Defence Life Science Journal, Vol. 9, No. 4, October 2024, pp. 342-351, DOI : 10.14429/dlsj.9.19660

Food Production in Ergonomically Designed Unit with Low Energy Consuming Thick Film Hot Plate

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ABSRACT

The Temperature in the cold region falls much below subzero and this makes the thermal supplementation necessary for normal functioning of man, machines, and crops. The Trans-Himalayan region of Ladakh is a cold desert where the temperature drops as low as -45 °C. The region is strategically very important and large numbers of troops are deployed for national security. Availability of basic needs is necessary for deciding their performance at such tough locations. Food constitutes one of the most important requirements and its unavailability causes nutritional deficiency in the deployed troops and locals, affecting their performance. Average low temperatures and mountainous soil make cultivation difficult at such locations. Suitable nutritious crops for the region grown in multitier, standardised, portable structures with soilless media integrated with energy efficient renewable energy based thermal supplementation system look potential solution for meeting nutritional requirements. Studies revealed that the crops of the B*rassicaceae* family like Radish, Cabbage, etc., and the fenugreek crop of the *fabaceae* family were found to be most suitable for the region considering its germination time and germination rate. Further 5:2:1 prepared media mixture of coco-peat, vermiculite, and perlite was found most suitable compared to soil, compost, and media mixture with other different compositions. Multitier aluminum frame-based structure with 16mm polycarbonate cladding material integrated with Alumina substrate-based low energy consuming (8W) thick film technology found suitable for average temperature maintenance of 18 °C to 20 °C at -25 °C to -40 °C outside ambient temperature. 24 number of low energy consuming small hotplates integrated with standardised structure of volume 1.05m^{3}is found capable of producing an average of 1000 g/trial/unit in a short period of 8-12 days during the winter period of 6-8 months for the targeted supply of 8-10 g/person/day with total energy consumption of approximately 20-25 KW/trial at ~3350 m to ~5400 m altitude above mean sea level.

Keywords: Passive; Active; Substrate; Screen printing

1. INTRODUCTION

The Trans-Himalayan region of Ladakh has extreme weather condition which includes wide variation in ambient temperature ranging from -45 °C to 45 °C, low humidity, low oxygen availability, harsh intense sunlight, etc. The region shares international borders and large numbers of troops are deployed. The inhospitable environment poses an adverse effect on the health and normal functioning of troops as well as the local population. In addition, the region mostly remains cut off from the outside world by heavy snowfall and avalanches en route, particularly during the long winter period. The dumping of essential food items having high shelf life and fossil fuels is carried out before the onset of winter. Fresh foods are hardly available to the inhabitants of the region and hence a special ration composed mostly of processed food containing food preservatives is provided to meet the essential nutritional requirements[1,2]. The nutritional value of food is an important contributor to physical and mental well-being that affects morale and operational efficiency and avoids diseases and disorders[2]. The Indian Council of Medical Research (ICMR) recommends a nutrition intake of 2000 to 2500 calories per healthy adult person per day with 250 g to 300 g of fresh vegetables (ICMR 2010, report); The World Health Organisation (WHO) also recommends 400 g of fresh vegetables and fruit per day (WHO/FAO report).

Fresh food cultivation is possible only by maintenance of suitable conditions inside the structures or by transportation from plain areas[3]. Transportation is difficult to such areas and even if transported erosion of nutrients takes place with time during transportation[2]. The temperatures recorded at Leh Ladakh, India were

Received : 28 November 2023, Revised : 12 April 2024
Accepted : 30 May 2024, Online published : 26 September 2024

in the range of -35 °C to 35 °C[3], and corresponding recorded temperatures inside existing structures were noticed much below subzero during winter months.

The inhabitants of the region along with army personnel are located in distant locations of the region where supplies of perishable items are not possible and further, they cannot be stored in bulk for regular supply. A crop with a short growing period and high nutritional value serves the purpose of fresh food supply at regular intervals as well as meeting nutritional deficiency. A small plantlet called Micro-greens is best suited due to its characteristics of a short growing period of 8-12 days in soilless media, the low space requirement for growing the same amount of fresh food (multitier), and more importantly high phyto nutrient content properties in comparison to mature counterpart[2,4].

It has been found that tiny plants (micro-greens) are also rich in different vitamins and minerals[5]. It has been observed that the minerals/vitamins content of tiny plants is comparable to their mature counterparts[2,4]. These plantlets have up to 4-40 times more vital nutrients than mature plants and are suitable for regions like Trans-Himalaya where there is water scarcity [2,7,8,9].

