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Shivanjali D Bhosale
M-tech Scholar (RES), CAET, DBSKKV, Dapoli, Maharashtra, India

Mohod AG
Department of Electrical and Other Energy Sources, CAET, DBSKKV, Dapoli, Maharashtra, India

Khandetod YP
Department of Electrical and Other Energy Sources, CAET, DBSKKV, Dapoli, Maharashtra, India

Dhande KG
Department of Farm Machinery and Power, CAET, DBSKKV, Dapoli, Maharashtra, India

Patil MB
Department of Electrical and Other Energy Sources, CAET, DBSKKV, Dapoli, Maharashtra, India

Corresponding Author:
Shivanjali D Bhosale
M-tech Scholar (RES), CAET, DBSKKV, Dapoli, Maharashtra, India

Studies on solar photovoltaic assisted lighting and water circulation system for indoor crop production

Shivanjali D Bhosale, Mohod AG, Khandetod YP, Dhande KG and Patil MB

Abstract
Modern concepts for vertical farming make use of indoor farming methods and controlled- environment agriculture (CEA) technology, allowing for the artificial control of all environmental parameters, including light, humidity, and temperature. The objective of this research is to study the solar photovoltaic assisted lighting and water circulation system for indoor crop production. Before developing the system for research, the photobiology of indoor crop production at Dapoli (17° 45’ N and 73° 26’ E) was studied. According to all recorded parameters in photobiology study, it is concluded that there is need to provide solar photovoltaic assisted lighting (i.e. LED grow lights) for indoor crop production to fulfil as much as possible requirement of Photosynthetically Active Radiations (PAR). This photobiology is suitable for long day plants like spinach, basil, etc. On the basis of this study, the vertical farming system with solar photovoltaic assisted lighting and water circulation system was developed and evaluated. Hydroponic vertical farming system with Deep Flow Technique (DFT) was developed. Evaluation of system reveals that the SPV assisted light of 32.5 µmol/m2/s was provided for the period of an extra 5 hrs than the indoor system without light. All the crop growth parameters measured for treatments T1 (Indoor plant in top row with lighting) and T2 (Indoor plant in bottom row with lighting) were greater than the treatments T3 (Indoor plant in top row without lighting) and T4 (Indoor plant in bottom row without lighting) due to the provided supplementary lighting and increased photoperiod.

Keywords: Vertical farming, SPV assisted light, Photosynthetically Active Radiations (PAR), photobiology, hydroponics, water circulation

1. Introduction

India’s population is growing at a rate of about 1.2% per year with 1.41 billion current population. The country only has about 2.4% of the world’s land area, but it is home to about 17.5% of world’s population. This means that the country’s land resources are under a lot of pressure. There is need in India to make investments in agriculture. One way to increase food production for growing population is to use vertical farming. This is a type of agriculture where crops are grown in vertically stacked layers in a controlled environment. In this study the Deep Flow Technique (DFT) of hydroponics was selected among the all other types of vertical farming. Crops were grown hydroponically in vertical farming system at two different locations i.e. indoor (partial sunlight area) and outdoor. The study area i.e. Konkan region is characterized as humid zone. There is need to provide additional light to the plants in Konkan region as there are cloudy days in this region between June and September which cut down on the amount of hours of bright sunshine. Also at the indoor location where partial sunlight reaches there is need to provide additional supplementary lighting to fulfill the light requirement of the plants for photosynthesis.

The sun is a primary source of energy and all form of energy on the earth is derived from it. The potential for solar energy is the highest of any renewable energy source. One of the most rapidly expanding renewable energy technologies in the world is solar PV. This is a result of its easy installation, adaptability in terms of size, low cost of operation and maintenance, and environmental friendliness due to the lack of hazardous greenhouse gas emissions. Here, solar energy is converted to electricity using solar PV panels. Supplementary lighting given to the plants was powered by Solar Photovoltaic (SPV) which uses sun as a renewable source of energy. From that same SPV panel the dc pump also powered which was used to circulate nutrient solution through the hydroponic vertical farming system.

This research work is aimed for developing vertical farming system with SPV driven supplementary lighting and water circulation using DC pump. Combining the supplementary lighting will help in increasing plant production.

2. Material and Methods

2.1 Study area

The development of SPV assisted lighting and water circulation system and its performance evaluation for indoor crop production was carried out at Dapoli, a city in Ratnagiri district of Konkan region. The Konkan region is characterized as humid zone. The climatic conditions are typical coastal i.e. hot and humid.

