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VERTICAL FARMING STRUCTURE FOR HOMESTEAD VEGETABLE CULTIVATION WITHIN RAINSHELTER

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ABSTRACT

Rainshelters, open-sided greenhouses suited for humid tropical climates, present an opportunity for homestead cultivation in Kerala. This study aimed to develop and evaluate a vertical farming structure tailored for rainshelters. A scientifically designed vertical farming structure was fabricated and compared with two existing counterparts, using Amaranthus CO-1 variety as the test crop. Drip irrigation at 1 litre per plant per day was employed. Data on climatic and biometric observations was used for the analysis of the structures' performance, with statistical analysis conducted using SPSS 16.0 software. Results indicated significant differences in light intensity, photosynthetically active radiation, and yield per plant between the structures and tiers, individually and in combination, at a 5% significance level. The newly fabricated vertical farming structure demonstrated a maximum benefit-cost ratio of 1.33. Positive net present worth values suggested project viability, with the new structure outperforming earlier counterparts in all aspects. The findings advocate for rainshelter cultivation of vegetables using vertical farming structures and drip irrigation, offering potential to enhance nutritional security in Kerala's homesteads.

Keywords: B: C ratio, Cost economics, Photosynthetically active radiation, Rainshelter, Vertical farming

It is predicted that by 2050 the global population could increase by additional 2 billion (UN, 2019), posing a significant challenge in terms of feeding the growing population (Frazer, 2020). Given that the majority of India's population relies on agriculture for their livelihoods, there's a pressing need to innovate, investigate, and adopt new techniques aimed at bolstering food resources (Bhangaonkar *et al.*, 2017). Adopting technologies such as vertical farming and high-tech agriculture is instrumental in addressing this challenge (Benke and Tomkins, 2017; Soojin and Chungui, 2023). Through the adoption of vertical farming (Despommier, 2013), it has become feasible to achieve higher crop yields using relatively smaller land areas. The controlled growing environment within a vertical farming structure situated inside a rainshelter contributes to enhanced productivity. The rain shelter effectively shields against ultraviolet rays, thereby augmenting the availability of photosynthetically active radiation. Additionally, crops can be safeguarded from harsh weather conditions. As population and urbanization rates surge, land becomes increasingly scarce. The concept of vertical farming is poised to gain broader acceptance and comprehension, facilitating the fulfillment of rising vegetable demands.

Nijwala and Sandhu (2021) highlighted vertical farming as a novel approach to sustainable agriculture, emphasizing its potential to bolster production to meet the demands of a burgeoning population while simultaneously conserving natural resources. Saxena (2021) explored advancements in sustainable urban farming, suggesting that widespread adoption of enhanced vertical farming methods globally could decrease energy expenditures and enhance farming profitability. Al-Kodmany (2018) delved into food security concerns, advocating for the integration of vertical farming alongside other high-tech agricultural practices like aquaponics and hydroponics, positing that such strategies would optimize food production by reducing operational costs and maximizing yields.

Bhangaonkar *et al.* (2017) examined the economic and environmental advantages of vertical farming employing a three-storey structure. Their findings revealed that this approach could yield three times more productivity and income compared to conventional methods. Al Mamun and Rahman (2018) assessed the sustainability of a red amaranth production trial within a vertical farm. The vertical farming setup comprised six plots across three vertical tiers, each positioned two feet above the next. They observed yield variability attributed to sunlight availability, noting that higher sunlight exposure in the upper layers resulted in increased yields. The primary objective of this study is to optimize the vertical space within the rain shelter.

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MATERIALS AND METHODS

Study area

The study was conducted within the rainshelter of the Precision Farming Development Centre (PFDC), situated in the instructional farm of KCAET, Tavanur, Kerala, India. Amaranthus crops were cultivated during September and October 2021 under this rainshelter. The location is positioned at approximately 10° 51' 18" N latitude and 75° 59' 11" E longitude, with an elevation of approximately 8.54 meters above mean sea level.

Development of Vertical Farming Structure (VFS)

The design of the vertical farming structure prioritized maximizing sunlight exposure, leveraging the relationship between solar altitude angle (β), crop height (H), and shadow length (L). To calculate the distance covered by the plant's shadow, the L/H ratio was multiplied by the plant's height. The selection of the L/H ratio depended on the solar altitude angle, with the highest solar irradiance typically observed during noon hours (11:00 AM to 3:00 PM), where the solar altitude angle is approximately $3\pi/8$ (Alonso *et al.*, 2020). Corresponding to this angle, a L/H ratio of 0.6 was chosen (Duncax, 1975).

