Project Report

Enhancing Greenhouse Productivity in India using optimized Heat Transfer techniques

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With the growing need for sustainable agricultural practices in India, optimizing energy efficiency in greenhouse systems has become increasingly vital. However, greenhouses in India often experience significant temperature fluctuations between day and night due to the country's diverse climatic conditions. During the daytime, solar radiation can cause excessive heating inside the greenhouse, while at night, the lack of solar input and inadequate insulation can lead to rapid heat loss. These sharp temperature variations can stress plants, reduce crop quality, and limit overall productivity if not properly managed. Commercial greenhouses, capable of delivering crop yields up to ten times higher than traditional open-field farming, currently rely heavily on fossil fuels, leading to significant operational costs and environmental concerns. This project investigates advanced heat transfer techniques—such as **Thermal Screens** and **Borehole Thermal Energy Storage (BTES)**—to enhance greenhouse productivity while reducing energy consumption, by maintaining optimum temperature levels inside the greenhouse throughout day and night, ensuring a stable environment for plant growth. A COMSOL model was developed to evaluate the impact of these methods on internal temperature regulation and plant growth. The results indicate notable improvements in thermal efficiency and cultivation performance. The study proposes cost-effective, sustainable strategies to boost greenhouse productivity tailored to Indian agro-climatic conditions.

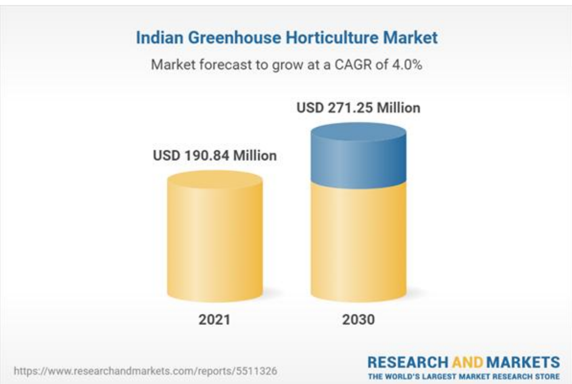
1. Introduction

According to the Indian Economic Survey 2020–21, agriculture remains a cornerstone of the Indian economy, employing over 50% of the workforce and contributing 20.2% to the national GDP. With a growing population, the pressure on agricultural productivity continues to intensify, demanding innovations that can maximize yield while minimizing resource consumption. In this context, **greenhouse cultivation** offers a promising solution, providing significantly higher yields per unit area compared to traditional open-field farming.
Greenhouses create a **controlled environment** that shields crops from external climatic stresses such as extreme temperatures, heavy rainfall, droughts, pests, and diseases. They enable **year-round cultivation**, protect against seasonal variability, and significantly improve the quality and quantity of produce. In India, greenhouses are particularly used for **high-value crops** such as **tomatoes, capsicum, cucumbers, strawberries, roses, gerberas, and exotic vegetables** like lettuce and bell peppers. These crops are sensitive to environmental fluctuations and thrive in the carefully managed conditions that greenhouses provide.
Regionally, greenhouse farming is gaining momentum in states such as **Maharashtra, Karnataka, Tamil Nadu, Himachal Pradesh, and Uttarakhand**, where farmers are leveraging it to produce export-quality flowers, fruits, and vegetables. In arid regions like Rajasthan and parts of Gujarat, greenhouses are helping to overcome water scarcity and harsh climate conditions, enabling profitable farming even in challenging environments.

Thus, greenhouses play a crucial role not only in boosting productivity but also in **diversifying agricultural income sources**, enhancing **food security**, and supporting **sustainable rural development** in India.

While greenhouses improve farming, maintaining a stable temperature inside them is a major challenge in India. Due to the country's diverse climate, greenhouses often face very hot days and cold nights. High daytime temperatures can cause heat stress, wilting, and plant damage, while nighttime cooling can slow growth and harm crops. Sensitive plants like tomatoes, capsicum, and strawberries are especially affected by these fluctuations, leading to poor yields and lower quality. In regions like semi-arid areas and hill states, the lack of proper temperature control often results in crop failures. Solving this problem is critical to make greenhouse farming more successful across India.

India's greenhouse horticulture market is witnessing steady growth, projected to reach USD 271.25 million by 2030. This rising demand for fruits, vegetables, and ornamental plants highlights the urgent need for effective strategies and optimized technologies, such as advanced energy storage and heat management techniques, to ensure sustainable and efficient greenhouse operations.



Another major challenge in greenhouse farming is the high energy requirement—both direct and indirect—for heating, cooling, lighting, and automation, which significantly affects sustainability and operational costs. In India, the share of electricity consumption in agriculture rose from **28.75% in 2009–10 to 37.1% in 2019–20**. In commercial greenhouses, heating alone can account for **up to 80%** of total energy consumption. With the rising cost of fossil fuels and increasing environmental concerns, it is crucial to develop energy-efficient and sustainable heating and cooling strategies.

A **closed greenhouse**, which remains fully sealed without openable windows for ventilation, offers potential advantages by minimizing heat loss. However, it also presents the challenge of precisely controlling internal temperature and humidity. Climate change exacerbates these challenges, particularly in India, where agriculture heavily depends on climate-sensitive factors like temperature and rainfall. High temperatures during the summer can cause excessive heat buildup leading to plant stress, while cold winter nights can result in heat loss, reducing yields and quality. Stabilizing internal climate is therefore critical to maintaining crop productivity.