2.2 Collection of data

The data for climatological parameters i.e. solar intensity, Photosynthetically Active Radiations (PAR), photoperiod, dry bulb temperature, wet bulb temperature and relative humidity required for the study of photobiology of indoor crop production were recorded for outdoor and indoor (partial sunlight area) conditions three times a day (8:00, 12:00, 16:00) during period of 1st January 2022 to 31st May 2022. The monthly average of all these recorded parameters was calculated and analysed for studying photobiology of indoor crop production.

2.3 Development of SPV assisted lighting and water circulation system for indoor crop production

Omponents of system

Solar panel (1095 X 535 X 30 mm size and voltage 12 V), storage battery (12V, 25 Ah), voltage regulator (stabilize voltage to 12 V), two full spectrum LED grow light strips each of 5 m length with 60 lights per meter (12 V, 14 Watt/m), DC water pump (12 V, 8W), vertical farming system and nutrient solution stock tank are the components of the indoor crop production system.

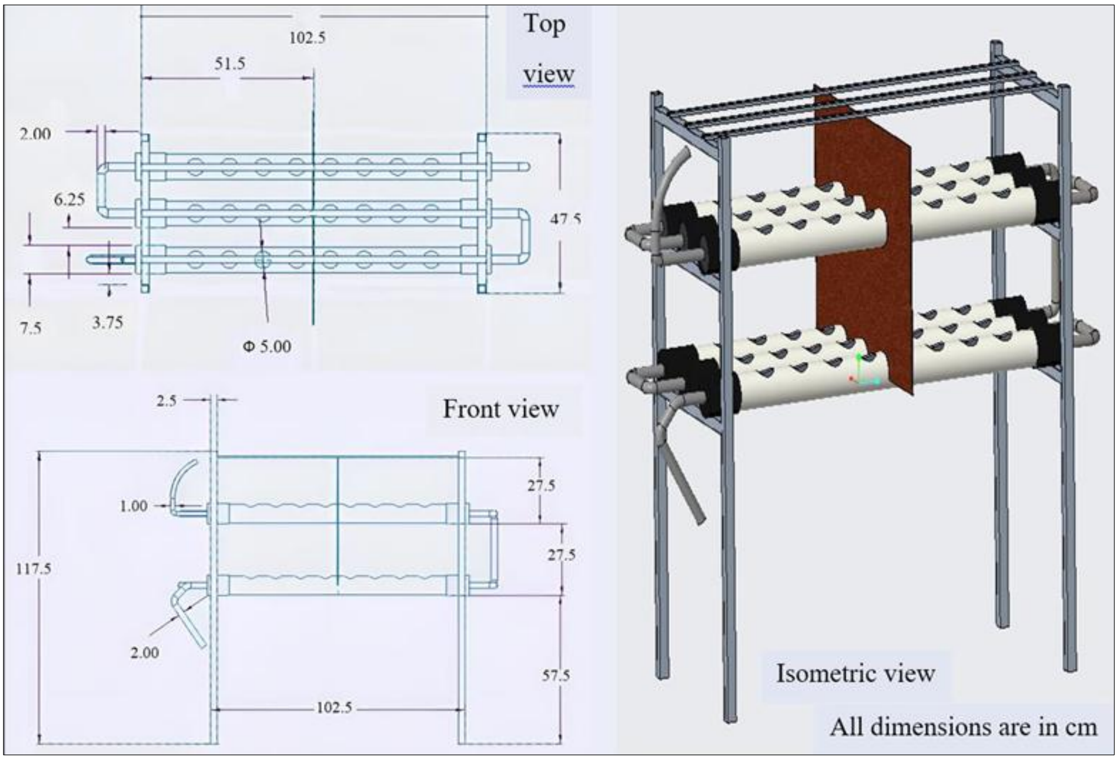

Fig 1: Schematic view of vertical farming system

2.3.1 Esign parameters of grow lights

LED grow lights were selected as supplementary lights with R:B ratio as 4:1 (Bian *et al.*, 2018). The wavelength of lies between 400 and 700 nm. Per day difference between atmosphere and in the indoor was calculated, and according to that difference the electrical power input for supplementary lighting was provided. LED lights were kept close enough to the plants where plants can get the required amount of light intensity.

2.3.2 Design of SPV system for supplementary lighting and water pumping system

The dc pump having power 8 W was run for 10 minutes per day and the LED grow lights having power 98 W runs for 8 hours per day. Depending upon this data SPV system was designed (G.D. Rai, 2017).