The vertical farming structure (VFS) consists of three platforms on each side projecting outward and one platform on the top. The dimensions of the platforms were determined based on the selected L/H ratio and the average height of the crop. With an L/H ratio of 0.6 and an average crop height of 50 cm, the platform's width and height were fixed at 30 cm and 50 cm, respectively.

The fabricated VFS (VFS I) (Fig. 1) has a base width of 210 cm and a height of 200 cm, with two slanting faces of rectangular cross-section measuring 175 cm x 200 cm each. Platforms were constructed across the slanting faces to support the grow bags. A total of 42 grow bags, each with a diameter of 40 cm and a height of 24 cm, were placed in the VFS, with each platform accommodating 6 grow bags. The structural frame was constructed using mild steel tubes of varying dimensions, with MS flats fixed between the square tubes to support the grow bags.

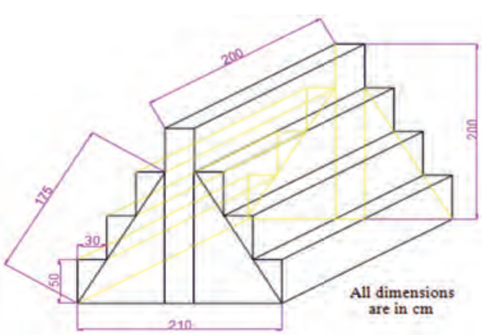
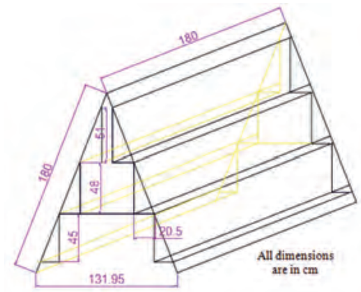


Fig. 1. Vertical Farming Structure I (VFS I)

Two vertical farming structures were chosen for the comparative performance evaluation of the newly fabricated structure within the rainshelter. VFS II (Fig. 2a) features a triangular cross-section with a base width of 131.95 cm and a height of 167 cm (Suhara and Nair, 2021). It comprises three platforms on each side, projecting inwardly. These platforms span the two slanting faces, each measuring 180 cm × 180 cm. The width of each platform is 20.5 cm, with heights of 51 cm, 48 cm, and 45 cm for the first, second, and third platforms from top to bottom, respectively. Each platform has the capacity to accommodate 4 grow bags, each with a diameter of 40 cm and a height of 24 cm.



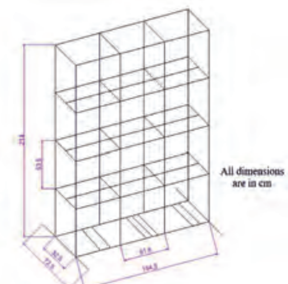


Fig. 2(a). Vertical Farming Structure II (VFS II) Fig. 2(b). Vertical Farming structure III (VFS III)

The current VFS III (Fig. 2b) is structured in tiers, standing at a height of 214 cm and spanning a width of 154.5 cm. It comprises four platforms stacked one above the other, each with a width of 32.5 cm. These platforms accommodate 3 grow bags, each with a diameter of 40 cm and a height of 24 cm.

Installation of VFS in rainshelter

The newly constructed VFS and two pre-existing VFSs were positioned within the rain shelter situated at the Precision Farming Development Centre (PFDC) on the instructional farm of KCAET. The rain shelter, measuring 20 m x 10 m x 4 m, is aligned in an East-West direction (Fig. 3). Its construction features 200-micron thick UV-stabilized polyethylene film for cladding material, while galvanized iron pipes form the frame structure.

