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Abhishek Kumar
Department of Soil and Water Conservation Engineering (SWCE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Vikas Kumar Singh
Assistant Professor, Department of Soil and Water Conservation Engineering (SWCE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Shivam
Assistant Professor, Department of Irrigation and Drainage Engineering (IDE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Sandeep Kumar Pandey
College of Agriculture, Azamgarh, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Vipin Kumar Roshan
Ph.D., Department of Soil and Water Conservation Engineering (SWCE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India.

Dewanshu Pandey
M.Tech. Department of Irrigation and Drainage Engineering (IDE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Devraj Rastogi
Ph.D., Department of Farm Machinery and Power Engineering (FMPE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Sunil Kumar
M.Tech., Department of Farm Machinery and Power Engineering (FMPE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Satendra Kumar
M.Tech. Department of Irrigation and Drainage Engineering (IDE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Corresponding Author:
Vikas Kumar Singh
Assistant Professor, Department of Soil and Water Conservation Engineering (SWCE), Mahamaya College of Agricultural Engineering & Technology (MCAET), Ambedkar Nagar, Uttar Pradesh, (ANDUAT, Kumarganj, Ayodhya), India

Climate-specific design of low tunnel structures for Eastern Uttar Pradesh

Abhishek Kumar, Vikas Kumar Singh, Shivam, Sandeep Kumar Pandey, Vipin Kumar Roshan, Dewanshu Pandey, Devraj Rastogi, Sunil Kumar and Satendra Kumar

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Abstract

The present study was undertaken to develop climate-specific low tunnel design recommendations for tomato cultivation under the agro-climatic conditions of eastern Uttar Pradesh. Tomato cultivation in open fields within this region often suffers due to low temperatures in winter, high temperatures in summer, unpredictable rainfall, and fluctuating humidity, necessitating appropriate protective cultivation structures. To fill this need, climatic data spanning 25 years (2000-2025) was sourced from the NASA POWER database and examined for variables such as maximum and minimum temperatures, rainfall, relative humidity, wind speed, and solar radiation. The findings indicated significant seasonal fluctuations, with the highest temperature reaching 46.15 °C in May and the lowest dropping to 4.58 °C in January. The heaviest rainfall, measuring 278.09 mm, occurred in July, while relative humidity ranged from 22.43% to 79.77% throughout the year. Drawing from the climatic analysis and existing low tunnel studies, a climate-specific low tunnel design was suggested, featuring a height of 0.6-1.0 m, a width of 1.0-1.5 m, UV-stabilized polyethylene covering, sufficient side ventilation, secure anchoring, raised beds, and effective drainage management. This proposed design aims to enhance the crop microclimate by improving temperature control, minimizing climatic stress, and fostering optimal conditions for tomato growth. The study offers a scientific foundation for developing and implementing low tunnel technology to achieve sustainable tomato production in eastern Uttar Pradesh.

Keywords: Low tunnel technology, protected cultivation, tomato (*Solanum lycopersicum* L.), climatic parameters, microclimate management

Introduction

India's agricultural sector is highly influenced by the climate, as the country's farming practices are largely dependent on weather conditions, which play a crucial role in crop development and overall agricultural productivity (Narvariya *et al.*, 2025) ^[20]. Important climatic variables that control physiological processes like photosynthesis, transpiration, respiration, and crop phenology include temperature, rainfall, relative humidity, and solar radiation. Particularly in light of increasing climate variability, variations in these variables have a significant effect on crop yield, quality, and production system stability (Neenu *et al.*, 2013; Mall *et al.*, 2006) ^[22, 18]. The variability in climatic parameters such as rainfall and temperature supports the need for protective cultivation structures. A recent editorial in also emphasized the challenges posed by rainfall deficits, reinforcing the importance of efficient water management and adaptive agricultural practices.

The primary goal of protected cultivation is to create a controlled microenvironment that shields crops from harsh weather, pests, and diseases, while also ensuring that environmental conditions remain ideal (Jain *et al.*, 2023) ^[9].

Protected cultivation includes a range of structures designed to modify the crop microclimate. Greenhouses are highly advanced structures made of glass or polycarbonate materials, allowing precise environmental control (Castilla, 2012) ^[2]. Polyhouses, constructed using plastic films, provide a comparatively controlled environment and are widely used due to their cost-effectiveness (Kanwar *et al.*, 2019) ^[13]. Net houses are simple and economical structures made of mesh materials, mainly used to protect crops from pests, birds, and mild weather variations

(Singh *et al.*, 2009) ^[25]. The choice of structure depends on climatic conditions, crop type, and available resources (Ganvit *et al.*, 2025) ^[6].

Objectives of the Study

- To analyze long-term climatic variability of eastern Uttar Pradesh using NASA POWER climatic data.
- To develop climate-specific low tunnel design recommendations for tomato cultivation.
- To evaluate the suitability of protected cultivation under prevailing climatic conditions.