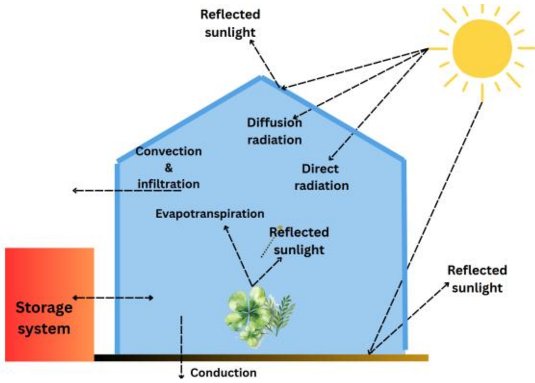


Fig. 1.1.a

Traditional greenhouses rely on open ventilation systems, resulting in significant energy losses to maintain optimal growing conditions. In contrast, our model focuses on **closed greenhouses** that minimize heat losses by using **thermal energy storage (TES)** systems. Here, excess solar heat captured during the day is stored and reused later for heating when needed. By decoupling from external fossil fuel inputs and leveraging **solar energy**, closed greenhouses become more self-sufficient and sustainable. Although initial capital investment for closed systems is higher, their cost-effectiveness improves with larger scale operations and optimized TES configurations.

The greenhouse itself can be seen as a **large solar collector**, capable of absorbing around **80% of incoming solar radiation**. With **300–330 sunny days annually** across much of India and an average solar incidence of **4–7 kWh/m²/day**, there is a vast potential to harness and store solar energy. The surplus energy captured on hot, sunny days can be stored in **underground thermal storage systems** for use during cooler periods, greatly improving energy efficiency.

To further optimize the greenhouse energy balance, **thermal screens** are introduced. Thermal screens are retractable materials installed inside greenhouses that help **reduce heat loss at night** and **control excessive solar gain during the day**. During winter nights, they act as an insulating barrier, minimizing heat exchange between the greenhouse interior and the outside environment, while during sunny days, reflective screens can be deployed to prevent overheating. Research has shown that using thermal screens can significantly **reduce heating energy consumption** and **improve internal temperature stability**, making greenhouses even more energy-efficient and productive.

A schematic of the closed greenhouse design highlights the heating and cooling processes based on a thermal energy storage (TES) system. During the heating phase, warm water is extracted from the TES and delivers low-temperature heat to a heat pump, which then charges a short-term buffer tank to meet the hourly heating demand of the greenhouse. In the cooling phase, cold water from the TES is pumped into the greenhouse, where it removes excess heat through a heat exchanger before returning the now warmer water back to the TES system. This integrated approach helps maintain stable internal temperatures while optimizing energy use. By integrating **thermal energy storage**, **heat pumps**, and **thermal screens**, closed greenhouses can achieve efficient year-round climate control, reduce reliance on external energy sources, and maintain consistent, high-quality crop yields in a sustainable manner.

Nomenclature

Latin Symbols

Symbol	Description	Units
Q	Heat load	W
a	Heat load coefficient	W/m²·K
m	Outdoor wind speed	m/s
I	Solar radiation	W/m²
T	Temperature	K
F	View factor	–
E	Emission coefficient	–
A	Surface area	m²
c_p	Specific heat capacity	J/kg·K
d	Thickness	m
V	Volume	m³
U_m–c–a–H_2O	Mass flow rate of water vapor from crop to indoor air	kg·H_2O/s
k_k–a–H_2O	Mass transfer coefficient of water vapor from crop to indoor air	m/s
C_k–H_2O_s	Saturation concentration of water vapor at crop temperature	kg·H_2O/m³
C_a–H_2O	Concentration of water vapor at indoor air temperature	kg·H_2O/m³
R_cut	Leaf cuticular resistance	s/m
R_s–H_2O	Stomata resistance	s/m
R_b–H_2O	Boundary layer resistance	s/m
R_min	Minimum internal crop resistance	s/m
f_I	Radiation dependency effect	–
f_Tc	Temperature dependency effect	°C
f_CO_2	CO_2 dependency effect	–
f_H_2O	H_2O dependency effect	–
LAI	Leaf area index	–

I_k–s	Heat absorbed by canopy	W/m²
Q_k–a–H_2O	Heat load from canopy to indoor air below screen	W
Q_a–sc–H_2O	Heat load from indoor air below screen to screen	W

Greek Symbols

Symbol	Description	Units
γ	Absorption coefficient (roof)	–
ρ	Density	kg/m³
σ	Stefan–Boltzmann constant	W/m²·K⁴
κ	Thermal conductivity	W/m·K
θ	Average air density	kg/m³

Subscripts

Symbol	Description
a	Inside air below screen
s	Inside soil
ri	Inside roof
o	Outside
c	Crop
nwi	Inside north wall
nwo	Outside north wall
a–s	Inside air to soil
sc–a	Screen to inside air below screen
sc–as	Screen to inside air above screen
sc–ri	Screen to inside roof
Cl_sc	Thermal screen closure
ss	Lower layer of soil
a–as	Below screen to above screen
s–c	Soil to crop
s–sc	Soil to screen
as–sc	Inside air above screen to screen
as	Inside air above screen
rd–ri	Radiation absorption by roof
s–ri	Soil to inside roof
ro–o	Roof to outside
sk	Sky
in	Inside room of greenhouse
a–sc	Inside air below screen to screen
ro–sk	Roof to sky
rd–s	Radiation absorption by soil
s–ss	Upper to lower soil
rd–c	Radiation absorption by crop
a–c	Inside air to crop
as–ri	Above screen to roof
ri–c	Inside roof to crop
sc–ri	Screen to inside roof
c–sc	Crop to screen

lf	Mean leaf width
R_b–heat	Leaf boundary layer resistance

2. Experiment

2.1 Heat and Mass transfer in a semi-solar greenhouse with thermal screen.

In this section, the heat and mass transfer equations used to predict the internal environment of the semi-solar greenhouse are discussed. The model estimates temperatures of the air below the screen (T_a), air above the screen (T_{as}), soil (T_s), cover (T_{ri}), crops (T_c), and the screen (T_{sc}) using six first-order differential equations based on energy balances.