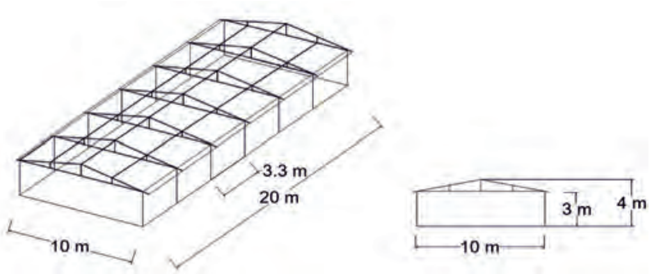


Fig. 3. Schematic drawing of rainshelter

Irrigation and fertilizer application

Daily irrigation was given via a drip irrigation system, ensuring sufficient water supply to the crop's root zone while minimizing water wastage. The discharge from the valve assembly flowed through the main pipe, where it was collected by lateral pipes. Water was delivered to the crops through micro tubes equipped with emitters with a discharge capacity of 2 litres per hour. The irrigation system operated for 30 minutes each day, guaranteeing that each plant received 1 litre of water per day. Fertilizers, including Factomphos-20:20:0:15, Urea-46:0:0, and Muriate of potash-0:0:60:17, were manually applied as basal doses in accordance with the recommendations of the Kerala Agricultural University. Following each harvest, top dressing was carried out using cow dung slurry, cow urine, or urea.

Planting method

Amaranthus CO-1 variety was selected for the study. Sowing was done on 07-08-2021**.** The seedlings were transplanted into the grow bags 25 days after sowing. Soil: Sand: Cowdung: Vermicompost in the ratio 1: ½: 1: ½ by volume was used as the growing media.

Observations on climatic and biometric parameters

Climatic parameters, including temperature and relative humidity within the rain shelter, were logged hourly over an 8-week period using a datalogger. Light intensity and photosynthetically active radiation (PAR) across various tiers of all three structures were assessed during morning (8:00 AM), afternoon (1:00 PM), and evening (5:00 PM) hours. Light intensity was gauged using a lux meter, while PAR was quantified using a quantum sensor. Two random plants from each of the four tiers within each vertical farming structure were designated as observation plants. Biometric data, encompassing plant height, number of branches, and yield of each observation crop, were recorded prior to each harvest

Statistical analysis

The impact of two independent variables, namely structure and tier, on dependent variables such as light intensity, PAR, yield, plant height, and number of branches, was examined through two-way Analysis of Variance (ANOVA) with replication using SPSS 16.0. Means were separated using Tukey's test.

Cost economics

The economic viability of Amaranthus cultivation in VFS within the rain shelter was assessed by considering current input and produce prices. Benefit-Cost (B-C) ratio, Net Present Worth (NPW), and Internal Rate of Return (IRR) were computed. The B-C ratio compares the present value of plant benefits to the investments made, serving as an indicator of financial feasibility. It is calculated as the present worth of total benefits divided by the present worth of total costs.

NPW represents the difference between the present value of cash inflows and outflows. It involves discounting the net cash flow of the project back to the present, thus determining the total present worth of all cash flow transactions.

IRR refers to the annual discount rate at which the present worth of two streams of cash flow is equal, or when the net present worth equals zero. It is determined by cash flows and remains unaffected by interest rates.

RESULTS AND DISCUSSION

Temperature and Relative humidity

Air temperature and relative humidity (RH) inside the rainshelter were measured during the study period using a datalogger and the recorded values at 8 am, 1 pm and 5 pm are plotted in Fig. 4, 5 and 6, respectively.