Low Tunnel

Low tunnel structures play a crucial role in agriculture by offering a controlled microenvironment for growing crops. These structures are composed of short frames covered with clear or semi-clear materials like polyethylene films, which shield plants from harsh weather, pests, and diseases (Kunjam *et al.*, 2024) ^[16]. By adjusting temperature, humidity, and light exposure, low tunnels can prolong the growing season, enhance crop quality, and boost yields (Santosh *et al.*, 2017) ^[24]. Their importance lies in helping farmers optimize crop growth in areas with unpredictable or difficult climates, providing a cost-effective and flexible way to improve agricultural productivity (Murad *et al.*, 2018) ^[19]. Low tunnels are miniature structures that produce a greenhouse-like effect. This type of structure covers rows of plants, hence the name 'row cover' (Jayasurya *et al.*, 2021) ^[11]. Low tunnels are made from locally available materials like bamboo (Bhatt *et al.*, 2016) ^[1] and wood, or with GI wires, plastic, or metal bars to form semi-circular frames. They are covered with thin plastic sheet (PE or PVC 30-50 μ) or nylon screen (Kang *et al.*, 2013) ^[12].

Importance of climate-specific design for low tunnels

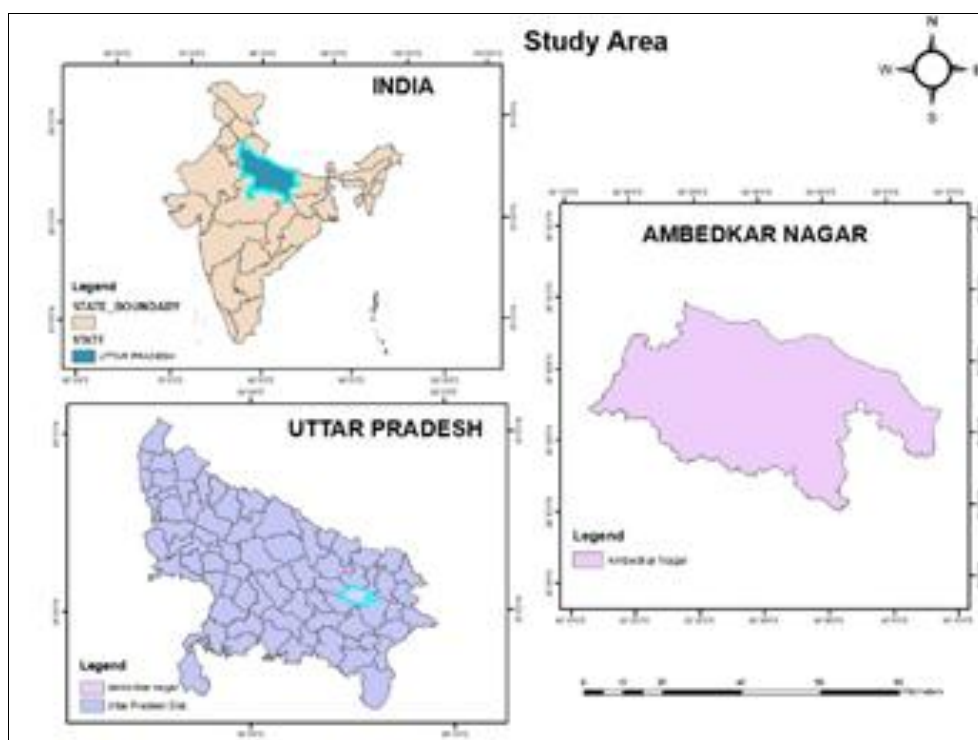
India's agriculture heavily depends on weather conditions,

making the nation's climate crucial for crop development and agricultural output. Key climatic factors such as temperature, precipitation, humidity, and sunlight influence essential physiological processes like photosynthesis, transpiration, respiration, and crop phenology (Nayak & Solanki, 2022) ^[21]. With the rise in climate variability, fluctuations in these factors significantly affect crop yields, quality, and the stability of production systems (Neenu *et al.*, 2013; Mall *et al.*, 2006) ^[22, 18].

As climate conditions continue to change, the significance of protected cultivation has grown, with low tunnel technology being crucial in reducing the impact of climate-related stresses on crops (Dongre *et al.*, 2025) ^[4]. In contrast, growing vegetables in open fields often results in lower quality produce and reduced financial returns. By establishing a favourable micro-climate through the use of protected cultivation structures like low tunnels, vegetable farming can be sustained throughout the year (Jalwania *et al.*, 2025) ^[10]. Low tunnels are essentially small-scale adaptations of the greenhouse model, featuring steel frames covered with polythene roofs (Lodhi *et al.*, 2015) ^[17]. In open-field vegetable farming, crops like tomatoes are particularly vulnerable to unpredictable rainfall, extreme heat, and other climate changes, which can lead to decreased productivity and less stable yields (Mall *et al.* 2006) ^[18].