An Aluminum frame-based portable polycarbonate sheet micro-farming structure has been developed after several trial results. A customised low energy- consuming thick-film hot plate has also been conceptualised, developed, and integrated inside developed micro-farming units for maintaining the desired temperature necessary for micro-green cultivation. Thick-film technology has being used in the electronic industry for last so many years to produce hybrid circuits for various applications[6]. Hot plates based on thick film are highly rugged and reliable. Being miniature in size, weight, and volume they consume less power. Thick films are deposited through screen printing of pastes, usually formed with glass and metal powder, onto a substrate. The hotplates are connected through a temperature control mechanism in a manner that they get turned on automatically during the night or as per requirement for maintaining the desired temperature in the range of 15 °C - 20 °C. Trials have also been carried out for the selection of suitable crops for the region along with formulation of media mixture formulations.

2. MATERIALS AND METHODS

A Suitable environment is necessary for the cultivation of crops and temperature is one of the most essential parameters which decides the success or failure of crop production. Maintenance of temperature is the only way to cultivate fresh food, especially in cold regions. Studies confirm that the average preferable temperature in the range of 17 °C to 24 °C is a suitable range for most agricultural crops[15].

Fresh food (Micro-greens) can be grown in several ways however selection of suitable micro-farming units, thermal supplementation system, growing media, crop selection, and light intensity is essential[2] for achieving higher yield.

2.1 Micro-Farming Units

2.1.1 Phase-Wise Unit Design

Phase-wise studies have been carried out to find out the possibility of micro-green production in different closed small structures. It includes standardisation of size, cladding, frame material selection, and integration of supplementary thermal energy supply systems using renewable (solar) energy-based technology for micro-climate maintenance during the winter period. These designed units are small and portable and can be kept inside or outside the dwelling place. The Design of the micro-farming unit has been done in a phased manner and geometry is generated in software (AutoCAD).

Initially, a Passive structure (Figure 1.1) was designed and developed and it was found suitable only during a brief summer period. Structure with the provision of temperature, humidity, light, and water sprinkling system is then conceptualised and developed (Figure 1.2). This system is found capable of successful crop cultivation throughout the year, but at the same time, energy consumption is on the higher side. Trial results confirm temperature is the only parameter needed to be maintained.

Finally, an aluminum frame-based triple layer 16mm polycarbonate structure integrated with low energy consuming alumina substrate-based thick film hot plates (Fig 1.3) thermal supplementation system was finalised based on strength, lifespan (10-15 years), corrosion resistance, and lightness of aluminum and transparency of 60-80 %and high thermal resistance (R-value) of 2.5-2.8 K.m^2/W of polycarbonate sheet. A Structure with good light transmission and good insulation properties is of utmost importance.

The phase-wise developed units are shown below in Figure 1.1 to Figure 1.3 and details of developed units are given in Table 1.

Phase 1

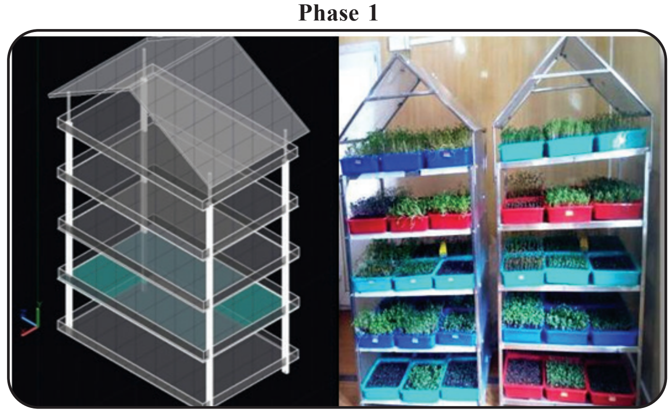


figure 1.1. Passive unite.

