.23	1.42	0.145	2.650	53.4	27.8	35.6	138.2
N_1		0.32	4.19	0.097	1.944	55.3	27.6	23.0	133.4
N_2		0.68	0.23	0.149	2.570	63.0	28.2	35.3	169.1
N_3		0.30	0.82	0.182	3.269	59.7	30.1	39.9	188.2
N_4		0.63	1.84	0.160	2.663	55.4	33.0	44.4	159.2
C_1N_1		0.20	3.02	0.112	2.404	51.1	25.0	17.0	122.9
C_1N_2		1.00	0.28	0.143	2.521	64.5	36.6	41.4	207.8
C_1N_3		0.60	2.01	0.107	2.658	68.5	25.3	29.3	151.2
C_1N_4		1.00	5.10	0.120	2.073	72.1	42.7	58.9	125.0
C_2N_1		0.25	4.49	0.123	1.898	49.4	21.9	19.9	116.0
C_2N_2		0.95	0.22	0.164	2.640	70.2	24.8	30.8	158.3
C_2N_3		0.10	0.24	0.219	3.565	61.9	38.2	54.9	269.2
C_2N_4		0.80	0.18	0.196	2.977	48.8	30.7	33.2	246.8
C_3N_1		0.50	5.05	0.056	1.529	65.3	35.9	32.0	161.4
C_3N_2		0.10	0.19	0.139	2.549	54.4	23.0	33.8	141.3
C_3N_3		0.20	0.21	0.221	3.583	48.7	26.8	35.3	144.1
C_3N_4		0.10	0.24	0.166	2.939	45.2	25.6	41.2	105.9
Grand mean		0.48	1.77	0.147	2.611	58.3	29.7	35.6	162.5
C	SED	0.01	0.04	0.000	0.004	0.4	0.9	0.8	0.1
	CD at 5 %	0.03	0.09	0.001	0.010	0.8	2.0	1.7	0.2
N	SED	0.02	0.05	0.000	0.005	0.4	1.1	0.9	0.1
	CD at 5 %	0.04	0.10	0.001	0.011	1.0	2.3	2.0	0.2
C × N	SED	0.03	0.08	0.001	0.009	0.8	1.8	1.6	0.2
	CD at 5 %	0.06	0.18	0.001	0.019	1.7	4.0	3.4	0.3

treatments C_1N_3(0.170 mg g^{-1}), C_1N_4(0.169 mg g^{-1}) and C_2N_4 (0.151 mg g^{-1}), which were at par. Better seed germination and seedling growth in the portraiture could be attributed to the controlled environment, which provides ideal amounts of light, space, temperature and moisture. Areca plates, being organic, might have slowly decomposed as the microgreens grow. This decomposition process could release small amounts of nutrients into the growing medium. Vermiwash is a rich source of various nutrients, including nitrogen, magnesium and iron, all of which are essential for chlorophyll synthesis. Plants might have absorbed major elements present in seaweed extract, particularly macronutrients, which could have activated chlorophyll production. Good availability of these elements through vermiwash could have promoted chlorophyll content.

Total carotenoid content

There is evidence showing the abundant presence of phytochemicals such as carotenoids and phenolic compounds in microgreens (21). These compounds are powerful antioxidants present in plants that have enormous health benefits for humans. Carotenoids help to improve the immune system. An areca plate with Hoaglands' solution (C_3N_2) gave the highest carotenoid content in red amaranth microgreens (6.079 mg g^{-1}). An areca plate with vermiwash spray (C_3N_3) and, areca plate on a plastic tray with vermiwash solution (C_2N_3) gave carotenoid content of 3.583 mg $g^{-1}$and 3.565 mg $g^{-1,}$ respectively, in coriander microgreens, which were at par with each other. In purple radish, the carotenoid content was high (4.629 mg g^{-1}) in the treatment with areca plate on plastic tray with seaweed extract (C_2N_4). Protray on plastic tray with seaweed extract (C_1N_4) gave the maximum carotenoid content in fenugreek (2.558 mg g^{-1}), which was at par with the carotenoid content in the treatments C_2N_4 (2.546 mg g^{-1}), C_3N_2 (2.528 mg g^{-1}). The presence of macro and micro minerals in the seaweed extract has helped to boost chlorophyll and carotenoid levels in leaves (22). Vermiwash is abundant in several nutrients and compounds that promote growth.