The model makes the following assumptions:

- Greenhouse components are treated as lumped systems.
- Temperatures of air, crop, cover, screen, and top soil are uniform.
- No soil evaporation occurs.
- Inside air does not absorb or emit radiation.
- Condensed water on the roof and screen is removed and not re-evaporated.
- Windows remain closed with no ventilation during the test period.
- CO_2 concentration effects on evapotranspiration are ignored.

Selection of greenhouse shape

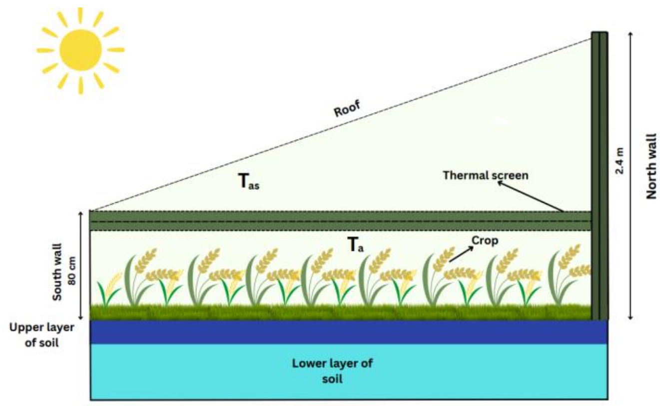


Fig. 2.1.a

The semi-solar greenhouse shape was selected as shown in Fig. 2.1.a because it captured the highest amount of solar radiation among five tested designs, based on long-term meteorological data from North-West Iran. Its East–West orientation, combined with a cement north wall and an internal thermal screen, helped reduce heat loss and store energy during colder periods. Covered with 4 mm thick glass, the greenhouse provided better insulation and light transmission. Experimental validation through cabbage cultivation confirmed the structure's efficiency in minimizing energy consumption and maintaining favourable growing conditions.

Heat transfer methods in greenhouse

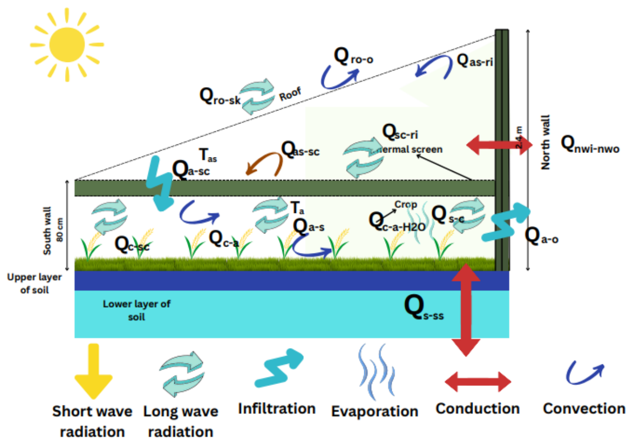


Fig. 2.1.b

The Fig.2.1.b illustrates the heat and mass transfer processes inside a semi-solar greenhouse equipped with a thermal screen. During the day, shortwave solar radiation enters the greenhouse, heating the soil, plants, air, and structural components such as the south wall and roof. Heat transfer inside the greenhouse occurs through several mechanisms: conduction through the walls and soil, convection between the air and internal surfaces, and longwave radiation exchanges between surfaces like the soil, plants, and thermal screen. Notably, longwave radiation is the dominant mode of heat loss during nighttime, particularly under clear sky conditions. To mitigate this, a thermal screen is installed, which can reduce overnight heat losses by approximately 35–60%. The thermal screen not only limits radiative and convective losses but also helps maintain more stable temperatures around the crops, minimizing temperature fluctuations and reducing the risk of dew formation on plant surfaces.

Evapotranspiration from plants adds moisture to the air, while limited air infiltration and exfiltration through structural openings further influence the greenhouse's internal climate. Different arrows and colours in the diagram represent these various heat and mass transfer modes, providing a comprehensive view of the thermal behaviour within the greenhouse system.

System of Equations

1. $\frac{dT_a}{dt} = \begin{cases} \frac{Q_{a-s}-Q_{a-c}-Q_{as-ri}-Q_{nwi-nwo}}{\rho_a c_{p-a} V_a}, & \text{if } C_{sc} = 0 \\ \frac{Q_{a-sc}+Q_{as-sc}-Q_{a-c}-Q_{as-ri}-Q_{nwi-nwo}}{\rho_a c_{p-a} V_a + \rho_{as} c_{p-a} V_{as}}, & \text{if } C_{sc} = 1 \end{cases}$

2. $\frac{dT_{as}}{dt} = \begin{cases} \frac{Q_{a-as}+Q_{as-sc}-Q_{as-ri}-Q_{nwi-nwo}}{\rho_{as} c_{p-a} V_{as}}, & \text{if } C_{sc} = 1 \\ \frac{dT_a}{dt}, & \text{if } C_{sc} = 0 \end{cases}$

3. $\frac{dT_s}{dt} = \frac{Q_{rd-s}+Q_{a-s}-Q_{s-c}-Q_{s-ri}-Q_{s-ss}-Q_{s-sc}}{(0.7\rho_s C_{p-s}+0.2\rho_{H_2O} C_{p-H_2O}+0.1\rho_a C_{p-a})V_s}$

4. $\frac{dT_c}{dt} = \frac{Q_{rd-c}+Q_{a-c}+Q_{ri-c}+Q_{s-c}-Q_{c-a-H_2O}-Q_{c-sc}}{\rho_c C_{p-c} V_c}$

5. $\frac{dT_{ri}}{dt} = \frac{Q_{rd-ri}+Q_{as-ri}+Q_{s-ri}+Q_{sc-ri}-Q_{ri-c}-Q_{ro-o}-Q_{ro-sk}}{\rho_r C_{p-r} V_r}$