Phase 2

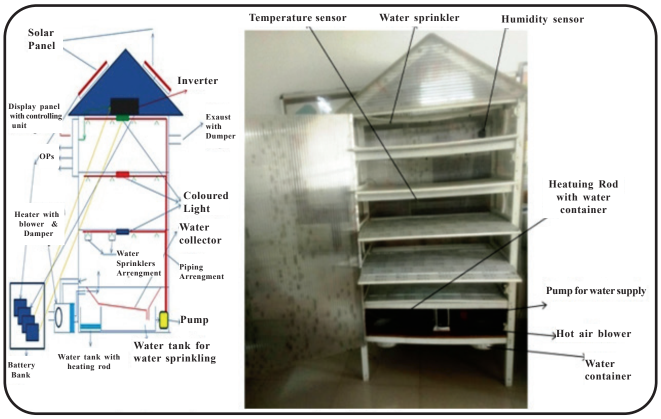


Figure 1.2. Automatic unit.

Phase 3

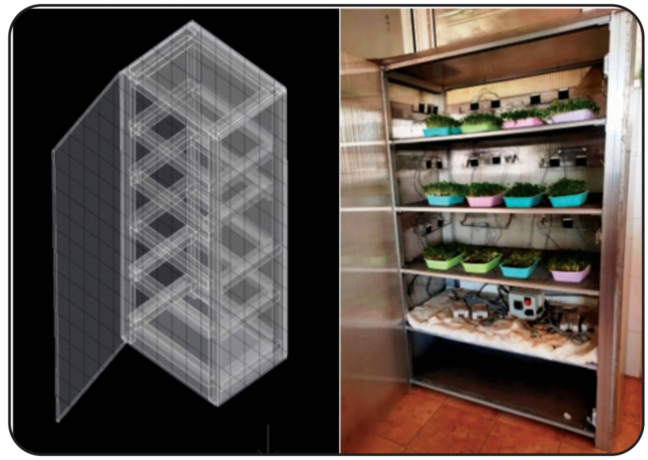


Figure 1.3. Aluminum unit integrated with thick film hot plate.

Table 1. Detail of different units

Materials/sensors/parameters	Passive Unit	Climate controlled unit	Thick-film hot plate based unit
Cladding material	None/acrylic	16mm triple layer polycarbonate	16mm triple layer polycarbonate
Frame/skelton	Steel/Alum.	PVC/Aluminum	Aluminum
Overall volume	$0.61m^3/1.19m^3$	$1.05m^3$	$1.05m^3$
Heating mechanism	None	1000W hot air blower	8W thick-film hot plates
Temperature sensor	None	RTD(PT 100)	Thermocouple
Humidity unit	None	Heating rod (500W) immersed in tank	None
Humidity sensor	None	12 V COTS sensor	None
Fan	None	4" 18 W Fan	12 V Fan
Water sprinkling systesm	None	Motor/pump 100W with Sprinklers over each tray.	None
Wheels	None	None	Yes
Weight of the units	31/33 kilograms	47 Kilograms	34 Kilograms
Thickness of partition shelf and type	2.16mm (steel)/0.39mm (Iron mesh)	0.39mm (Iron mesh)	0.39mm (Iron mesh)
Number of shelves	5/5	5	5
Inter-shelf distance	23cm/25cm	23cm	27cm

2.2. Media and Crop Selection

Several trials were carried out in Trans-Himalayan region conditions (Annual average ambient temperature 10.5-12°C)with soil, compost, and media mixture with different ratios like 1:1:1, 3:2:1, 5:2:1, etc. (Figure 2.) to comparatively analyse the best media for crops in terms of output viz. micro-greens germination percentage, germination time and harvesting time. The ideal pH for plant growth is 5.5 to 7.5[10] and the selected media mixture pH can be adjusted. Trials were also carried out in a media mixture of 5:2:1 composition with different crops to find the suitable crops for the region based on certain parameters like less germination time, fresh weight, output for the same input (seeds), etc.

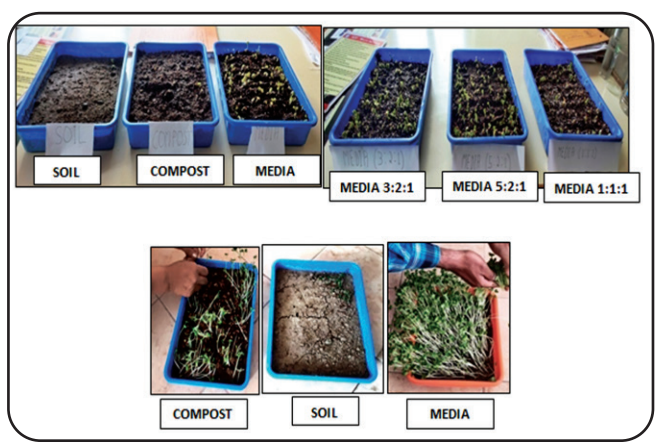


Figure 2. Trial with radish in different media mixture, soil & compost.