Carbohydrate content

Among all the treatment combinations, the carbohydrate content of purple radish microgreens was maximum (4.70 g 100 g^{-1}) when grown on an areca plate on a plastic tray with vermiwash spray (C_2N_3), which was at par with the treatment C_2N_2 (4.20 g 100 g^{-1}). Protray on plastic tray with vermiwash (C_1N_3) gave the maximum carbohydrate content in red amaranth (1.61 g 100 g^{-1}) microgreens. Moreover, decomposition of the areca plates due to the moisture content might have leached some of the nutrient compounds, which, when absorbed by the microgreens, exhibited strong biochemical parameters. Fenugreek microgreens, when grown in the treatment (C_3N_3), only the areca plate with vermiwash spray gave the highest carbohydrate content (2.80 g 100 g^{-1}), which was at par with the treatment combination C_1N_3 (2.75 g 100 g^{-1}). Carbohydrate content of coriander microgreens was high (1.00 g 100 g^{-1}) in the sample grown in the treatment (C_1N_4), protray on a plastic tray with seaweed extract and (C_1N_2), protray on a plastic tray with Hoaglands' solution. The increase in chlorophyll and carotenoids has improved photosynthesis, nutrient uptake and ultimately led to increased carbohydrate production by plants (23, 24).

Protein content

Protray on plastic tray with seaweed extract (C_1N_4) yielded the highest protein content in purple radish (4.00 g 100 g^{-1}) and coriander (5.10g 100 g^{-1}) microgreens. Treatment (C_2N_4) areca plate on plastic tray with seaweed extract gave the highest protein content in red amaranth microgreens (1.54 g 100 g^{-1}). Fenugreek microgreens protein content was high (2.05 g 100 g^{-1}) in the sample grown in the treatment (C_2N_3) areca plate on plastic tray with vermiwash solution, which was less than the protein content (3.33 g 100 g^{-1}) of fenugreek microgreens found earlier (25). The carbohydrate and protein content of fenugreek and red amaranth microgreens obtained in this experiment was more or less at the same level as per previous studies (26). Seaweed extract and vermiwash are rich sources of nutrients like nitrogen, phosphorus, calcium and magnesium. Increased uptake of nitrogen, which is the precursor of amino acids, might also be the reason for better protein content in microgreens

(27). Metabolites such as proteins, sugars, glycosides, saponins, starch and steroids were found in the areca leaves' sheaths (28). Areca plates, being organic, might have decomposed slightly and released some nutrients. This might have influenced the biochemical contents of all four microgreens.

Ascorbic acid

Ascorbic acid is a powerful antioxidant having many health benefits. Protray on plastic tray with vermiwash solution (C_1N_3) showed maximum vitamin C content in fenugreek (71.1 mg100 g^{-1}) and red amaranth (112.5 mg 100 g^{-1}) microgreens. Vitamin C content of fenugreek and red amaranth microgreens obtained in this experiment was 5-6 times greater than in other studies (26). Vitamin C content of coriander microgreens (72.1 mg 100 g^{-1}) was high in the treatment portrayed on a plastic tray with seaweed extract (C_1N_4). Vitamin C content of purple radish microgreens was comparatively high (476.0 mg 100 g^{-1}) when grown on an areca plate on a plastic tray with vermiwash (C_2N_3), which was at par with the treatment C_1N_4 (470.0 mg 100 g^{-1}).

Total phenols and flavonoids

Phenols and flavonoids are the secondary metabolites present in plants that help to repair the damage caused due to free radicals. The highest total phenol (75.3 mg g^{-1}) and flavonoid (55.2 mg g^{-1}) content of purple radish microgreens was obtained when it was grown in the treatment (C_1N_4), i.e. protray on a plastic tray with seaweed extract. Protray on plastic tray with seaweed extract (C_1N_4) also gave maximum phenol (58.9 mg g^{-1}) and flavonoid (42.7 mg g^{-1}) content in coriander microgreens. The highest total phenol in fenugreek microgreens (34.1 mg g^{-1}) was recorded in samples grown in an areca plate on a plastic tray with seaweed extract (C_2N_4), which was at par with C_1N_3 (33.4 mg g^{-1}). Red amaranth microgreens had maximum total phenol content (30.8 mg g^{-1}), which was 12 times higher than the earlier study in treatment with an areca plate with Hoaglands' solution spray (C_3N_2) (29). Total flavonoid content of fenugreek microgreens (67.39 mg g^{-1}) and red amaranth microgreens (28.0 mg g^{-1}) was high when grown in protray on plastic tray with vermiwash solution (C_1N_3).