6. $\frac{dT_{sc}}{dt} = \frac{Q_{c-sc}+Q_{s-sc}+Q_{a-sc-H_2O}+Q_{sc-a}+Q_{sc-as}-Q_{sc-ri}}{\rho_{sc} C_{p-sc} V_{sc}}$

7. $Q_{a-c} = A_c \alpha_{a-c}(T_a - T_c)$

8. $Q_{a-s} = A_s \alpha_{a-s}(T_a - T_s)$

9. $Q_{as-ri} = A_r \alpha_{as-ri}(T_{as} - T_{ri})$

10. $Q_{ro-o} = A_r \alpha_{ro-o}(T_{ro} - T_o)$

11. $Q_{a-sc} = A_{sc} \alpha_{a-sc}(T_a - T_{sc})$

12. $Q_{as-sc} = A_{sc} \alpha_{as-sc}(T_{as} - T_{sc})$

13. $Q_{a-as} = \rho_a c_{p-a} P_{a-as}(T_a - T_{as})$

14. $Q_{s-ss} = \frac{A_s \lambda_s}{d_s}(T_s - T_{ss})$

15. $Q_{nwi-nwo} = \frac{A_{nw} \lambda_{nw}}{d_{nw}}(T_{nwi} - T_{nwo})$

16. $\alpha_{a-c} = \frac{\rho_a c_{p-a}}{R_{b-\text{heat}}}$

17. $\alpha_{a-s} = \begin{cases} 1.7|T_a - T_s|^{1/3}, & T_a < T_s \\ 1.3|T_a - T_s|^{0.25}, & T_a \geq T_s \end{cases}$

18. $\alpha_{as-ri} = 3|T_{as} - T_{ri}|^{1/3}$

19. $\alpha_{ro-o} = \begin{cases} 2.8 + 1.2v_o, & v_o < 4 \\ 2.5v_o^{0.8}, & v_o \geq 4 \end{cases}$

20. $\alpha_{a-sc} = Cl_{sc} \times 3|T_a - T_{sc}|^{1/3}$

21. $\alpha_{as-sc} = Cl_{sc} \times 3|T_{as} - T_{sc}|^{1/3}$

22. $\Phi_{a-as} = V_{a-as} \times A_{sc}(1 - Cl_{sc})$

23. $R_{b-\text{heat}} = \frac{1174\sqrt{l_f}}{(l_f|T_c - T_a| + 207v_o^2)^{1/4}}$

24. $Q_{rd-ri} = A_r \eta_{ri-Is} I_r$

25. $Q_{rd-c} = A_s \eta_{c-Is} I_{in}$

26. $Q_{rd-s} = A_s \eta_{s-Is} I_{in}$

27. $Q_{s-c} = A_s E_s E_c F_{s-c} \sigma(T_s^4 - T_c^4)$

28. $Q_{s-ri} = A_s E_s E_{ri} F_{s-ri} \sigma(T_s^4 - T_{ri}^4)$

29. $Q_{s-sc} = A_s E_s E_{sc} F_{s-sc} \sigma(T_s^4 - T_{sc}^4)$

30. $Q_{ri-c} = A_r E_{ri} E_c F_{ri-c} \sigma(T_{ri}^4 - T_c^4)$

31. $Q_{ro-sk} = A_r E_{ro} E_{sk} F_{ro-sk} \sigma(T_{ro}^4 - T_{sk}^4)$

32. $Q_{c-sc} = A_s E_c E_{sc} F_{c-sc} \sigma(T_c^4 - T_{sc}^4)$

33. $Q_{sc-ri} = A_{sc} E_{sc} E_{ri} F_{sc-ri} \sigma(T_{sc}^4 - T_{ri}^4)$

34. $T_{sk} = 0.0552(T_o)^{1.5}$

35. $\Phi_{m-c-a-H_2O} = \max\{A_c k_{c-a-H_2O}(C_{c-H_2O,s} - C_{a-H_2O}), 0\}$

36. $k_{c-a-H_2O} = \frac{1}{R_{b-H_2O} + \frac{R_{\text{cut}} R_{S-H_2O}}{R_{\text{cut}} + R_{S-H_2O}}}$

37. $R_{s-H_2O} = R_{\min} f_I f_{Tc} f_{CO_2} f_{H_2O}$

38. $f_I = \frac{I_{c-s}/(2L_S)+4.3}{L_S/(2LAI)+0.54}$

39. $f_{Tc} = \begin{cases} 1 + 0.005(T_c - T_0 - 33.6)^2, & I_{c-s} \leq 3 \\ 1 + 0.022593(T_c - T_0 - 24.512)^2, & I_{c-s} > 3 \end{cases}$

40. $f_{\mathrm{H_2O}} = \frac{4}{\sqrt[4]{1+255e^{-0.5427\Delta_{\mathrm{pc \cdot H_2Om}}}}}$

41. $Q_{c-a-H_2O} = r_w \Phi_{m-c-a-H_2O}$

42. $\Phi_{m-as-ri-H_2O} = \max\{A_r k_{as-ri-H_2O}(C_{as-H_2O} - C_{ri-H_2O,s}),0\}$

43. $k_{as-ri-H_2O} = \frac{\alpha_{as-ri}}{\rho_{as} c_{p-a} Le^{2/3}}$

44. $Q_{as-ri-H_2O} = r_w \Phi_{m-as-ri-H_2O}$

45. $\Phi_{m-a-sc-H_2O} = \max\{A_{sc} k_{a-sc-H_2O}(C_{a-H_2O} - C_{sc-H_2O,s}),0\}$

46. $\Phi_{m-as-sc-H_2O} = \max\{A_{sc} k_{as-sc-H_2O}(C_{as-H_2O} - C_{sc-H_2O,s}),0\}$

47. $k_{a-sc-H_2O} = \frac{\alpha_{a-sc}}{\rho_a c_{p-a} Le^{2/3}}$

48. $k_{as-sc-H_2O} = \frac{\alpha_{as-sc}}{\rho_{as} c_{p-a} Le^{2/3}}$

49. $Q_{a-sc-H_2O} = r_w \Phi_{m-a-sc-H_2O}$

50. $Q_{as-sc-H_2O} = r_w \Phi_{m-as-sc-H_2O}$

51. $\Phi_{m-a-as-H_2O} = P_{a-as}(C_{a-H_2O} - C_{as-H_2O})$

Table 2.1.c - Input parameters used for calculations.