2.3 Thick-film Hotplates

Thick-film hotplates (Figure 2.1 & Figure 2.1.1) were found suitable for required temperature maintenance at low energy-consuming property, portability, lightweight, miniature size, and ruggedness. It produces heat based on the principle of Joule heating or resistive heating and the power of a hotplate is equal to $I^2 R$, where I is the input current and R is the resistance of the hotplate[11,12,13]. Due to the inherent advantages of alumina ceramic including chemical inertness, rugged and reliable, the hotplates are fabricated using alumina substrates in conjunction with thick-film screen printing technology and integrated inside a micro-farming unit. The Screen material used is Stainless steel (SS) due to its best dimensional stability for thick-film printing.

2.3.1 Manufacturing Process

The hotplates were developed using alumina substrates of thickness 25 mil (635 µm) over which heater and conductor material were patterned in the desired geometry by a screen printing process. Layout design of the hotplate was done using HYDE software followed by the generation of masks. For further fabrication process steps, screens for conductor tracks, heater patterns, and protection layers were prepared as per the design layout. Ruthenium-oxide (RuO_2) based compatible thick-film resistor paste was used as heater material. The conductor tracks necessary for electrical interconnections were printed using palladium silver (Pd/Ag) paste. The substrates were screen-printed and fired after each printing process at the requisite time-temperature profile with a peak firing temperature of 850 °C.

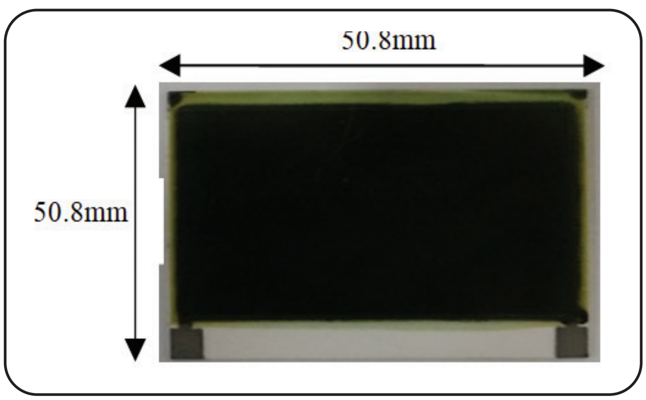
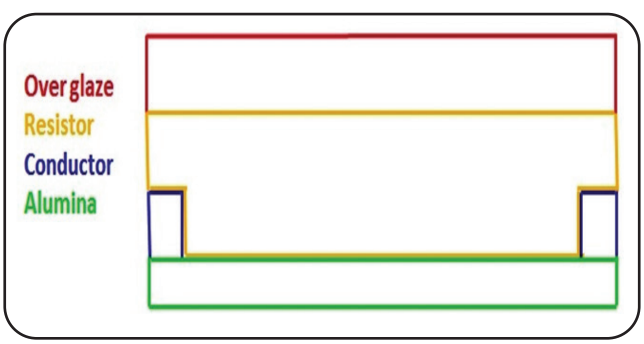


Figure 2.1. Fabricated thick - film hot plate.



2.1.1 Cross Sectional View of the Hotplate

A protective layer of over-glaze material was printed over the patterned substrate and fired subsequently. Over-glaze material is dried at 150 deg. °C for 10 minutes and fired at a peak temperature of 525 °C with a dwell time of 10 minutes at peak temperature. The fabricated hotplate has overall dimensions 50.8mm X 50.88mm of as shown in Fig. 2.1.

2.3.2 Characterisation of Hotplates

The developed hotplates were characterised using a constant DC Keithley power source (Model No. 2231A-30-3). Voltage was applied across the hotplate terminals and the surface temperature was observed using a K-type thermocouple wire & a Eurotherm temperature indicator. At a constant 12 V DC, the hotplate consumes ~8 W of power and provides a surface temperature of 90-100°C.