Total antioxidants

Total antioxidant content of purple radish microgreens was high (206.8 mg g^{-1}) in the sample grown on protray on plastic tray with seaweed extract (C_1N_4), which was at par with the treatment combination C_3N_3 (203.5 mg g^{-1}). Fenugreek microgreens raised in an areca plate on a plastic tray with seaweed extract (C_2N_4) showed maximum antioxidant content (84.3 mg g^{-1}), which was at par with the treatment combination C_1N_3 (82.1 mg g^{-1}). Areca plates with Hoaglands' solution (C_3N_2) gave increased antioxidants in red amaranth microgreens (204.4 mg g^{-1}). Total antioxidant content of coriander microgreens was high (269.2 mg g^{-1}) in the sample grown on an areca plate on a plastic tray with vermiwash solution (C_2N_3). Research indicates that the leaves of the areca palm are rich in secondary metabolites like tannins, phenolic acids, flavonoids, terpenoids, alkaloids, coumarins and saponins etc (30). Nutrient solutions provided the essential macro and micronutrients needed for optimal growth. These balanced nutrients have ensured that the microgreens have building blocks to synthesise a variety of secondary metabolites, including phenols, flavonoids and antioxidants.

Mineral elements

The mineral nutrients of microgreens grown in the best treatment combination (Table 5) were analysed. The nutrient values of microgreens obtained in the study were compared with the nutrient content of mature counterparts using the secondary data (Supplementary Table 1-8). From the comparison, it was evident that microgreens are rich in nutrients compared to the mature counterparts and can supplement the recommended dietary

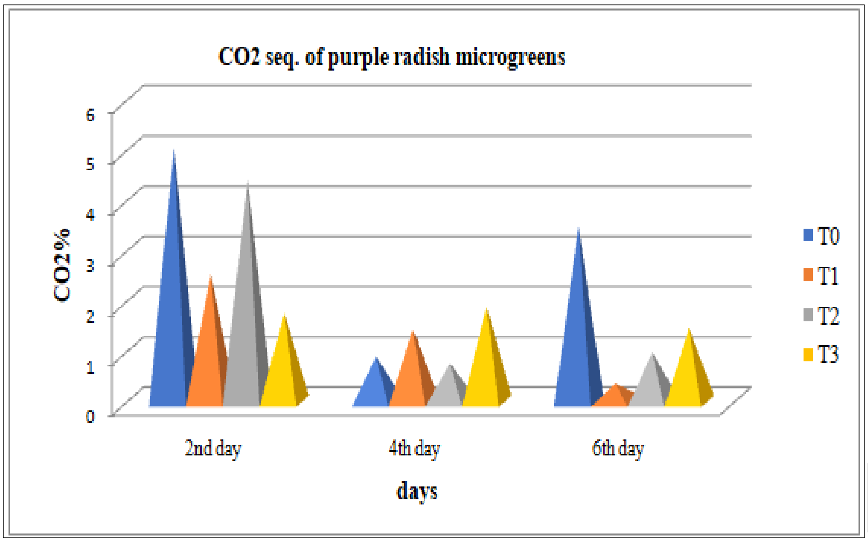
Table 5. Elemental profile of microgreens species