Parameter	Value	Parameter	Value	Parameter	Value
$\eta_{ri\text{-}Is}$	0.0173	ρ_a	$1.29\frac{T_0}{T_a}$	A_s	15.36
E_s	0.7	c_{p-a}	1000	λ_s	0.6
E_{sk}	0.8	f_a	1	ds	0.65
$F_{ri\text{-}sk}$	0.86	A_r	17.7	V_s	9.984
A_{nw}	11.52	V_r	0.0708	$C_{p\text{-}s}$	800
λ_{nw}	0.397	V_a	26.4	ρ_s	1400
dnw	0.25	ρ_r	2500	$F_{s\text{-}ri}$	0.8
c_{p-r}	840	σ	5.67051×10^{-8}	$\eta_{s\text{-}Is}$	0.86
E_{ri}	0.95	$F_{s\text{-}ri}$	0.8	ρ_{H_2O}	998
A_c	$2LAI \times A_s$	$\overline{\rho_a}$	$1.29\frac{2T_0}{T_a + T_a}$	v_a	0.09
A_{sc}	15.36	l_f	0.04	$\eta_{c\text{-}Is}$	0.5
E_c	$1 - \tau_{c-1l}$	$F_{s\text{-}c}$	$F_{s-c} = 1 - \tau_{c-II}$	V_{as}	12.25
E_{sc}	0.9	F_{S-sc}	$F_{s-sc} = Cl_{sc}(1 - F_{s-c})$	E_{ro}	0.95
$F_{ro\text{-}sk}$	A_S / A_r	F_{c-sc}	$F_{c-sc} = Cl_{sc}(1 - \tau_{c-II})$	ρ_{sc}	200
LAI	1	$F_{sc\text{-}ri}$	$F_{sc\text{-}ri} = Cl_{sc}$	$I_{c\text{-}s}$	$\eta_{c\text{-}Is} \times I_0$
ρ_{as}	$1.29\frac{T_0}{T_{as}}$	$F_{ri\text{-}c}$	$\tau_{c-Il} = e^{-k_{c\|\|\|} \times LAI}$	C_{p-H_2O}	4186
ρ_c	700	ρ_r	450	c_{p-sc}	1500
R_{min}	82.003	$k_{c\text{-}Is}$	0.48	E_c	$1 - \tau_{c-1l}$
d_{sc}	0.002	Le	0.89	E_{sc}	0.9
V_{sc}	3.07	$k_{c\text{-}II}$	0.64		

We used MATLAB software to solve these set of 51 equations with the use of input parameters shown in Table 2.1.c at once. The solution of these enables us to get the temperatures of the air below the screen (T_a), air above the screen (T_{as}), soil (T_s), cover (T_{ri}), crops (T_c), and the screen (T_{sc}) temperature as a function of time. The Fig. 2.1.d shows the plot of these as a function of time.

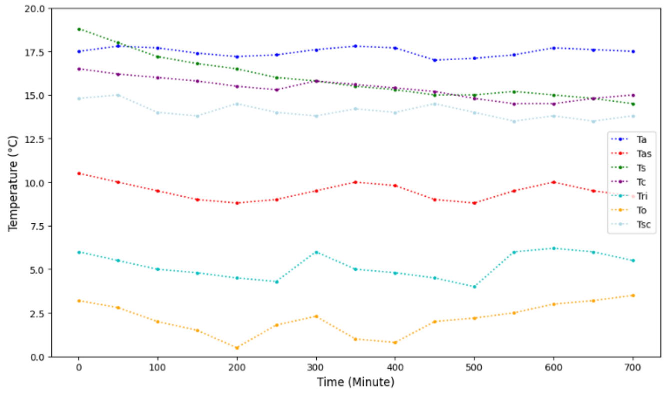


Fig.2.1.d

The table 2.1.e shows a statistical comparison of the crop temperature (T_c) without and without the thermal screen. And the results show that with the use thermal screen the fluctuations of crop temperature are reduced.

Table 2.1.e : Crop temperature fluctuations with and without Thermal Screen.			
Variable	Standard deviation	Skewness	Variance
Tc (with thermal screen)	0.58	0.18	0.33
Tc (without thermal screen)	1.91	4.28	3.64

The crop temperature was plotted with and without the thermal screen as shown in Fig.2.1.f and it can be observed that use of thermal screen reduces the fluctuations in temperature.

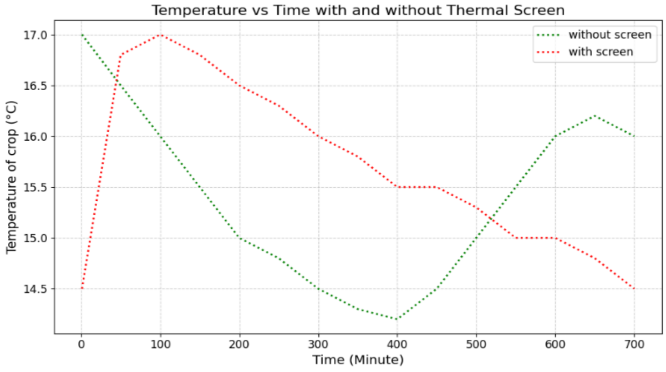


Fig.2.1.f

COMSOL Model Analysis

Link to simulation - https://github.com/sujalmadaan/CLL251_PROJECT

A 3D model of the semi-solar greenhouse as shown in Fig. 2.1.g was developed using COMSOL Multiphysics to simulate the thermal and environmental behaviour inside the structure. The greenhouse model features a length of 4.8 meters, a width of 3.2 meters, and a height of 2.5 meters, closely matching the experimental setup. The covering material used for the greenhouse is 4 mm thick glass, selected for its high solar transmittance and durability. To enhance thermal performance, an internal thermal screen made of cloth material was included, serving to reduce heat loss during colder periods. Additionally, the north wall of the greenhouse was modelled as a concrete wall, acting as a thermal mass to store heat during the day and release it during the night, contributing to improved energy efficiency.