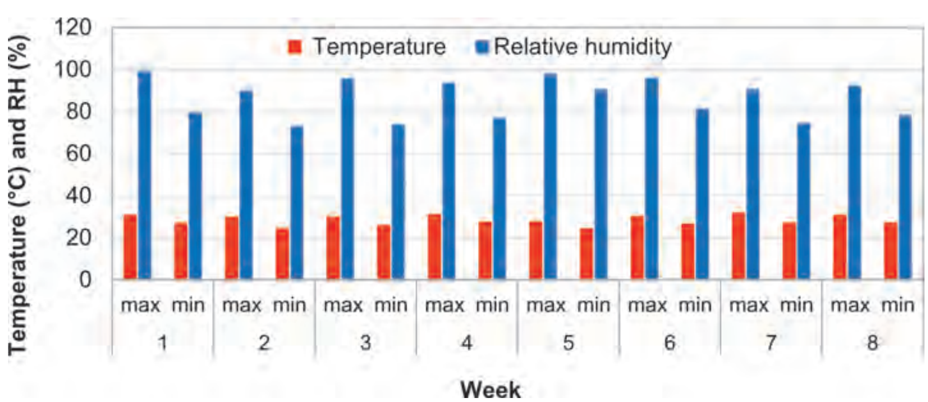


Fig. 4. Variation in temperature and RH (maximum and minimum) at 8 AM

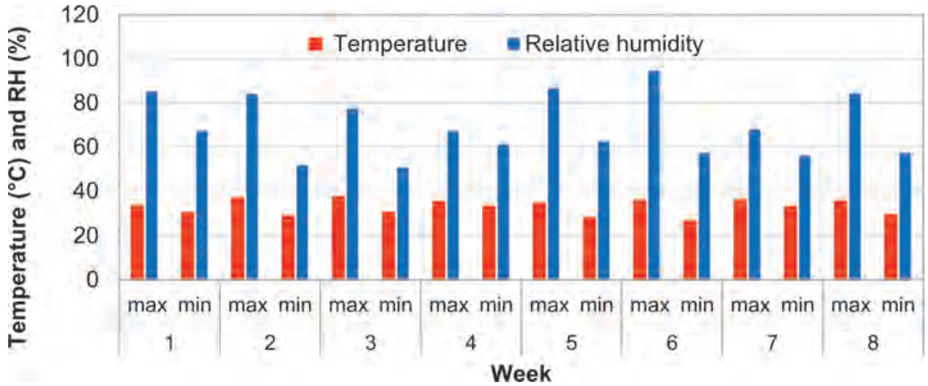


Fig. 5. Variation in temperature and RH (maximum and minimum) at 1.00 PM

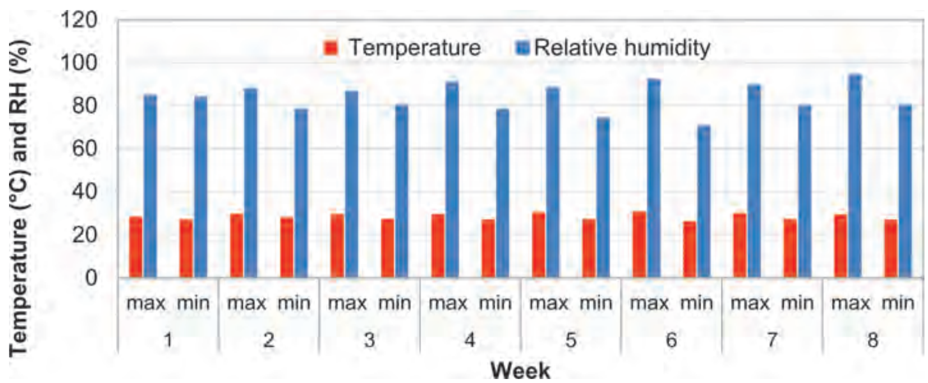


Fig. 6. Variation in temperature and RH (maximum and minimum) at 5.00 PM

The temperature and relative humidity variation inside the rainshelter showed a similar trend in all weeks. Higher temperature was recorded during afternoon hours and lower temperature was recorded during early morning hours. At 8:00 AM, maximum temperature recorded was 31.6°C (7th week) and minimum temperature recorded was 24.1°C (5th week). During afternoon hours, temperature recorded a maximum value of 37.28°C (3rd week) and minimum value of 26.6°C (6th week). Maximum and minimum temperature recorded at 5:00 PM were 30.4°C (6th week) and 26°C (6th week), respectively. Higher relative humidity was recorded during early morning hours and lower relative humidity was recorded during afternoon hours. At 8:00 AM recorded a maximum RH of 98.9% (1st week) and minimum RH of 72.8% (2nd week). At 1:00 PM, maximum RH recorded was 94.5% (6th week) and minimum RH recorded was 50.59% (3rd week). At 5:00 PM recorded a maximum and minimum RH of 94.3% (8th week) and 70.5% (6th week), respectively.

Light intensity

The variation of light intensity inside and outside the rainshelter was measured to understand the percentage reduction of light intensity inside the rainshelter compared to outside and is plotted in Fig. 7. Almost 40% reduction in light intensity was observed inside the rainshelter when compared to that of outside.

Fig. 8. shows the variation of light intensity with respect to VFS I, VFS II and VFS III and different tiers at 1:00 PM.