Direct current required (A)	Battery size (Ah)	Battery charging current (A)	No. of batteries required	Total Solar plate current (A)	Total power supplied from solar plates (W)	No. of solar plates required
6.5	25	2.5	1	9	108	2

2.2.4 Design of hydroponic vertical farming system

For this study Deep Flow Technique (DFT) of hydroponics was selected with cockpit and vermicompost as a growth material. Depending on photobiology, the long day plants spinach and basil were chosen for growing them into the system. In this system, six PVC pipes were used, three pipes each for the top and bottom layer of the system. All the pipes were connected to each other with laterals. Eight holes of 5 cm diameter were made in each pipes for the net pots filled with growth material. With the help of car board partition, system was vertically divided into two parts as one part with supplementary lighting and another part without supplementary lighting. Similar PVC pipes were kept at outdoor.

2.4 Performance evaluation of developed system

2.4.1 Details of plantation of experimental crop

Initially seeds were collected from local market, then media was prepared and the ratio in which cockpit and vermicompost used was 3:1, V/V (Bian et al., 2018). Sowing was done on 10th June, 2022 and final harvesting was done on 25th July, 2022, following the initial harvest on 10th July, 2022.

2.4.2 Performance evaluation of SPV assisted lighting unit

2.4.2.1 Details of treatments

All the treatments were given same to both the selected plants (spinach and basil). For recording observations 5 replications of each treatment were selected. The treatments are: T1 – Indoor plant in top row with lighting, T2-Indoor plant in bottom row with lighting, T3-Indoor plant in top row without lighting, T4 - Indoor plant in bottom row without lighting, T5 - Outdoor plants.

2.4.2.2 Parameters measured during crop production period

All the climatological parameters as mentioned earlier in 2.2 were recorded for outdoor condition as well as for indoor condition with supplementary light and without supplementary light, three times a day i.e. at 8:00, 12:00, and 16:00.

2.4.4.3 Plant growth parameters

All the plant growth parameters i.e. days required for germination, number of leaves per plant, height of plant (cm), leaf length (cm), leaf width (cm), leaf area (cm2), shoot fresh weight (g), root fresh weight (g), shoot dry weight (g), root dry weight (g), leaf fresh weight (g), leaf dry weight (g), Root-to-shoot ratio, Specific Leaf Area (cm2/ g), Leaf Area Ratio (cm2/ g), Relative Growth Rate (g/g/day) and Net Assimilation Rate (g/cm2/day) were determined by randomly selecting 5 plants each of spinach and basil from each treatment (Phadnis, 1999: Prasanna, 2019: Chandrakar, 2019: Brazaityte *et.al.*, 2010).

2.4.3 Performance evaluation of SPV based water pumping system

According to Hassan *et al.*, 2019, the developed SPV based water pumping unit was evaluated as follows:
The efficiency of PV panel to calculate the gained energy from the incident solar energy was determined using the following equation:

IP�× VP�
�� × AP� × 100 (1)

Where
ηPV = PV efficiency, %
I_{PV} = Output current of PV, Ampere
V_{PV} = Voltage output PV, Volt
A_{PV} = Surface area of PV panel, m^2
SR = Average solar radiation intensity, W/m^2

The required electrical energy for operating the pump was calculated as the following equation

$$Ee = I \times V \times \text{operating time} \quad (2)$$

Where,
Ee = Electrical energy of the pump (Wh)
I = Current intensity (Ampere)
V = Voltage (Volt)

Operating time per day = 10 min = 0.17 hrs

$$Q = V/t \quad (3)$$

Where,
Q = Discharge of pump (m3/s)
V = Volume of water (m3)
t = Time (sec)

The output hydraulic energy of pump was calculated as the following equation

$$Eh = \frac{\rho \times g \times Q \times t \times TDH}{3600} \quad (4)$$

Where,
Eh = Hydraulic energy of pump (Wh)
ρ = water density (1000 kg/m^3)
g = gravity acceleration (9.81 m/s^2)

TDH = the total dynamic head of pump (m), it concludes the head of pump and the head required to overcome friction loss (hf)

$$TDH = H + hf \quad (5)$$

Where,
hf = required head to overcome friction loss taken (20% of H).
The total efficiency of the pump was calculated by the following equation:

Where,
ηtp = Eh
Ee × 100 (6)

Where,
ηtp = Total efficiency of the pump (%)

2.4.4 Nutrient solution for hydroponics

The pH, electrical conductivity and temperature of nutrient solution were checked on daily basis to administer nutrient solution.

3. Results and Discussion

3.1 Photobiology of indoor crop production

The monthly average of recordings of all the parameters measured during study of photobiology of indoor crop production were given in the Table 1.
Depending on this photobiology, the long day plants spinach and basil were selected for the cultivation in vertical farming system.