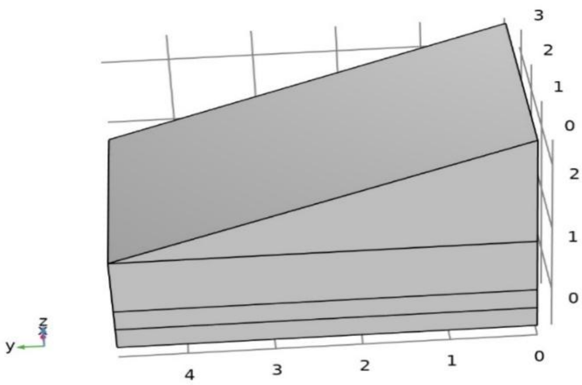


Fig. 2.1.g

Outside temperature function

The outside temperature modelled as skew sinusoidal function as shown below tries to model the variation of temperature over a day in Srinagar city in India. Maximum temperature T_{max} = 293K occurs at 12 noon and minimum temperature T_{min} = 268K occurs at midnight. Fig.2.1.h shows the same.

$$T = 268\ \mathrm{K} + 12.5\ \mathrm{K} \times \left(1 + \sin\left(\frac{2\pi(t + 13 \times 3600\ \mathrm{s})}{86400\ \mathrm{s}} - \frac{\pi}{2}\right)\right)$$

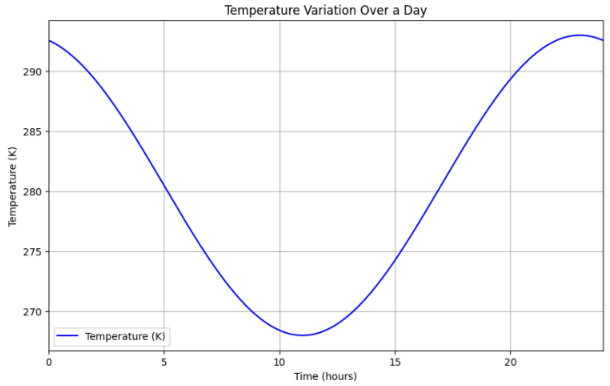


Fig. 2.1.h

Thermal Screen function

- With thermal screen

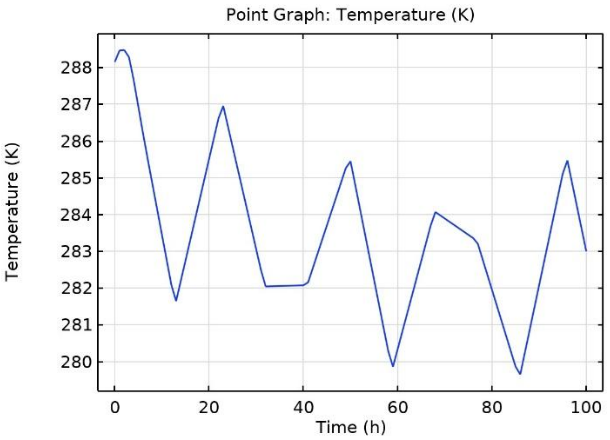


Fig. 2.1.i

- Without thermal screen

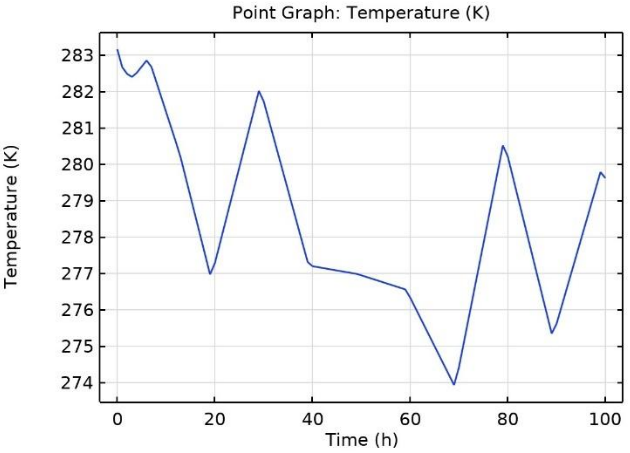


Fig. 2.1.j

The temperature variation over the day inside the greenhouse, below the thermal screen position, is shown for two cases: with and without the thermal screen (Fig. 2.1.i and Fig. 2.1.j, respectively). As seen in Fig. 2.1.i, the temperature fluctuations over time are significantly reduced when the thermal screen is in place, compared to Fig. 2.1.j, where larger temperature fluctuations are observed. This clearly demonstrates that the use of the thermal screen has effectively reduced the temperature fluctuations inside the greenhouse.