Elements	Purple radish microgreens	Fenugreek microgreens	Red amaranth microgreens	Coriander microgreens
Macro elements (mg 100 g^{-1})				
Phosphorous(P)	1116.23	1601.3	1755	952.69
Potassium (K)	5297.7	13204	8684.67	5946.5
Calcium (Ca)	191.7	246	288.19	188.4
Magnesium (Mg)	408.32	535.44	679.6	269.23
Sodium (Na)	1255	1701.7	2331.6	1105.36
Micro and Trace elements (mg 100 g^{-1})				
Boron (B)	16.44	5.068	8.149	3.906
Aluminium (Al)	5.1	45.87	11.126	10.7345
Barium (Ba)	0.3391	1.816	0.6468	0.5122
Iron (Fe)	22.05	129.9	0.3143	29.301
Copper (Cu)	5.03	27.9	7.8668	6.164
Zinc (Zn)	4.2	6.35	10.18	6.42
Manganese (Mn)	2.44	9.44	5.72	4.3559
Beryllium(Be)	0.004	-	-	0.004
Molybdenum(Mo)	0.1387	0.0501	0.1372	-
Silver (Ag)	-	0.0111	0.02	-
Vanadium (V)	0.0141	0.1105	0.037	0.037
Arsenic (As)	0.0073	0.0252	0.0102	-
Nickel (Ni)	0.12	0.17	0.353	-
Cadmium (Cd)	0.012	0.014	0.0086	-
Tin (Sn)	0.0339	0.04	0.0196	0.0101
Lead (Pb)	0.0073	0.014	0.0141	-
Lithium (Li)	0.03	0.032	0.0179	0.0125
Chromium (Cr)	0.05	0.19	0.1429	0.058
Cobalt (Co)	0.073	0.3643	0.1452	0.1331
Titanium (Ti)	0.803	2.536	1.2337	0.857
Antimony (Sb)	-	0.0087	0.0101	0.0003
Mercury (Hg)	0.0893	0.354	1.32	0.1144
Cesium (Cs)	0.0047	0.0113	0.0043	
Cadmium (Cd)	-	-	-	0.0038
Thallium (Tl)	0.0002	0.0015	-	0.0002

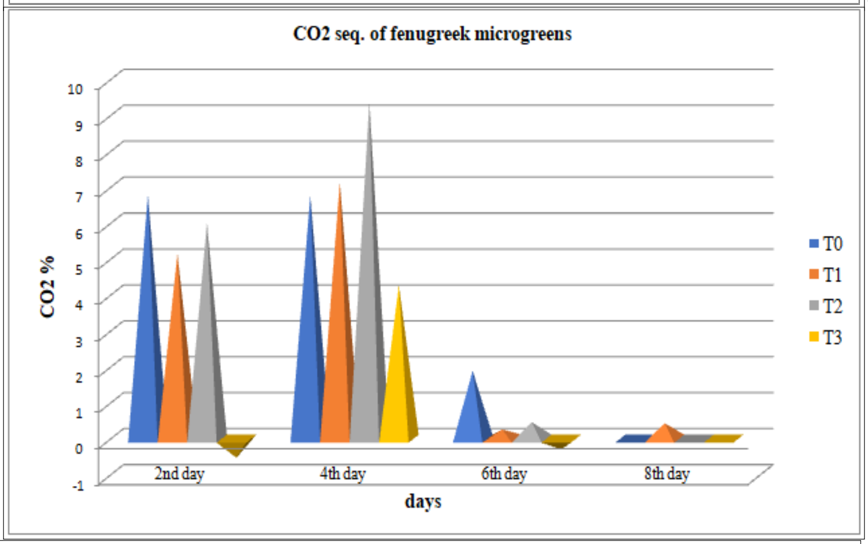
allowance (RDA) effectively.

Carbon sequestering ability of microgreens

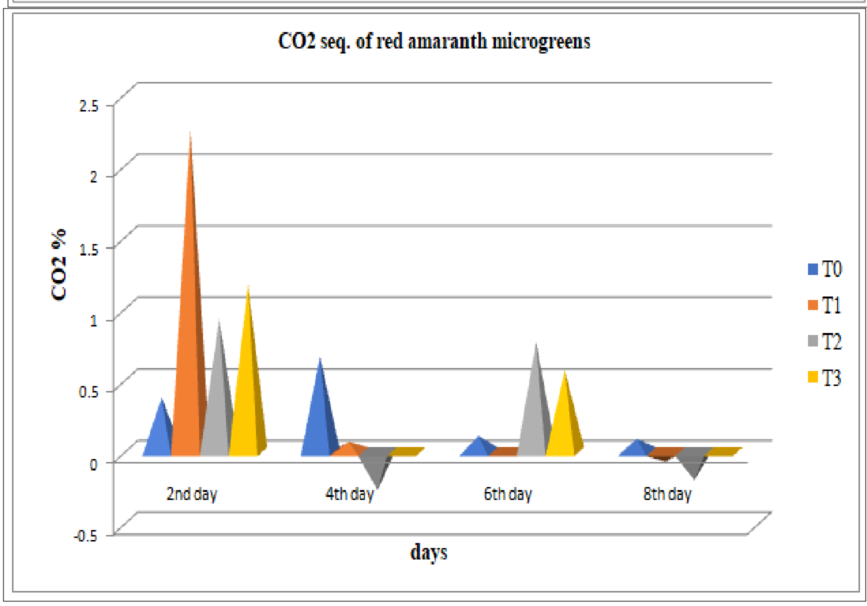
Carbon sequestering ability of individual microgreens species (Fig. 6A-6D) was attempted and it was found that fenugreek, red amaranth and coriander microgreens, though initially showed negative results, later turned positive for carbon sequestration. Carbon sequestration patterns differed for each microgreens species. It was visually observed that, when the size of the cotyledonary leaf (canopy) increased, the carbon fixation was higher. An increase in crop canopy enhances carbon sequestration by expanding the leaf area available for photosynthesis. A larger canopy captures more light and atmospheric CO_2, leading to higher photosynthetic rates and biomass production. It was reported that greater leaf area index (LAI) improves carbon uptake and promotes carbon storage in both plant tissues and soil through increased litter input (31). In microgreens, a denser canopy therefore contributes to higher carbon fixation efficiency and overall carbon accumulation. Hence, it is correlated that in the later stage of microgreens growth, a