3. THICK-FILM HOTPLATE INTEGRATED MICRO FARMING UNIT

The aluminum frame-based triple- layer polycarbonate unit integrated with hot plates is shown in Figure 3 (a & b). The placement of hotplates was done in a manner to achieve uniform heat distribution on each shelf of the unit. For a unit of known dimensions, the energy required to maintain the inside temperature in the range of 15-20 °C was calculated. Special aluminum frames with cavities were fabricated which were used for fixing the hotplates inside the unit. The heat generated from the hotplates was circulated uniformly by mounting two DC fans (12 V Fan) inside the micro farming unit. The voltage required by the hotplates was provided using a 12 V DC portable power source. A temperature control system was used to continuously monitor and control temperature inside the unit. The system was equipped with a thermocouple as a temperature sensor & provided feedback to the control system. The details of different units (passive, climate-controlled, and thick-film hotplate type) are compared and presented in Table 1.

Figure 3. Micro Farming Unit.
(a) Unit Integrated with Hotplate.
(b) Enlarged Image.

4. RESULTS AND DISCUSSION

Experimental trials were carried out in the ambient atmospheric condition (Average temperature 10.5 °C -12 °C) for the selection of suitable media and crops for the region; the result confirms that media mixture in the ratio of 5:2:1 of coco-peat, vermiculite, and perlite is most suitable and crops like radish, cabbage, and fenugreek are far better than other crops (Table 2 & Table 3)

Table 2. Harvesting of micro-greens in different media.

Parameters	Soil	Compost	Media 1:1:1	Parameters 5:2:1	Soil 3:2:1
Av. Germ. (%)	5	45	65	75	72
Germination time (days)	10	4	2-3	2	2-3
Harvesting Time (days)	15^{th}	12th	10th	8th	9th
Fresh Wt.	------	22 g	42 g	55 g	48 g

Table 3. Trial outcomes for crop parameters.

Crops	D (%)	W/T	O.T	S.T	O/I	A
Radish	8(80)	53	12-20	4	5.89	Y
Cabbage	14(70)	25	14-18	4	6.66	Y
Cauli Flower	13(65)	27	17-20	4	5.76	Y
Broccoli	14(65)	22	20-26	4	5.31	N
Knol Khol	10(65)	23	15-25	4	5.37	Y
Fenugreek	14(75)	41	18-22	7	5.51	Y

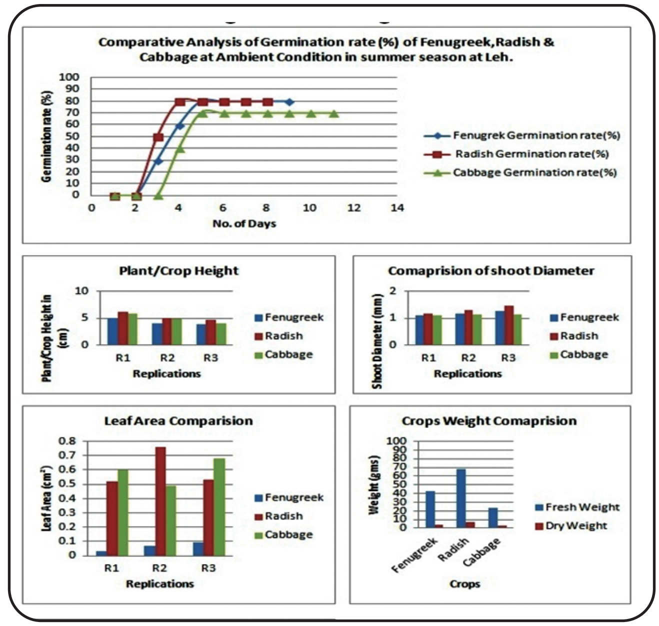
D (%) - Average harvesting time in days (Average Germination)
W/T - Fresh weight
O.T - Optimum temperature
S.T - Survival temperature
O/I - Out to input ratio
A - Availability

The normal passive units work well during summers when average temperatures recorded were in the range of 15°C to 20 °C Figure 4. However due to the absence of a heating system, these units failed to grow crops during the winter period.

An Automatic micro-climate-controlled active unit was found suitable for the cultivation of nutritious micro-green during winter and trial results are shown in Figure 5.