Thermal Body Map

- With thermal screen

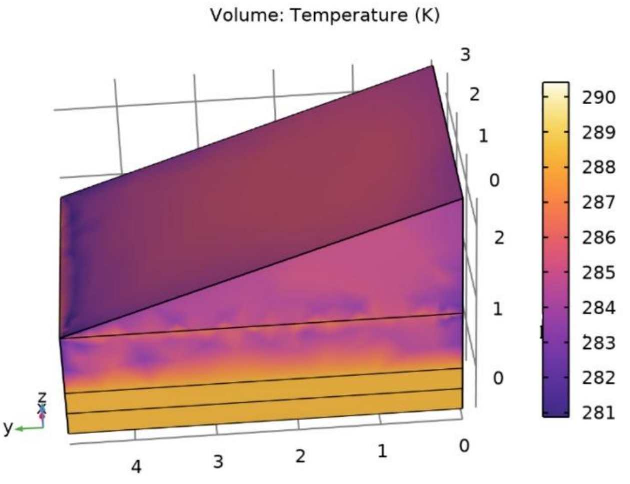


Fig. 2.1.k

- Without thermal screen

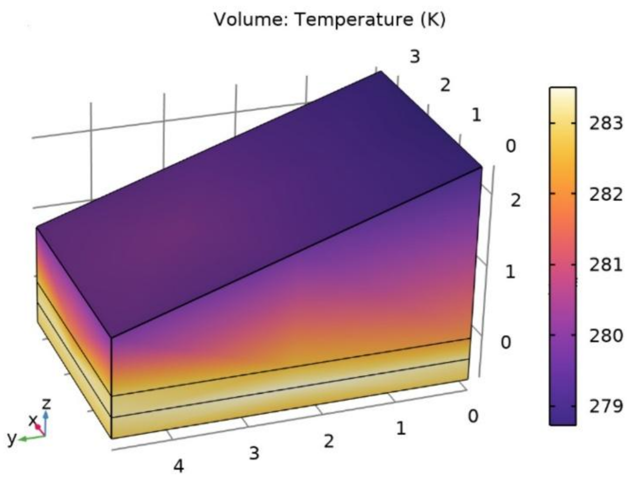


Fig. 2.1.l

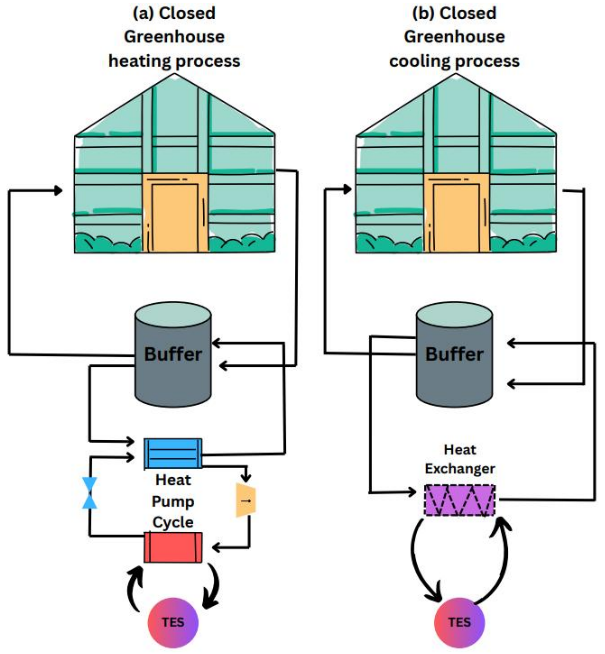


Fig. 2.2.a

Fig. 2.1.k and **Fig. 2.1.l** show the thermal heat maps at midnight, where the temperature reaches its minimum, making the use of the thermal screen particularly important. By visualizing both heat maps, we can observe that the thermal screen helps to maintain a higher temperature inside the greenhouse compared to the case without the thermal screen.

2.2 Thermal energy storage techniques for effective energy storage techniques.

In modern greenhouse management, energy storage systems play a vital role in optimizing both heating and cooling processes, ensuring stable environmental conditions for plant growth while reducing operational costs and energy waste. The diagram above illustrates the integration of thermal energy storage (TES) in a closed greenhouse system, highlighting its dual function across seasonal climate demands.

During the heating process, as shown in part (a) of the Fig. 2.2.a, the greenhouse utilizes a buffer tank in conjunction with a heat pump cycle. When external or internal heat is available-such as from solar gain or surplus renewable electricity-the heat pump transfers this energy into the buffer. The buffer acts as an intermediary reservoir, storing thermal energy until it is needed. When the greenhouse environment requires heating, the stored energy is circulated from the buffer into the greenhouse space, maintaining optimal temperatures for plant health. The TES unit, connected to the buffer and heat pump, serves as a long-term storage medium, allowing excess heat to be retained over extended periods, such as from day to night or even across several days of variable weather. This approach not only reduces reliance on conventional fossil-fuel-based heating but also improves energy efficiency by capturing and reusing surplus heat that would otherwise be lost.

Conversely, during periods of excessive heat, the cooling process depicted in part (b) of the diagram becomes essential. In this mode, the greenhouse system employs a heat exchanger to transfer unwanted thermal energy from the greenhouse air into the buffer and subsequently into the TES unit. The heat exchanger facilitates the efficient movement of heat away from the greenhouse interior, where it can be stored in the TES for later use or dissipated when appropriate. By buffering and storing excess thermal energy during the hottest parts of the day, the system prevents overheating, protects crops from heat stress, and maintains a more consistent internal climate.

The combined use of a buffer tank and TES in both heating and cooling cycles enables a closed-loop energy management strategy. This not only smooths out daily and seasonal temperature fluctuations but also allows greenhouses to make better use of intermittent renewable energy sources, such as solar or wind power. Ultimately, such integrated energy storage solutions contribute to more sustainable, resilient, and cost-effective greenhouse operations, supporting higher crop yields and improved resource efficiency.