The statistical analysis of light intensity as influenced by structures and tiers was carried out. The P-value obtained after carrying out the Analysis of Variance (ANOVA) was less than 0.05 (Table 1). It indicates that the light intensity at 1:00 PM significantly varied between the structures and tiers individually and in combination at 5 % level of significance. Light intensity increased with increase in height of the VFS. Maximum and minimum light intensity was observed in Tier 4 and Tier 1, respectively. VFS I showed maximum light intensity in all tiers. Minimum light intensity was observed in VFS III except for Tier 4 as the Tier 4 of VFS III was at a height more than Tier 4 of EVFS I. Maximum intensity observed was 34093 lux in Tier 4 of VFS I and minimum intensity recorded was 16464 lux in Tier 1 of VFS III.

Photosynthetically active radiation (PAR)

The variation in PAR with respect to VFS I, VFS II and VFS III and different tiers at 1:00 PM is shown in

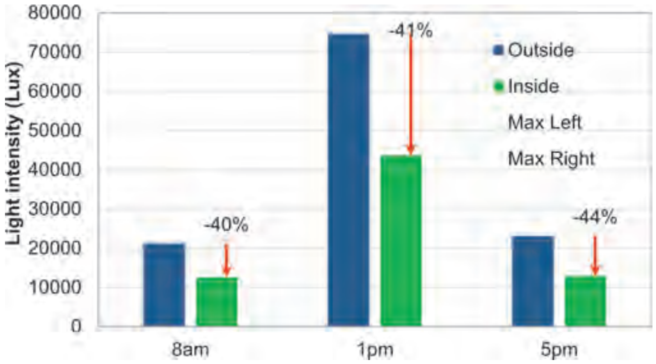


Fig. 7. Variation in light intensity inside and outside the rainshelter

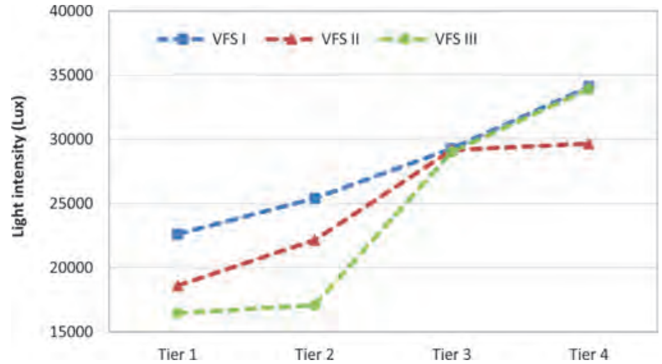


Fig. 8. Variation in light intensity with structures and tiers

Table 1. Statistical analysis of variation in different parameters with respect to structure and tier

	Light Intensity	PAR	Yield	Height of plants	No. of branches
Source			P-value		
Corrected Model	0.000	0.000	0.000	0.000	0.008
Intercept	0.000	0.000	0.000	0.000	0.000
Structure	1.59E-10	8.81E-08	2.6E-13	0.000189	0.000412
Tier	2.35E-16	9.83E-11	2.26E-12	9.48E-05	0.005622
Structure * Tier	1.64E-09	4.71E-05	2.53E-07	0.672	0.105

Fig 9. The results obtained during statistical analysis of PAR as influenced by structures and tiers are given in Table 1. A P-value less than 0.05 indicate that the PAR also significantly varied between the structures and tiers individually and in combination at 5% level of significance. PAR increased with increase in height of the VFS. Maximum and minimum PAR was observed in Tier 4 and Tier 1, respectively. VFS I showed maximum PAR in all tiers. Minimum PAR was observed in VFS III except for Tier 4. The reason is that Tier 4 of VFS III was at height more than Tier 4 of VFS II. Maximum PAR observed was 676 µmol m^{-2} s^{-1} in Tier 4 of VFS I and minimum PAR recorded was 294 µmol m^{-2} s^{-1} in Tier 1 of VFS III.

Yield

The total number of harvests obtained were four. First harvest was obtained 25 days after planting. Then, at 10 days interval each, three more harvests were done. The variation of yield data in structures with respect to tiers is shown in Fig. 10. From the ANOVA results (Table 1), it is clear that P-value is less than 0.05, which implies that the yield showed a significant difference between structures and tiers individually and in combination at 5 % level of significance. Since light intensity and PAR was more in VFS I, maximum yield was obtained in VFS I followed by VFS II and VFS III, respectively. Yield increased with increase in height of the structure with Tier 4 having the maximum yield and Tier 1 having the minimum yield. Maximum yield of 330 g was observed in Tier 4 of VFS I and minimum yield of 118 g was observed in Tier 1 of VFS III.