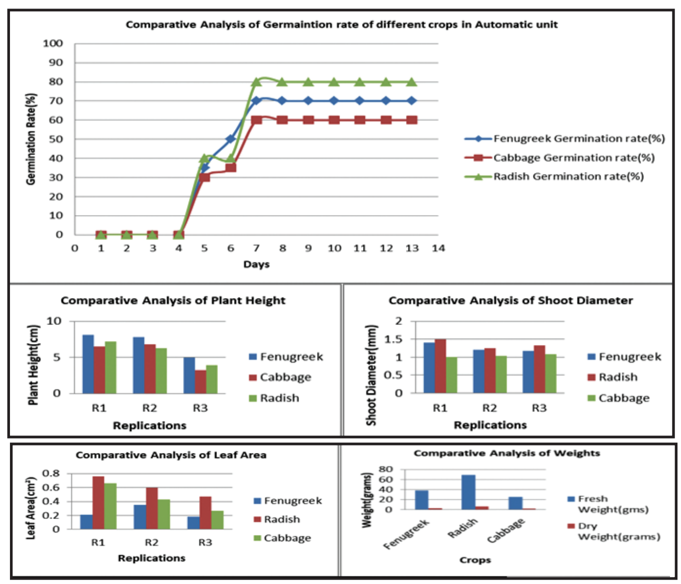
The energy consumption for cultivation in automatic units is on the higher side. The trial proves that temperature is the only parameter deciding the success or failure of crop cultivation besides media, crop, and light requirements. Temperature below 8 °C hampers the growth of the growing plantlets and no germination of crops takes place if the temperature dips below 10 °C. The effect of ambient temperature on germination, harvesting time, and yield was also studied and ambient temperatures of 15 °C-20 °C were found suitable (Table 4). Ambient humidity is sufficient to maintain a suitable humidity level in the unit for proper growth[2,14]. The Average watering frequency is also on the lower side and varies generally from every 4-6 hours a day (8 liters to 17 liters).

Thick-film hotplate integrated micro-farming unit is found to be most suitable for round-the-year micro-



Av. ambient Temperature = 17.6 ^{0}C
Av. Inside Temperature(Acrylic unit)= 19.7 ^{0}C
Av. Ambinet Humidity$_{relative}$ = 32 %
Av.Indside Humidity$_{relavtive}$ = 51 %

Figure 4. Crop parameter collected in a national unit.



Average ambient outside Temperature = -8.8 ^{0}C
Average inside temperature=17.1^{0}C
Average ambient humidity$_{relative}$ = 33 %
Average inside humidity$_{relative}$= 61 %

Figure 5. Crop paramter collected in auto unit.

Table 4. Temperature effect on crop parameters

Month	Average Temp. (^{0}C)	Germin. (%)	Germin. Time (days)	Harvesting Time (days)	Yield (g)
Apr-May	12-15	65-70	3-5	10-14	52
Jun-Jul	18-20	70-80	2-3	7-9	58
Sept.	15-17	70-75	3-4	8-12	53
Oct.	7-10	50-60	5-7	12-16	44

Table 5. Optimistation of number of plates

No. of plates in each shelf	Total no. of plates	Average temp. in Shelves	Initial time taken to reach 20 ^{0}C	Av. Active (ON) time (minutes)	Av.inactive(ON) time(minutes)	Total plates active time(minute)/24 hours	Total energy consumption per day(kwh)
8	24	17.1^{0}C	27 minutes	4	3	768	0.1024
6	18	16.5^{0}C	38 minutes	5.30	1.30 to 2	1000	0.1334
4	12	14.8^{0}C	65 minutes	8.30 to 9	1	1270	0.1693

Table 6. Collectesd crop parameters with different plates/shelf

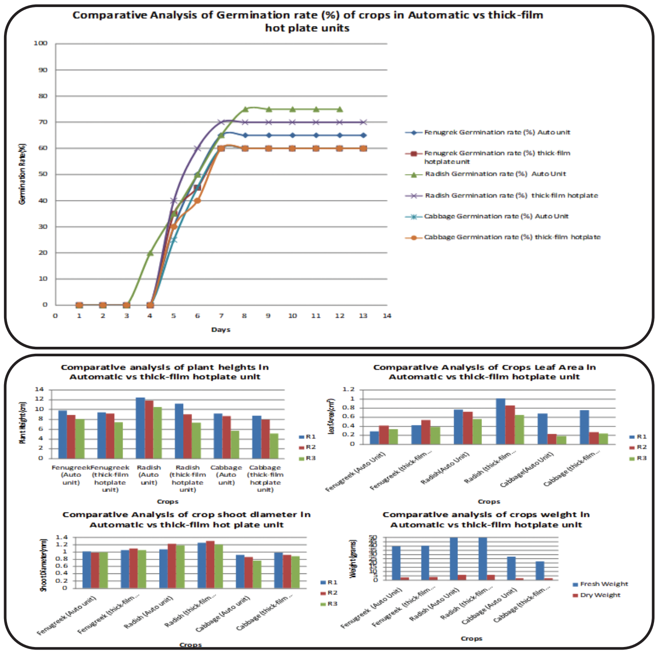
Parameters	8 plates/shelf			6 plates/shelf			4 plates/shelf		
	Fenugreek	Radish	Cabbage	Fenugreek	Radish	Cabbage	Fenugreek	Radish	Cabbage
Harvesting(Days)	12th days	9th days	13th days	14th days	10th days	14th days	14th days	10th days	14th days
Shoot Diameter(mm)	1.02	1.3	0.81	1.03	1.4	0.83	1.05	1.4	0.85
Plant Height(cm)	9.1	12	9.2	7.3	8	4.5	5.8	6	3.2
Leaf area(cm$^{2)}$	0.25	0.6	0.39	0.38	0.7	0.41	0.40	0.75	0.43
Fresh Weight (grms)	42.4	56	22	35.3	43	19	32.9	39	17
Dry Weight (grms)	4.2	5.5	2.1	3.3	4.1	1.86	3.1	3.5	1.65