Study Area

Ambedkar Nagar district is located in the eastern region of Uttar Pradesh, India. It lies between 26°09' and 26°40' North latitude and 82°12' and 83°09' East longitude, covering a geographical area of approximately 2350 km². The study area location map was prepared using ArcGIS 10.4 software, showing the position of Ambedkar Nagar district within Uttar Pradesh and India. Figure 1 illustrates the geographical location of the study area.



Source: Prepared by authors using ArcGIS 10.4

Fig. 1 Location Map

Materials and Methods

Climatic data collection

For this study, climatic data were sourced from the NASA POWER database, covering a 25-year span from 2000 to 2025 for the region of Ambedkar Nagar. The dataset includes critical parameters such as the maximum and minimum Temperatures, Relative humidity, Wind speed, and Precipitation, which are vital for evaluating the area's climatic conditions. Utilizing long-term data allowed for a more precise capture of the variability and trends in climatic conditions, thus offering a dependable foundation for analysis.

Data processing and analysis

The climatic data collected from 2000 to 2025 were analyzed to calculate the monthly averages of essential parameters such as maximum and minimum temperatures, relative humidity, rainfall, wind speed, and solar radiation. This extensive dataset was methodically arranged by month, from January to December, to discern the overall climatic trends in the study region. In addition to calculating averages, the data were thoroughly analyzed to detect extreme values and observe seasonal

variations throughout the months. This analysis was instrumental in gaining insights into the fluctuations of climatic parameters and their potential effects on crop growth. The monthly averages derived from this analysis were also employed to determine the appropriateness of climatic conditions for the construction of low tunnel structures.

Assessment of microclimatic needs for low tunnel crops

The microclimatic needs of crops grown under low tunnels were evaluated by examining climatic factors like temperature, humidity, wind speed, and solar radiation. The findings highlighted the necessity of using protective structures to ensure optimal growing conditions for crops during unfavourable weather.

Results

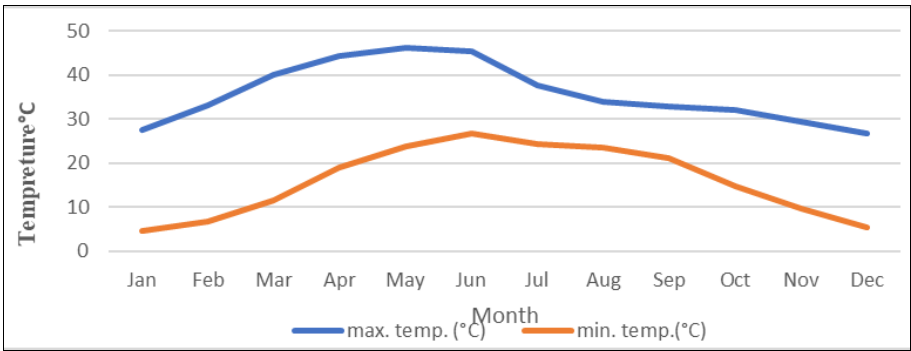
The study of long-term climate records has identified significant seasonal changes in temperature, humidity, rainfall, wind speed, and solar radiation in Ambedkar Nagar. These changes have a direct impact on crop growth, emphasizing the need for low tunnel structures to adjust the microclimate.

Table 1: Monthly average climatic data of Ambedkar Nagar district (2000-2025)

Sr. No.	Month	Tmax. (°C)	Tmin. (°C)	RH 2m height (%)	Solar Radiation (MJ m ⁻² day ⁻¹)	Wind speed (m/s)	Rainfall (mm)
1	Jan	27.55	4.58	50.51	10.21	1.70	13.74
2	Feb	33.2	6.89	42.56	15.97	1.93	14.74
3	Mar	40.07	11.51	30.36	20.63	2.15	11.21
4	Apr	44.41	18.97	22.43	23.39	2.38	10.9
5	May	46.15	23.91	28.72	22.44	2.43	35.34
6	Jun	45.47	26.73	44.47	19.58	2.69	134.32
7	Jul	37.5	24.29	72.41	15.87	2.51	278.09
8	Aug	33.93	23.55	79.77	16.14	2.08	232.73
9	Sep	32.86	21.06	79.4	15.83	1.85	164.18
10	Oct	31.98	14.76	68.5	15.83	1.33	41.34
11	Nov	29.27	9.77	57.92	12.59	1.36	1.9
12	Dec	26.63	5.41	52.66	9.88	1.52	4.89