Height

The variation of height of the plant with respect to VFS I, VFS II and VFS III and different tiers is shown in Fig 11. After carrying out statistical analysis (Table 1), it is evident that a P-value less than 0.05 indicates that the height of the Amaranthus plant significantly varied between the structures and tiers individually at 5 % level of significance. There was no significant difference in height with combination of structure and

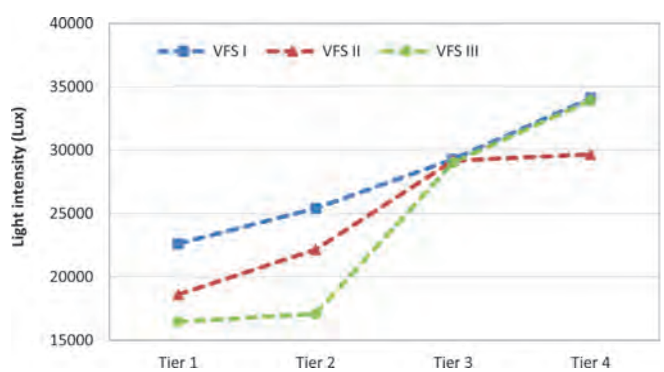


Fig. 9. Variation in Photosynthetically active radiation (PAR) with structures and tiers

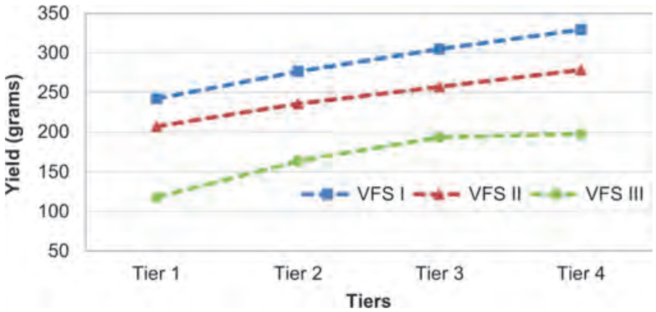


Fig. 10. Variation in yield with structures and tiers

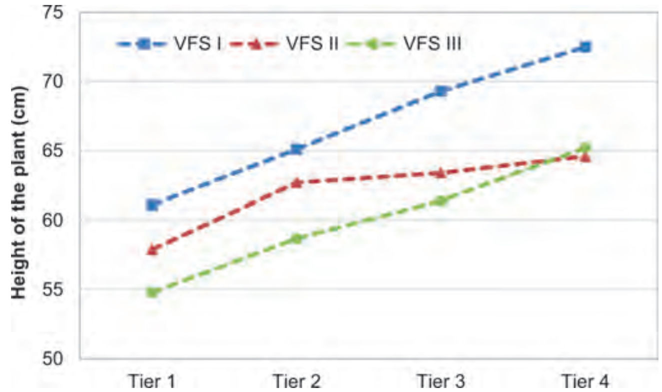


Fig. 11. Variation in plant height with structures and tiers

tier. With increase in height of the VFS, plant height also increased. Plants in VFS I recorded maximum height. Minimum height was observed in VFS III except in Tier 4 as the Tier 4 of VFS III was at a height more than Tier 4 of VFS II. Maximum height (72.5 cm) was observed in Tier 4 of VFS I and minimum height (54.8 cm) was observed in Tier 1 of VFS III.

Number of branches

Fig. 12 shows the variation in number of branches with respect to VFS I, VFS II and VFS III and different tiers. The statistical analysis of number of branches as influenced by structures and tiers is given in Table 1. The results from statistical analysis showed that P-value is less than 0.05, which indicates that the number of branches of the Amaranthus plant varied significantly between the structures and tiers at 5 % level of significance. Number of branches doesn't show any significant difference in combination of structure and tier. With increase in height of the VFS, number of branches increased. The maximum number of branches was recorded in VFS I and the minimum in VFS III except for Tier 4. The reason is that Tier 4 of VFS III was at a height more than Tier 4 of VFS II. Maximum number of branches was observed in Tier 4 of VFS I and minimum number of branches was observed in Tier 1 of VFS III.