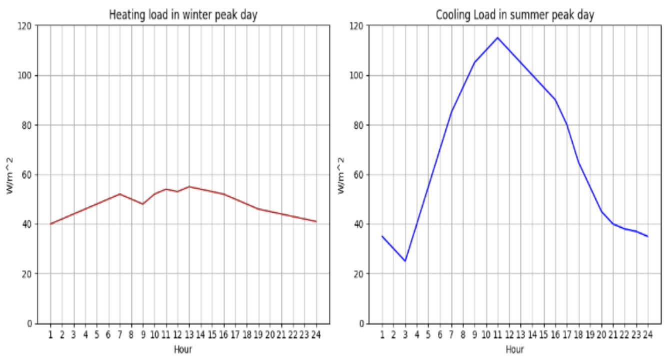


Fig. 2.2.b

The Fig. 2.2.b displays two graphs comparing the hourly variation of heating and cooling loads over a 24-hour period on peak days for winter and summer, respectively. In the left graph, the heating load during a winter peak day remains relatively stable, fluctuating gently between approximately 40 and 60 W/m², with a slight increase during the early morning hours and a modest peak around midday before gradually declining in the evening. In contrast, the right graph illustrates the cooling load on a summer peak day, which starts at about 30 W/m² in the early hours, rises sharply from 5 AM onward, and reaches its maximum of around 110 W/m² in the early afternoon. After peaking, the cooling load steadily decreases through the evening and night. These trends reflect the typical daily patterns of heating and cooling demands, with heating being more consistent throughout the day in winter, while cooling shows a pronounced midday peak in summer due to increased solar gains and outdoor temperatures.

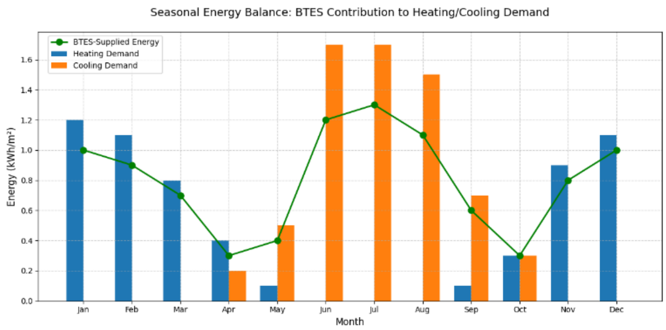


Fig. 2.2.c

Figure 2.2.c illustrates the **hourly heating and cooling load profiles** for a closed greenhouse during peak winter and summer days. The two panels-(a) heating load in winter and (b) cooling load in summer-demonstrate the asymmetric energy demands of a closed greenhouse located in Stockholm, Sweden. The **x-axis** represents time in hours over a 24-hour period, while the **y-axis** shows the thermal load in watts per square meter (W/m²). The winter heating load peaks at **59 W/m²** during nighttime when solar gain is absent, reflecting heat loss through glazing and minimal ventilation. Conversely, the summer cooling load peaks at **113 W/m²** at midday, driven by intense solar radiation and latent heat from plant transpiration. These profiles highlight a critical design insight: **cooling demand is nearly double the heating demand**, making it the dominant factor in sizing thermal energy storage (TES) systems. The curves also reveal diurnal variability, with heating demand rising sharply at night and cooling demand spiking during daylight hours. This asymmetry underscores the need for hybrid storage strategies-seasonal borehole thermal energy storage (BTES) for baseline loads and short-term storage (e.g., stratified chilled water or phase change materials) to manage peak cooling.

3. **Conclusions**

- This project demonstrates that optimized heat transfer techniques significantly enhance greenhouse productivity in India, where large daily temperature variations challenge sustainable farming practices. By integrating thermal screens and thermal energy storage (TES) systems into a closed greenhouse design, substantial improvements in internal temperature stability and energy efficiency were achieved.
- Thermal screens proved highly effective in minimizing nighttime longwave radiation losses and maintaining more stable temperatures around crops. Stabilizing the internal environment is critical because many sensitive crops, such as tomatoes, capsicum, and strawberries, grow best at temperatures between **18°C and 25°C**. Reducing temperature fluctuations helps prevent plant stress, reduces the risk of dew formation on leaves, and improves crop quality and yield.
- The COMSOL simulations and thermal body maps confirmed that greenhouses equipped with thermal screens and thermal mass walls retained more heat during cold nighttime periods, creating a more favorable microclimate for plant growth. The use of TES systems further optimized greenhouse performance by balancing daily heating and cooling demands. During peak summer conditions, cooling loads reached up to **113 W/m²**, while during winter nights, heating needs peaked around **59 W/m²**. Properly designed TES systems allowed for efficient energy storage and retrieval, reducing reliance on external energy sources.
- Overall, the combined use of thermal screens and thermal energy storage leads to greener, more resilient, and more cost-effective greenhouse operations. These strategies not only enhance productivity but also support the long-term sustainability of greenhouse farming in diverse Indian climatic conditions. Future studies could explore integrating renewable energy inputs and developing dynamic climate control strategies to further improve greenhouse performance.

4. Author Contributions

The contributions of each author to this research report are as follows:

- Conceptualization: [Sujal, Shobhit] - Developed the research concept and design.
- Methodology: [Sujal, Shobhit] - Designed the methodology and approached data collection/analysis.
- Software: [Shobhit] - Developed or applied software tools for data analysis or simulation.
- Validation: [Deepanshu, Rishabh] - Verified the results and conducted experiments.
- Formal Analysis: [Sujal, Shobhit] - Analyzed the data and interpreted results.
- Investigation: [Piyush, Deepanshu] - Conducted experiments or data collection.
- Resources: [Piyush, Rishabh] - Provided resources such as materials, equipment, or data.
- Writing – Original Draft: [Sujal] - Wrote the initial draft of the report.
- Writing – Review & Editing: [Shobhit] - Reviewed and edited the draft for accuracy and clarity.
- Visualization: [Rishabh, Deepanshu, Piyush] - Created visualizations such as graphs or diagrams.
- Supervision: [Sujal] - Supervised the research process.
- Project Administration: [Shobhit, Sujal] - Managed and coordinated the project.

5. Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this report. All team members have contributed impartially, and no external funding or personal interests have influenced the outcomes of this research.

6. Acknowledgements

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7. Link to Simulation

https://github.com/sujalmadaan/CLL251_PROJECT

8. Notes and references

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