Source: NASA POWER database (2000-2025), processed by authors

Temperature



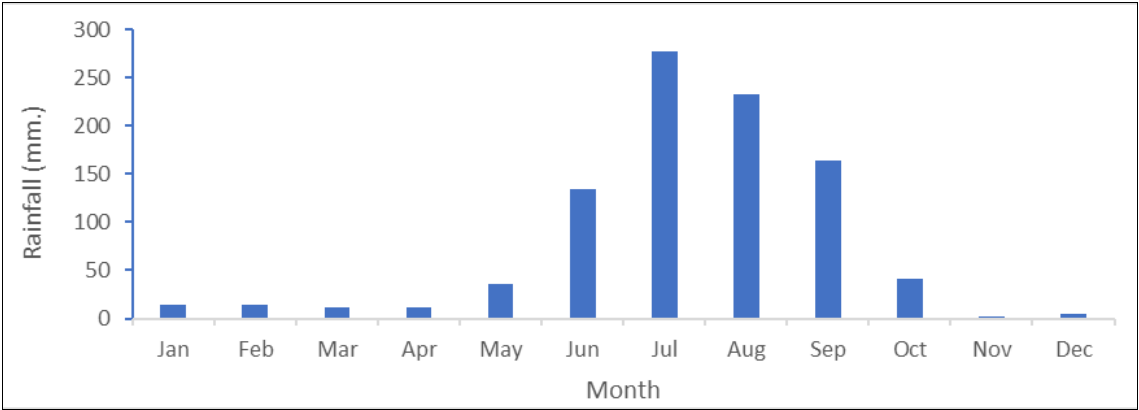
Source: NASA POWER database (2000-2025), processed by authors.

Fig 2: Monthly variation in maximum and minimum temperature (2000-2025)

Figure 2, presents the monthly temperature changes in Ambedkar Nagar, showcasing a distinct seasonal pattern. Beginning in January, the highest temperatures progressively climbed, reaching their zenith in May and June, indicative of the intense summer heat. Conversely, the lowest temperatures were observed in December and January, which could potentially hinder seed germination and the initial phases of crop growth. These cold conditions highlight the necessity for protective

strategies, such as low tunnel structures, to establish a conducive microclimate. Low tunnels modify the microclimate by trapping solar radiation and reducing heat loss, thereby increasing the temperature around the crop canopy, especially during night and early morning hours. This increase in temperature improves germination, growth, and early yield (ICAR, 2017; Kumar *et al.*, 2013) [8, 15].

Rainfall

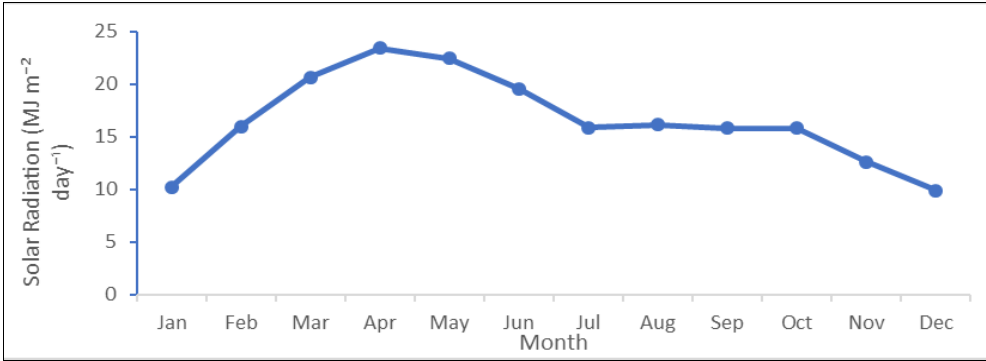


Source: NASA POWER database (2000-2025), processed by authors.

Fig. 3: Monthly rainfall distribution pattern (2000-2025)

According to Figure 3, rainfall follows a distinct seasonal trend, with the monsoon period from June to September receiving the most rainfall. July experiences the peak of this precipitation, succeeded by August and September, whereas the winter months register the least rainfall. This pattern underscores the region's significant reliance on monsoon rains for its agricultural needs. This uneven distribution of rainfall highlights the region's dependence on monsoon rains for crop production. However,

limited rainfall during winter creates moisture stress conditions, which are unfavourable for crop growth, particularly during early stages. Under such conditions, the adoption of protected cultivation techniques such as low tunnels, along with efficient irrigation methods like drip irrigation, becomes essential to ensure adequate moisture availability and maintain a favourable microclimate for crop growth (IMD, 2020; FAO, 1998) [7, 5].



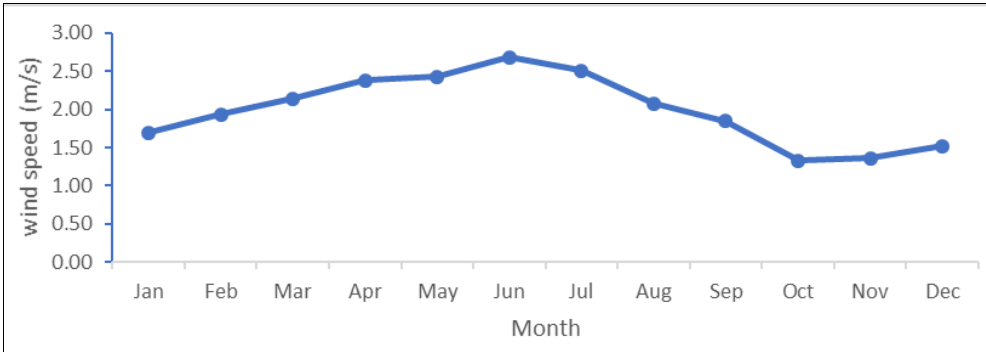
Source: NASA POWER database (2000-2025), processed by authors.