Table 1: Monthly average of all the climatological parameters measured during study of photobiology of indoor crop production

Month	SI (W/m2)		PAR (µmol/m2/s)		Photoperiod, hr		Dry bulb temp., °C		Wet bulb temp., °C		Relative humidity, %	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
January	115.74	340.29	149.89	791.89	1.22	7.77	23.28	23.37	19.51	19.65	72.77	73.04
February	145.42	425.43	183.72	863.03	2.49	9.38	25.24	25.47	20.69	20.84	68.37	69.16
March	182.43	535.68	217.28	865.69	3.94	11.58	28.11	28.38	23.32	23.57	66.91	68.19
April	214.20	624.12	255.41	1061.14	5.93	12.49	31.87	32.09	25.97	26.21	62.09	62.61
May	204.64	603.17	246.88	883.09	5.45	11.81	31.58	31.82	27.34	27.53	65.82	66.42

Table 2: Average of all the climatological parameters measured during crop production period

Para.	SI (W/m2)			PAR (µmol/m2/s)					Photoperiod, hr			Dry bulb temp. °C		Wet bulb temp., °C		Relative humidity, %	
Location	1		3	1		2		3	1	2	3	1	3	1	3	1	3
	A	B		A	B	A	B										
Avg	74.10	70.40	183.77	121.24	116.57	153.64	149.17	338.37	2.47	7.47	8.22	27.73	27.84	26.14	26.27	82.7	83.07

Here, 1- Indoor, 2- Indoor with light, 3- Outdoor, A- Top layer, B- Bottom layer

3.2 Performance evaluation of SPV assisted lighting unit

3.2.1 Parameters measured during crop production period

The climatological parameters which were measured during crop production period i.e. from 10th June 2022 to 25th July 2022 during performance evaluation *viz.* solar intensity, Photosynthetically Active Radiation, photoperiod, dry bulb temperature, wet bulb temperature and relative humidity were recorded three times a day i.e. at 8:00, 12:00 and 16:00. There average values were given in Table 2. It can be seen that the supplementary light of 32.5 µmol/m2/s was provided for extra 5 hrs than the indoor system without light.

3.2.2 Plant growth parameters

- **a. Days required for germination:** A good percentage of germination in spinach and basil was obtained within 7-8 days.
- **b. Number of leaves per plant:** The highest and lowest number of leaves of spinach was reported in treatment T5 (17.8) and treatment T4 (9.4), respectively. The highest and lowest number of leaves of basil recorded in treatment T1 (18.2) and treatment T4 (8.8), respectively.
- **c. Height of plant:** The highest and lowest plant height of spinach recorded in the treatment T5 (20.00 cm) and treatment T4 (7.64 cm), respectively. Similarly, the highest and lowest plant height of basil recorded in the treatment T1 (16.24 cm) and treatment T4 (6.78 cm), respectively.
- **d. Leaf length:** The highest and lowest leaf length of spinach recorded in the treatment T5 (8.68 cm) and treatment T4 (3.94 cm), respectively. Similarly, the highest and lowest leaf length of basil recorded in the treatment T5 (4.50 cm) and treatment T4 (2.48 cm), respectively.
- **e. Leaf width:** The highest and lowest leaf width of spinach recorded in the treatment T5 (4.08 cm) and treatment T4 (2.20 cm), respectively. Similarly, the highest and lowest leaf width of basil recorded in the treatment T5 (3.58 cm) and treatment T4 (1.52 cm), respectively.
- **f. Leaf area:** The highest and lowest leaf area of spinach recorded in the treatment T5 (23.819 cm2) and treatment T4 (5.862 cm2), respectively. Similarly, the highest and lowest leaf area of basil recorded in the treatment T5 (11.466 cm2) and treatment T4 (2.702 cm2), respectively.
- **g. Shoot fresh weight:** The highest and lowest shoot fresh weight of spinach recorded in the treatment T5 (19.254 g) and treatment T4 (5.206 g), respectively. Similarly, the highest and lowest shoot fresh weight of basil recorded in the treatment T5 (14.338 g) and treatment T4 (6.718 g), respectively.
- **h. Root fresh weight:** The highest and lowest root fresh weight of spinach recorded in the treatment T5 (4.694 g) and treatment T4 (0.936 g), respectively. Similarly, the highest and lowest root fresh weight of basil recorded in the treatment T5 (3.854 g) and treatment T4 (1.342 g), respectively.
- **i. Shoot dry weight:** The highest and lowest shoot dry weight of spinach recorded in the treatment T5 (7.722 g) and treatment T4 (1.744 g), respectively. Similarly, the highest and lowest shoot dry weight of basil recorded in the treatment T5 (6.070 g) and treatment T4 (2.190 g), respectively.
- **j. Root dry weight:** The highest and lowest root dry weight of spinach recorded in the treatment T5 (2.700 g) and treatment T4 (0.420 g), respectively. Similarly, the highest and lowest root dry weight of basil recorded in the treatment T5 (2.392 g) and treatment T4 (0.768 g), respectively.
- **k. Leaf fresh weight:** The highest and lowest leaf fresh weight of spinach recorded in the treatment T5 (17.044 g) and treatment T4 (3.246 g), respectively. Similarly, the highest and lowest leaf fresh weight of basil recorded in the treatment T5 (12.028 g) and treatment T4 (4.398 g), respectively.
- **l. Leaf dry weight:** The highest and lowest leaf dry weight of spinach recorded in the treatment T5 (3.500 g) and treatment T4 (1.242 g), respectively. Similarly, the highest and lowest leaf dry weight of basil recorded in the treatment T5 (4.650 g) and treatment T4 (1.510 g), respectively.
- **m. Root-to-shoot ratio:** The highest and lowest leaf length of spinach recorded in the treatment T5 (0.3483) and treatment T4 (0.2823), respectively. Similarly, the highest and lowest leaf length of basil recorded in the treatment T2 (0.3930) and treatment T4 (0.3547), respectively.
- **n. Specific Leaf Area:** The highest and lowest root-to-shoot ratio of spinach recorded in the treatment T5 (6.8048 cm2/g) and treatment T4 (4.6833 cm2/g), respectively. Similarly, the highest and lowest root-to-shoot ratio of basil recorded in the treatment T1 (2.4870 cm2/g) and treatment T4 (1.7917 cm2/g), respectively.
- **o. Leaf Area Ratio:** The highest and lowest Leaf Area Ratio of spinach recorded in the treatment T5 (2.2813 cm2/g) and treatment T4 (2.0900 cm2/g), respectively.