A



B



C

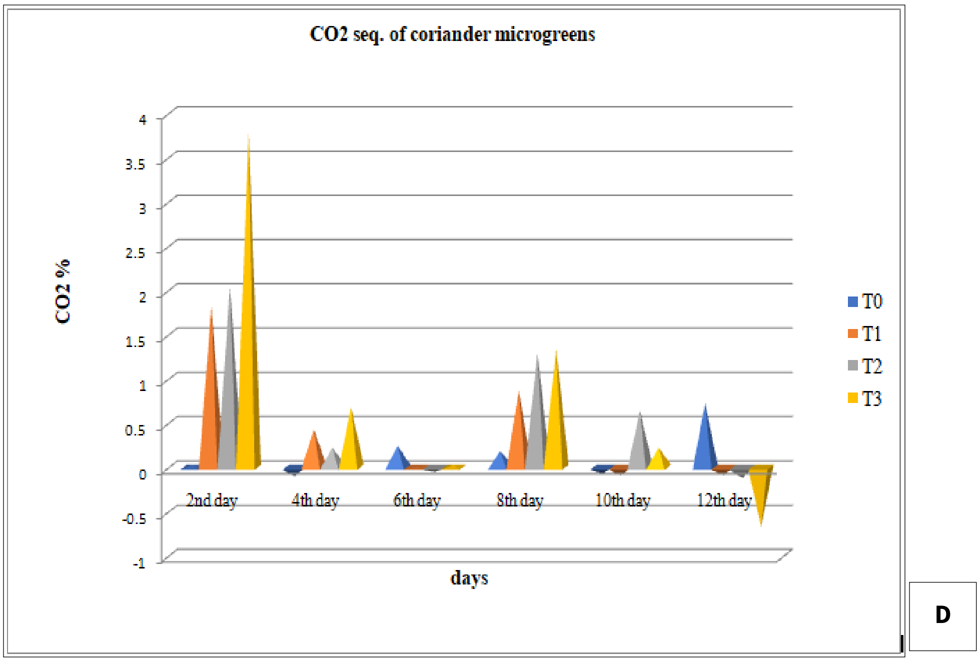


Fig. 6. Carbon sequestration of microgreens: **A.** Purple radish, **B.** Fenugreek, **C.** Red amaranth, **D.** Coriander.

high amount of carbon was sequestered. Purple radish microgreens showed negative results for carbon sequestration.

Conclusion

Among all the treatment combinations, 'Protray on plastic tray with seaweed extract' gave the best results for purple radish and coriander microgreens and 'Protray on plastic tray with vermiwash solution' gave the best results for maximum parameters in fenugreek and red amaranth microgreens in a vertical A-frame. It was also noted that microgreens are capable of supplementing the recommended dietary allowance (RDA). Though microgreens showed promising results in carbon sequestration, more research is required to fully understand the potential, as the type of growing system significantly influences the final carbon balance. In a nutshell, it may be concluded that microgreens in vertical A frame under a hydroponic system can be commercially exploited in urban landscapes, especially in the open terraces, balconies and other available spaces. This system gives the benefit of efficient utilisation of space, resources and high output for per unit of input.

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Authors' contributions

SP conducted the research, analysed the data and wrote the research article. SM guided in framing the research, gave financial assistance for conducting the research and corrected and proofread the research article. SS and AR contributed in the statistical analysis and proofread the research article. GI, SK and BK assisted during the set-up of the experiment and drafting the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflict of interest.

Ethical issues: None

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