Fig 4: Monthly variation in solar radiation (2000-2025)

Solar radiation

Figure 4, illustrates a distinct seasonal pattern in solar radiation, with levels rising from January and peaking in April and May. During the monsoon season, there is a decrease due to increased cloudiness, followed by lower levels in winter. Solar radiation is vital for crop development as it affects photosynthesis and

temperature conditions. Solar radiation is essential for crop development as it affects both photosynthesis and temperature conditions. By effectively managing these factors with protective structures like low tunnels, crop performance can be enhanced (Kläring & Krumbein, 2013) [14].



Source: NASA POWER database (2000-2025), processed by authors.

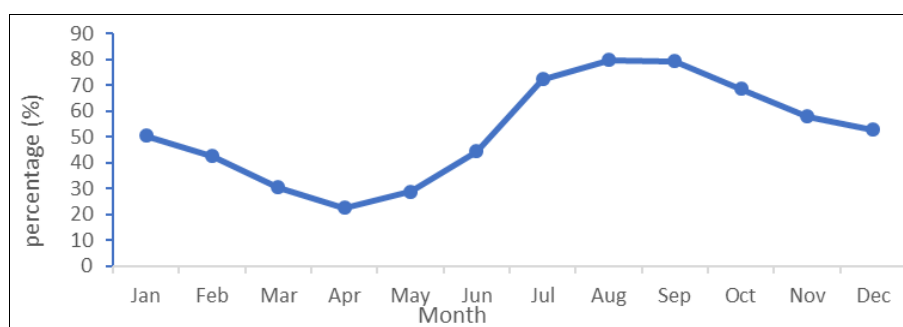
Fig 5: Monthly average wind speed 2m (m/s)

Wind speed

Figure 5 illustrates that the average monthly wind speed (WS2M) exhibited an upward trend from January through June, peaking at approximately 2.7 m/s in June. Following this peak, the wind speed gradually declined, reaching its lowest point of around 1.3 m/s in October, highlighting the seasonal fluctuations in wind conditions over the year.

During the summer, increased wind speeds can lead to higher rates of evapotranspiration and may exert mechanical stress on

crops. In contrast, moderate wind conditions in winter tend to be more beneficial for crop growth. Nevertheless, uncontrolled wind can negatively impact plant development and hinder soil moisture retention. In this scenario, low tunnel structures are crucial as they serve as a physical barrier, decreasing wind speed around the crop canopy, reducing moisture loss, and establishing a stable microclimate that supports improved crop growth and development (FAO, 1998; ICAR, 2017) ^[5, 8].



Source: NASA POWER database (2000-2025), processed by authors.

Fig 6: Monthly variation in relative humidity (%)

Relative humidity

Figure 6, shows the monthly changes in relative humidity (%). Beginning at 50.51% in January, the relative humidity reached its lowest point in April at 22.43%. It then steadily climbed, peaking in August at 79.77%. Following a slight dip to 79.4% in September, the humidity gradually decreased, concluding the year at 52.66% in December. Overall, the monsoon season was characterized by higher humidity levels, whereas the summer months saw a decline in humidity.

Low relative humidity during summer increases evapotranspiration, leading to rapid soil moisture depletion and potential plant stress. In contrast, higher humidity during the monsoon season creates favourable conditions for crop growth but may also increase the risk of diseases. Under such varying conditions, low tunnel structures help in moderating the microclimate by conserving moisture during dry periods and providing partial protection against excessive humidity fluctuations. This results in improved plant growth, better water use efficiency, and enhanced crop performance (FAO, 1998; ICAR, 2017) ^[5, 8].

Effect of prevailing climatic conditions on the design of low tunnel structure

The weather patterns in Ambedkar Nagar play a crucial role in shaping the design and management of low tunnel structures used for growing tomatoes. Elements like temperature, humidity, rainfall, wind speed, and solar radiation are key in determining the choice of covering materials, the size of the tunnels, and the ventilation systems. These low tunnel structures are essential for creating an optimal microclimate that supports improved crop growth, earlier production, and increased yields despite changing weather conditions.

Effect of temperature

The area being examined experiences notable temperature variations, with the peak temperature reaching about 46.15 °C in May and the minimum falling to roughly 4.58 °C in January. During winter, low tunnel structures are advantageous as they trap solar heat, creating optimal temperature conditions for crops. A tunnel height between 0.6 and 1.0 meters and a width

of 1.0 to 1.5 meters is considered effective for retaining heat. However, in summer, excessive heat can build up inside the tunnel, requiring proper ventilation or partial removal of the covering material to prevent heat stress and flower drop in tomato plants.