Table 7. Comparison of the automatic climate-controlled unit with thick-film hotplate intergrated unit

Parameters	Automatic climate controlled unit	Thick-film hotplate integrated unit
Temperature at source	105^{0}C-120^{0}C	90^{0}C-10^{0}C
Average recorded temperature when system stops at 20^{0}C	18.3^{0}C	17.1^{0}C
Humidity maintained	60%-70%	Ambient atmospheric humidity(33% to 37%)
Watering frequency	Every 4-6 hours	-
Initial time taken (min) to reach 20^{0}C	14-17 minutes	27-30 minutes
Average active (ON) time (minutes)	Every 2 minutes	Every 4 minutes
Average active (OFF) time (minutes)	Every 7-8 minutes	Every 3 minutes
Total active time (minutes) 24 Hours.	300 minutes	768 minutes
Total approximate energy consumption/24 hours for temperature maintenance	1200W/Hours=5x1200W=6000Watts=6kw	10W/Hours=12.8x8Wx24=2457.6W=2.5kW

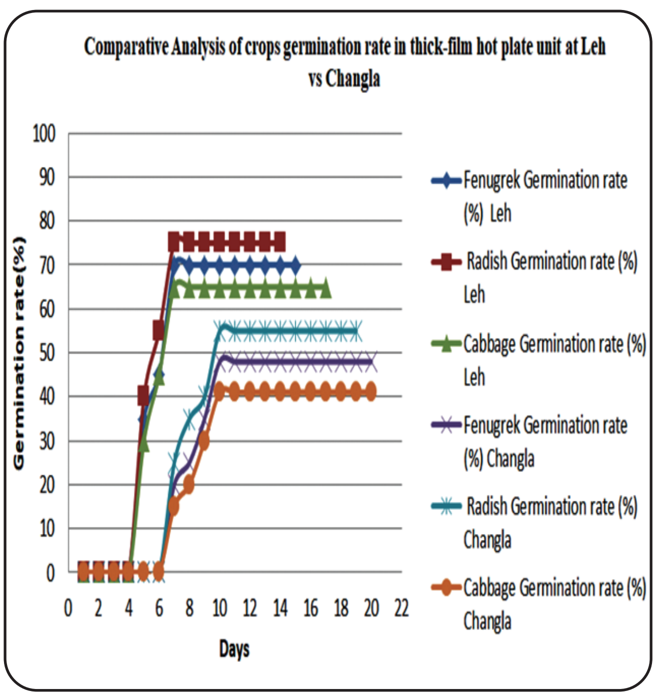
*Average ambient temperature during trial =8.6^{0}C, Average ambient humidity $_{relative}$ =35%, Average Inside humidity $_{relative}$ (Thick film hotplate integrated unit)=51%, Average inside humidity $_{relative}$(climate controlled unit)=65%

green cultivation due to its low energy consumption. The Comparative trial result is shown in Figure 6. Successful trials were carried out with thick-film hotplates integrated developed unit at Leh (3500 m) and Changla (5391 m). Comparative Analysis of Crop parameters inside a unit at both locations is shown in Figure 7. Standardisation for the number of hotplates in each shelf for maintaining average inside temperature at low energy consumption is also carried out (Table 5). The effect of the number of hotplates per shelf on various crop parameters is also studied as shown in Table 6. Comparison in terms of total energy consumption (approx.) per day and other details between the automatic unit and thick-film hotplate integrated unit is shown in Table 5.