Similarly, the highest and lowest Leaf Area Ratio of basil recorded in the treatment T5 (1.3589 cm2/g) and treatment T4 (0.9040 cm2/g), respectively.

p. **Relative Growth Rate:** The highest and lowest Relative Growth Rate of spinach recorded in the treatment T5 (0.0314 g/g/day) and treatment T4 (0.0223 g/g/day), respectively. Similarly, the highest and lowest Relative Growth Rate of basil recorded in the treatment T5 (0.0854 g/g/day) and treatment T4 (0.0702 g/g/day), respectively.

q. **Net Assimilation Rate:** The highest and lowest Net Assimilation Rate of spinach recorded in the treatment T5 (0.0139 g/cm2/day1) and treatment T4 (0.0107 g/cm2/day1), respectively. Similarly, the highest and lowest Net Assimilation Rate of basil recorded in the treatment T5 (0.0630 g/cm2/day1) and treatment T4 (0.0520 g/cm2/day1), respectively.

From the readings it is clear that of all the parameters of spinach and basil were greater in the plants grown under treatment T1 and T2 than treatment T3 and T4. This is because the supplementary light of 32.5 µmol/m2/s was provided for extra 5 hrs in the treatments T1 and T2 than the indoor system without light.

3.3 Performance evaluation of SPV based water pumping system

PV panel which is used in study have efficiency of 16.48 %. The electrical energy of dc pump used is 10.2 Wh. 0.000067 m3/s is the discharge of the pump. The calculated hydraulic energy is 7.846 Wh. Total efficiency of SPV based water pump is 76.92 %.

4. Conclusion

1. Solar photovoltaic assisted lighting and water circulation system for indoor crop production was successfully developed and the plants spinach and basil were grown.
2. From photobiology it was observed that there is difference of 110-550 W/m2, 90-1220 µmol/m2/s PAR and 6.25-7.75 hrs photoperiod between indoor and outdoor conditions.
3. There is negligible difference between indoor and outdoor dry and wet bulb temperature.
4. The supplementary light of 32.5 µmol/m2/s was provided for extra 5 hrs than the indoor system without light.
5. All the crop growth parameters measured for treatments T1 (indoor plants in top row with lighting) and T2 (indoor plant in bottom row with lighting) were greater than the treatments T3 (indoor plant in top row without lighting) and T4 (indoor plant in bottom row without lighting) due to the provided supplementary lighting and increased photoperiod.

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