Effect of solar radiation

In the study area, solar radiation ranges from approximately 9.88 to 23.39 MJ m⁻² day⁻¹, with the highest levels occurring in April and May. Elevated solar radiation leads to increased tunnel temperatures and higher evapotranspiration losses. Consequently, using a transparent UV-stabilized polyethylene film with around 80-90% light transmissivity is effective as a covering material to harness solar energy efficiently during the winter months. To mitigate heat stress and maintain optimal conditions inside the low tunnel during periods of intense radiation, shade nets providing 30-50% shading can be employed.

Effect of relative humidity

In the study area, relative humidity ranges from approximately 22.43% to 79.77%. During the summer, low humidity levels lead to an increased need for water in crops, whereas the high humidity of the monsoon season promotes the development of diseases. Consequently, adequate side ventilation in low tunnel structures is essential to decrease excess moisture and ensure proper air circulation within the tunnel.

Effect of wind speed:

In the research area, wind velocities generally range from about 1.3 to 2.7 m/s. Strong winds have the potential to damage tunnel structures and remove plastic coverings. Therefore, it is crucial to firmly secure low tunnels with durable materials such as galvanized iron (GI) hoops, bamboo, PVC pipes, and UV-stabilized polyethylene sheets to improve their stability under field conditions.

Effect of rainfall

The study area receives heavy rainfall during July to September, with maximum rainfall of about 278.09 mm in July. Excess

rainfall may cause waterlogging, high humidity, and disease incidence in tomato crops. Therefore, proper drainage channels, raised beds, plastic mulch, and UV-stabilized polyethylene covering are recommended to maintain suitable moisture conditions and protect the crop under rainy conditions. Based on

the climatic analysis of the study area, a schematic sketch of the recommended low tunnel structure was prepared (Figure 2) to illustrate the proposed design and its suitability for tomato cultivation under local climatic conditions.

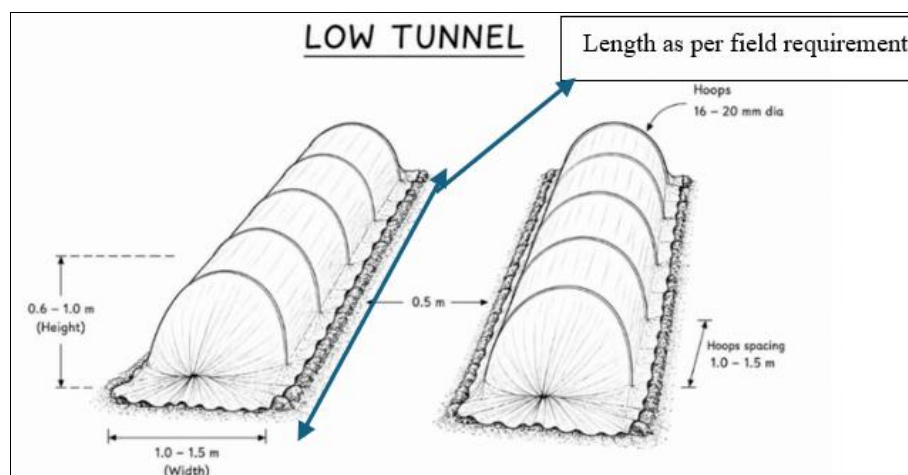


Fig 7: Low tunnel design description

Statistical Analysis

Descriptive statistics and graphical analysis were used to evaluate long-term climatic variability and seasonal patterns of the study area. Monthly averages of climatic parameters were computed and interpreted for developing climate-specific low tunnel design recommendations.

Discussion

Figure 1 illustrates that low temperatures during the early stages of crop growth can impact seedling establishment and vegetative development, highlighting the importance of using low tunnel structures for crop protection. Conversely, elevated temperatures in the later stages can lead to increased evapotranspiration and heat stress within the tunnel, necessitating effective ventilation and temperature control. These observations align with previous research on protected cultivation systems.

The depiction of relative humidity in Figure 2 indicates that the accumulation of moisture within low tunnels could foster an environment suitable for fungal diseases. Thus, it is essential to ensure proper air movement and ventilation to sustain a microclimate conducive to healthy crop development. Additionally, Figure 3 reveals fluctuations in rainfall, pointing to the potential for adverse weather conditions that might influence both the growth of crops and the structural integrity of tunnels in open-field environments.

Given the current climate conditions, UV-stabilized polyethylene sheets are advised as appropriate coverings for low tunnel structures. A 50-micron UV plastic sheet can offer cost-effective short-term protection during the initial stages of crop growth, while thicker sheets (75-100 microns) provide enhanced durability and resistance to temperature fluctuations, rain, and wind. Maintaining the correct tunnel height is crucial for ensuring effective air circulation and temperature regulation. An east-west orientation might enhance sunlight distribution, and side ventilation openings can help prevent excessive heat accumulation inside the tunnel. Additionally, the tunnel structure should be securely anchored to endure strong winds and heavy rain.