Cost economics

The economic assessment of vertical farming structures within rain shelters was conducted based on

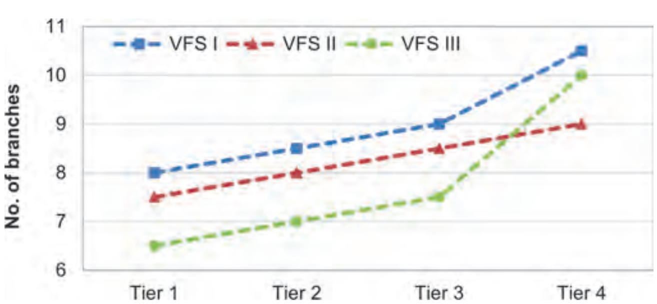


Fig. 12. Variation in number of branches with structures and tiers

the following assumptions. Given that Amaranthus was the cultivated crop in the experiment, it was presumed that four crops of Amaranthus could be grown in a year, considering the maximum crop period of only 2.5 months after transplantation.

Assumptions and basic data:

Expected life of the system is 12 years

Annual growth rate of costs and benefits is 5%

Salvage value is nil

The costs and benefits are discounted at 12%

Size of the rainshelter: 20 x 10 m

Cost of construction of rainshelter: Rs 750/ m^2

Cost of UV sheet: Rs 65/m^2 and cost of irrigation system: Rs 75/m^2

Price of amaranthus: Rs 38/kg

Capital cost: Cost of construction+cost of irrigation system+cost of VFS

Cost economics of VFS I in rainshelter

The cost economics of VFS I in rainshelter was done based on the following data:

Cost of VFS I: Rs 1500/m^2

Cost of cultivation of Amaranthus: Rs 60/m^2

Yield of Amaranthus: 3 kg/m^2

Benefit- Cost ratio: 1.33; Net Present Worth (Rs): 193764; Internal Rate of Return (IRR): 21.6%

Cost economics of VFS II in rainshelter

The cost analysis of VFS II within the rain shelter was conducted based on the following assumptions and is presented below:

Assumptions

Cost of VFS II: Rs 1300/m^2

Cost of cultivation of Amaranthus: Rs 58/m^2

Table 2. Economic analysis of VFS I in rainshelter

Year	Capital Cost	O&M Cost	Production Cost	Total Cost	Benefits	Discount Factor	Present worth of Costs	Present worth of Benefits	Cash Flow	NPW
1	465000		12000	477000	91200	1.000	477000	91200	385800	385800
2			12600	12600	95760	0.893	11250	85500	83160	74250
3			13230	13230	100548	0.797	10547	80156	87318	69609
4		13650	13891	27542	105575	0.712	19603	75146	78034	55543
5			14586	14586	110854	0.636	9270	70450	96268	61180
6			15315	15315	116397	0.567	8690	66047	101081	57356
7		15802	16081	31883	122217	0.507	16153	61919	90334	45766
8			16885	16885	128328	0.452	7638	58049	111442	50411
9			17729	17729	134744	0.404	7161	54421	117014	47260
10		18292	18616	36908	141481	0.361	13309	51020	104573	37710
11			19547	19547	148555	0.322	6294	47831	129008	41537
12			20524	20524	155983	0.287	5900	44841	135459	38941
Total		47744	191006	703749	1451642		592815	786579	747893	193764

Currency units: INR

Yield of Amaranthus: 2.5 kg/m^2

Benefit-Cost ratio: 1.19; Net Present Worth (Rs): 106118; Internal Rate of Return (%): 17.8

Cost economics of VFS III in rainshelter

The cost economics of VFS III in rainshelter was done making the following assumptions and is presented below.

Assumptions

Cost of VFS III: Rs 900/m^2

Cost of cultivation of Amaranthus: Rs 55/m^2

Yield of Amaranthus: 2 kg/m^2

Benefit-Cost ratio: 1.13; Net Present Worth (Rs): 60196; Internal Rate of Return (%): 16.1

For VFS I, the benefit cost ratio of 1.33 was noted. VFS II and VFS III obtained a lower benefit cost ratio of 1.19 and 1.13, respectively. Net present worth was found to be Rs 1,93,764 for VFS I, Rs 1,06,118 for VFS II and Rs 60,196 for VFS III. The positive values of NPW indicated that the project is viable. Internal rate