Average ambient temerature during trial = -9.4⁰C
Average ambient humidity = 35%
Average inside temperature during trial$_{Rel}$ = 16.5⁰C
Average inside humidity$_{Rel}$ = 53%

Figure 6. Comparative analysis of crop parameters in auto vs thick-film hot plate unit at Leh.



Average outside temperature at Leh during trial = -9.6⁰C
Average Inside temperature = 17.1⁰C
Average ambient humidity$_{reltive}$ at Leh = 31%
Average inside humidity$_{relative}$ at cangla during trial=-19.2⁰C
Average inside temperature = 14.1⁰C
Average ambient humidity$_{relative}$ at changla = 21%
Average inside humidity$_{relav\ ive}$ =39%

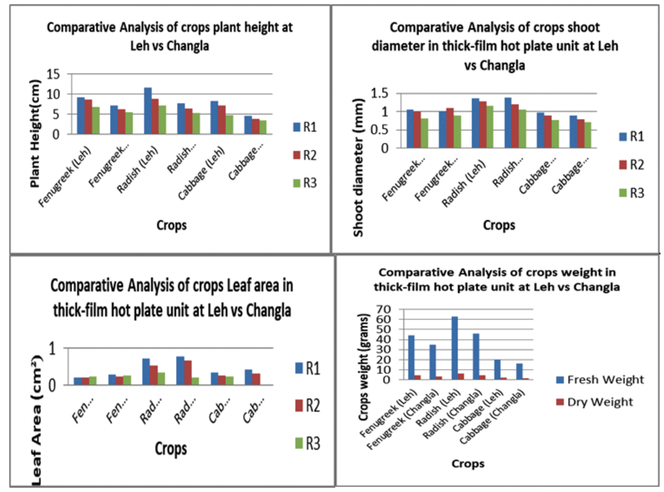


Figure 7. Comparative analysis of crops in thick-film hot plate unit at Leh & Changla.

5. CONCLUSION

Temperature maintenance in the Trans-Himalayan region (average elevation 3000 m to 8000 m) is very difficult owing to harsh weather conditions. Maintenance of temperature is very essential and plays a key role in the survivability of man, machines, crops, etc. Human habitation structures mostly use fossil fuel-based systems in the region, but maintenance of temperature for the production of fresh food or micro-green with fossil fuel-based systems looks inappropriate and also not justified. It is found that temperature maintenance is the major criterion for round-the-year micro-green cultivation along with proper selection of growing media and crops.

It is also found that average ambient relative humidity i.e. 30-40 % is sufficient which inside the units rises to 50-60 % as per the collected data during the trials. Furthermore, the watering frequency per day is very low showing no requirement.

The present study shows that temperature maintenance inside the micro-farming units is possible with a heating element (hot air blower) based unit and low power-consuming thick-film hotplate technology. Successful trials were carried out for the cultivation of micro-green in the unit throughout the year at Leh and Changla. Thick-film hotplates are energy efficient and consume only 8 W per hotplate as compared to the arrangement comprising a hot air blower. The average temperature at the sources i.e. hot air blower and hot plates were also collected and found approximately 110 °C and 98 °C respectively when in operation. Thick-film hotplates can be further customised to fulfill other temperature maintenance requirements viz. human habitation, material and machine storage, etc.

6. RECOMMENDATIONS FOR FURTHER STUDY

Although the present active Thick-film integrated unit is suitable for the production of micro-greens in prepared medium throughout the year in cold regions. The work on a selection of better insulating material to minimise thermal losses and hence costs can also be carried out.

Trials with different colors and wavelengths of light can be done to study the effect on the micro-green growth pattern, and nutrient content along with the effect of photoperiod and identification on effect of different colors and wavelengths of light on different micro-green crops. A Study on the effect of light intensity and PAR on crop growth can also be carried out. The phytonutrients are thousand in numbers and they have their role to play in maintaining health in single and in combination. Thus more varieties of edible plants need evaluation.

ACKNOWLEDGEMENTS

All the authors are highly grateful to the Defence Research and Development Organisation for providing the facilities at the Defence Institute of High-Altitude Research, Leh Ladakh, India. Also, the authors express their sincere thanks to Director CSIR-CEERI Pilani and members of the Micro-system Packaging & HFDS Group.

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