The recommended tunnel height (0.6-1.0 m) and width (1.0-1.5 m) were selected based on the climatic conditions of the study

area and published recommendations for low tunnel cultivation. These dimensions provide effective heat retention during winter, adequate ventilation during warmer periods, and structural stability under local wind conditions (Kumar *et al.*, 2013; ICAR, 2017) [15, 8]. Furthermore, similar low tunnel dimensions and covering materials have been reported by Murad *et al.* (2018) [19] and Jayasurya *et al.* (2021) [11], supporting the suitability of the proposed design for tomato cultivation under eastern Uttar Pradesh conditions.

Compared with advanced protected cultivation structures, low tunnel technology is relatively simple, low-cost, and easy to construct using locally available materials such as bamboo, GI wire, and polyethylene sheets. Due to its lower initial investment and operational requirements, it is particularly suitable for small and marginal farmers. The proposed low tunnel design can provide partial environmental protection and improve crop growing conditions without the high capital cost associated with polyhouse cultivation. Therefore, it offers a practical and economically feasible option for tomato production under the agro-climatic conditions of eastern Uttar Pradesh.

Recommendations for Low Tunnel Design under Prevailing Climatic Conditions

Based on the climatic analysis of the study area, the following recommendations are proposed for the design and development of low tunnel structures for tomato cultivation

1. Tunnel Dimensions

- Height: 0.6-1.0 m
- Width: 1.0-1.5 m
- Length: As per field requirement and ease of ventilation management

2. Cladding Material

- Use 30 - 50-micron UV-stabilized transparent polyethylene film during winter season.
- Use 30-50% shade nets during periods of excessive heat and radiation.

3. Hoop Spacing

- Recommended hoop spacing: 1.0-1.5 m

- Closer spacing should be maintained in windy conditions for better structural stability.

4. Ventilation Management

- Provide side ventilation openings to reduce excess heat and humidity.
- Use removable or roll-up plastic covers for temperature regulation.

5. Structural Stability

- Use GI hoops, PVC pipes, or bamboo frames with proper anchoring.
- Ensure firm fixation of cladding material against high wind velocity.

6. Drainage and Mulching

- Construct raised beds with drainage channels.
- Use plastic mulch to conserve moisture and suppress weeds.

7. Seasonal Operation

- Low tunnels are most suitable during winter and rainy monsoon months.
- Plastic covers may be partially or completely removed during high-temperature periods.

Limitations of the Study

- The recommended design for low tunnels was created with the specific agro-climatic conditions of eastern Uttar Pradesh in mind, and its effectiveness might differ in other environmental regions.
- The research focused mainly on climate analysis and structural suggestions for protected farming, but it did not thoroughly explore detailed performance assessments at the field level across various seasonal conditions.
- Economic feasibility, long-term durability, and large-scale validation of the proposed low tunnel structure were beyond the scope of the present study and require further research.
- The present study is based on climatic analysis and literature-supported design recommendations; therefore, field-scale thermal performance validation of the proposed low tunnel structure was beyond the scope of the study.

Conclusion

The present study highlights the importance of climatic factors such as temperature, relative humidity, rainfall, and wind speed in the planning and management of low tunnel structures. The observed climatic patterns indicated that lower temperatures during the initial crop growth stages and higher temperatures during later stages can significantly influence crop growth and productivity, thereby emphasizing the need for protected cultivation practices.

The study suggests that the use of low tunnel structures covered with UV-stabilized polyethylene sheets can improve the microclimatic conditions around the crop. A 50-micron polyethylene sheet may be suitable for short-term and economical applications, whereas thicker sheets (75-100 microns) provide better durability and protection under fluctuating climatic conditions. Proper tunnel height, east-west orientation, and adequate ventilation were also found important for efficient low tunnel performance.

The findings of the study may be useful for farmers, researchers, and agricultural engineers in selecting suitable low tunnel designs under varying climatic conditions. Further research is

required to optimize low tunnel parameters for specific crops, planting schedules, and advanced irrigation and fertigation practices to improve productivity and resource-use efficiency.