Table 3. Economic analysis of VFS II in rainshelter

Year	Capital Cost	O&M Cost	Production Cost	Total Cost	Benefits	Discount Factor	Present worth of Costs	Present worth of Benefits	Cash Flow	NPW
1	425000		11600	436600	76000	1.000	436600	76000	360600	360600
2			12180	12180	79800	0.893	10875	71250	67620	60375
3			12789	12789	83790	0.797	10195	66797	71001	56602
4		13650	13428	27078	87980	0.712	19274	62622	60901	43348
5			14100	14100	92378	0.636	8961	58708	78279	49747
6			14805	14805	96997	0.567	8401	55039	82193	46638
7		15802	15545	31347	101847	0.507	15881	51599	70501	35718
8			16322	16322	106940	0.452	7383	48374	90617	40991
9			17138	17138	112287	0.404	6922	45351	95148	38429
10		18292	17995	36288	117901	0.361	13086	42516	81613	29431
11			18895	18895	123796	0.322	6084	39859	104901	33775
12			19840	19840	129986	0.287	5704	37368	110146	31664
Total		47744	184639	657383	1209702		549365	655483	552319	106118

Currency units: INR

Table 4. Economic analysis of VFS III in rainshelter

Year	Capital Cost	O&M Cost	Production Cost	Total Cost	Benefits	Discount Factor	Present worth of Costs	Present worth of Benefits	Cash Flow	NPW
1	345000		11000	356000	60800	1.000	356000	60800	295200	295200
2			11550	11550	63840	0.893	10313	57000	52290	46688
3			12128	12128	67032	0.797	9668	53438	54905	43770
4		13650	12734	26384	70384	0.712	18780	50098	44000	31318
5			13371	13371	73903	0.636	8497	46967	60532	38469
6			14039	14039	77598	0.567	7966	44031	63559	36065
7		15802	14741	30543	81478	0.507	15474	41279	50935	25805
8			15478	15478	85552	0.452	7002	38699	70074	31698
9			16252	16252	89829	0.404	6564	36281	73577	29717
10		18292	17065	35357	94321	0.361	12750	34013	58964	21263
11			17918	17918	99037	0.322	5769	31887	81119	26118
12			18814	18814	103989	0.287	5408	29894	85175	24486
Total		47744	175088	567832	967761		464190	524386	399929	60196

Currency units: INR

of return came out to be 21.6%, 17.8% and 16.1% for VFS I, VFS II and VFS III, respectively. From the results of economic analysis, it was clear that cultivation in VFS I is more economical than VFS II and VFS III in Rainshelter. The VFS I was the newly designed and fabricated vertical farming structure, designed based on scientific principles so that maximum light intensity is available to all plants in all the tiers.

Shao *et al.* (2016) noted that the economic viability of most sun-fed vertical farms heavily depends on solar radiation availability. They found that, considering average plant price levels, these farms tend to barely break even in terms of financial returns. However, in the current study, since the benefit-cost ratios of all three structures exceed 1, it can be concluded that vertical farming is suitable within rain shelters for homestead cultivation in Kerala. Among the structures, VFS I demonstrates the best performance and highest economic output. This vertical farming approach could enhance productivity per unit area and indirectly reduce environmental footprint. Similar findings have been reported by other researchers (Benke and Tomkins, 2017; Kalantari *et al.*, 2017).

The comparison of vertical farming structures involved assessing climatic parameters (temperature, relative humidity, light intensity, and PAR) alongside biometric observations (yield, height, and number of branches). Statistical analysis revealed significant differences in light intensity and PAR at 1:00 PM among the structures and tiers individually, as well as in combination, at a 5% level of significance. Additionally, an increase in tier height corresponded to higher light intensity and PAR. Yield per plant also significantly varied between structures and tiers individually and in combination at a 5% level of significance.

It can be concluded that scientifically designed vertical farming structures offer significantly better sunlight intensity and PAR to crops compared to arbitrarily constructed structures. The improved growth and yield observed on scientifically designed structures can be attributed to enhanced sunlight incidence. Therefore, this study recommends the use of scientifically designed vertical farming structures wherever applicable. Rain shelter cultivation of vegetables, utilizing vertical space through vertical farming structures and drip irrigation, is suitable for increasing production in Kerala homesteads.

Moreover, the cost analysis revealed a maximum benefit-cost ratio of 1.33 for the scientifically designed vertical farming structure, indicating project viability. Positive NPW values further support project feasibility. Overall, the study results demonstrate that VFS I outperforms existing structures in all aspects.

Authors' contribution

Conceptualization of research work and design of experiments (GP, AV); Execution of field/lab experiments and data collection (GP); Analysis of data and interpretation (GP, AV); Preparation of manuscript (GP, AV).

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