References

1. Bhatt L, Maurya SK, Singh D. Economic feasibility of summer squash cultivation using low tunnel and black plastic mulch under tarai condition of Uttarakhand. *J Appl Nat Sci*. 2016;8(2):817-821.
2. Castilla N. Greenhouse technology and management. Wallingford: CABI; 2012.
<https://DOI.org/10.1079/9781780641034.0000>
3. Census of India. Census of India 2011.
<https://censusindia.gov.in/census.website/Census>
4. Dongre RN, Sharma M, Rajput R, Shankar R, Sonkar S, Patel V, *et al*. Protected cultivation of horticultural crops: A sustainable approach to climate-resilient agriculture in India. *Int J Adv Biochem Res*. 2025;9(5):714-720.
<https://DOI.org/10.33545/26174693.2025.v9.i5i.4414>
5. Food and Agriculture Organization. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome: FAO; 1998.
6. Ganvit JM, Masaye SS, Parma VK, Patel N. Types of protected structures in controlled environment horticulture. In: *Controlled Environment Horticulture*. Bentham Science; 2025. p. 22-38.
<https://DOI.org/10.2174/9798898810429125010008>
7. India Meteorological Department. Climatological data of India. New Delhi: Ministry of Earth Sciences, Government of India; 2020.
8. Indian Council of Agricultural Research. Protected cultivation of vegetable crops. New Delhi: ICAR; 2017.
9. Jain S, Kore DS, KK, Mohapatra A, Baksh H, Kumar V, *et al*. A comprehensive review on protected cultivation of horticultural crops: Present status and future prospects. *Int J Environ Clim Change*. 2023;13(11):3521-3531.
<https://DOI.org/10.9734/ijec/2023/v13i113528>
10. Jalwania R, Kumar P, Kumar A, Hansda S, Pandey P, Jagadala K, *et al*. Protected cultivation technologies for off-season vegetable production: A review. *J Sci Res Rep*. 2025;31(5):470-489.
<https://DOI.org/10.9734/jsrr/2025/v31i53045>
11. Jayasurya P, Chatterjee S, Biswas A, Viswanath M, Roy A. Low cost protected structures for off-season vegetable production: A review. *Pharma Innov J*. 2021;10:778-783.
12. Kang Y, Chang YCA, Choi HS, Gu M. Current and future status of protected cultivation techniques in Asia. *Acta Hortic*. 2013;987:33-40.
13. Kanwar MS. High-altitude protected vegetable cultivation A way for sustainable agriculture. In: *Applied agricultural practices for mitigating climate change*. Vol. 2. 2019. p. 51.
14. Kläring HP, Krumbein A. The effect of constraining the intensity of solar radiation on the photosynthesis, growth, yield and product quality of tomato. *J Agron Crop Sci*. 2013;199:xxx-xxx. <https://DOI.org/10.1111/jac.12018>
15. Kumar S, Tiwari KN, Jha MK. Performance of low tunnels for off-season vegetable production under North Indian conditions. *Indian J Hortic*. 2013;70(2):237-241.
16. Kunjam K, Samrath R, Sahu E, Paikra DS. Low tunnel technology: A review. *Int J Adv Biochem Res*. 2024;8(12 Suppl):434-436.
<https://DOI.org/10.33545/26174693.2024.v8.i12sf.3143>
17. Lodhi AS, Kaushal A, Singh KG. Low tunnel technology

- for vegetable crops in India. In: Singh KG, Goyal MR, Rudra RP, editors. Best management practices for drip irrigated crops. Canada: Apple Academic Press; 2015. p. 3-9.
18. Mall RK, Singh R, Gupta A, Srinivasan G, Rathore LS. Impact of climate change on Indian agriculture: A review. *Clim Change*. 2006;78(2):445-478.
 19. Murad R, Abdel-Wahed M, Hassan M, Raslan M. Performance of low agricultural tunnels for vegetables production. *Misr J Agric Eng*. 2018;35(2):641-656. <https://DOI.org/10.21608/mjae.2018.95809>
 20. Narvariya RK, Mishra A, Singh R. Climate change and agricultural productivity in India: Economic consequences and adaptation strategies. *J Sci Res Rep*. 2025;31(3):161-176. <https://DOI.org/10.9734/jsrr/2025/v31i32888>
 21. Nayak P, Solanki H. Effect of climate change on crop production in India. *Int Assoc Biol Comput Dig*. 2022;1(2):98-106. <https://DOI.org/10.56588/iabcd.v1i2.52>
 22. Neenu S, Biswas AK, Subba Rao A. Impact of climatic factors on crop production A review. *Agric Rev*. 2013;34(2):97-106.
 23. Prakash P, Kumar P, Kar A, Kishore P, Singh A, Immanuel S. Protected cultivation in Maharashtra: Determinants of adoption, constraints, and impact. *Agric Econ Res Rev*. 2022;34:217-228. <https://DOI.org/10.5958/0974-0279.2021.00031.8>
 24. Santosh DT, Tiwari KN, Singh VK. Influence of different protected cultivation structures on water requirements of winter vegetables. *Int J Agric Environ Biotechnol*. 2017;10(1):93-103.
 25. Singh HP, Dhankhar SS, Dahiya KK. Horticultural crops. New Delhi: Stadium Press (India) Pvt. Ltd.; 2009.
 26. The Hindu. Dry days: On rainfall deficit forecast. The Hindu. 2026 Apr 16.