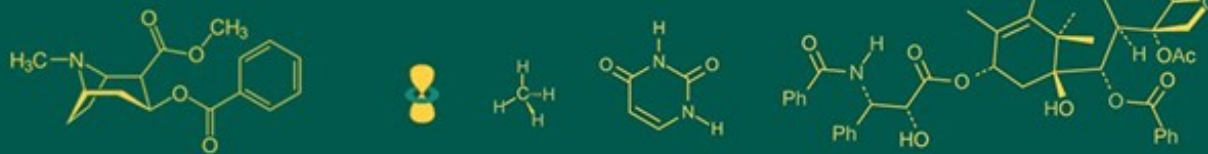


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 NAAS Rating (2026): 5.29
 Indexing: Embase
 IJABR 2026; SP-10(10): 995-998
www.biochemjournal.com
 Received: 24-08-2026
 Accepted: 25-09-2026
 Published: 10-10-2026

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Effects of crop cover systems on microclimate, growth, yield and quality of *Capsicum*

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i10SI.10413>

ABSTRACT

Capsicum (*Capsicum annuum* var. *Grossum* sendt.) is an economically important vegetable crop grown for its nutritional value, consumer demand and market potential. However, its growth, flowering, fruit development and yield are highly influenced by environmental conditions, particularly temperature, light intensity, relative humidity and soil moisture. Crop covering technology such as row covers, low tunnels, shade nets and non-woven polypropylene materials, provides an economic approach for altering crop microenvironment and ensuring protection against biotic and abiotic stresses. These covering systems influence the intensity and spectral quality of solar radiation reaching the crop canopy. Thereby affecting in the canopy temperature, humidity, plant morphology, physiological process, fruit development and overall crop yield. Low tunnels can also facilitate early crop production by providing protection against low temperature, cold winds, frost, heavy rainfall and certain insect pest. However, the effectiveness of a crop-covers depends on the type, colour, physical property and shading intensity of the covering material. Therefore, a proper bed preparation, hoop spacing, tunnel dimension, cover installation, ventilation, and timely removal of the cover material are the key factors to maintain a good microclimate of the crop. This review summarizes the impact of crop-cover systems on the microclimate, plant growth, yield, and quality of capsicum, focusing mainly on low tunnels and row covers, and discuss their management and potential use for protected and offseason production.

Keywords: *Capsicum*, Crop cover, Low tunnel, Row cover, Shade net, Non-woven polypropylene, Protected cultivation, Microclimate

1. Introduction

Vegetable crops play key role in food and nutritional security while contributing significantly to farm income and the diversified agricultural systems (Ebert, 2020)^[1]. *Capsicum* (*Capsicum annuum* var. *grossum* Sendt) is an important solanaceous vegetable crop widely grown for domestic and international market (Donas *et al.*, 2014)^[2]. *Capsicum*, also known as sweet pepper, bell pepper, green pepper, shimla mirch or dholbi mirchi, produces fruits of various colours and is consumed fresh as well as processed into a wide variety of ready-to-eat products. The commercial importance of capsicum has increased due to the growing demand for high-quality vegetables, especially in urban and peri-urban markets (Wani *et al.*, 2011)^[3]. However, despite its economic importance, capsicum is very sensitive to environmental fluctuations. Significant differences in vegetative growth, flowering, fruit set, fruit development and final yield can occur due to variations in temperature, solar radiation, relative humidity and soil moisture. As a result, adverse weather conditions may lead to poor crop establishment, lower reproductive development and reduced fruit quality. Thus, proper microenvironment management is a crucial aspect of successful capsicum production. Crop-cover systems offer a feasible strategy for altering the immediate growing environment (Shahak *et al.*, 2008)^[4]. Row covers, low tunnels, shade nets and non-woven polypropylene materials can mitigate the impact of adverse environmental conditions, while influencing light intensity, spectral quality, temperature, humidity and soil moisture. These changes in the physical environment also affect plant morphology and physiological processes, which in turn impact productivity and fruit quality, in addition to their effects. Covering materials, providing physical barriers to wind, rain, hail and insect pests, may also reduce mechanical and biological stress (Castellano *et al.* 2008)^[5]. Photo-selective nets and other specialized materials can additionally modify the spectral composition of solar radiation reaching the canopy, potentially altering plant developmental responses through light-sensitive physiological pathways (Jiao *et al.*, 2007)^[6]. The objective of this review is to examine the role of crop-cover systems, particularly low tunnels and row covers, in capsicum production. Emphasis is placed on their effects on the crop microclimate, light environment, vegetative growth, yield and crop management, together with practical considerations associated with bed preparation, hoop installation, ventilation and cover removal.

2. Crop covers and low-tunnel systems

2.1 Concept and principle of row covers and low tunnels

Low tunnels are relatively simple and economical protected cultivation structures designed to cover individual crop beds and create a favourable microenvironment around the crop canopy and root zone. Row covers similarly provide a protective layer over crop rows and reduce exposure to unfavourable environmental conditions (Pramanik *et al.*, 2020)^[7]. Generally, low tunnels are made with flexible support hoops that are placed over crop rows and covered with semi-transparent or shading films. The end result is a small greenhouse-like structure that alters the transfer of solar radiation and heat between the crop canopy and incident atmosphere. The covering material insulates and contributes to heat retention when temperature conditions are cool, and indoors temperature around the plants increases.

Row covers can increase air and soil temperature and provide physical protection against frost, hail, cold winds and mechanical injury. Under favourable conditions, these modifications can accelerate crop establishment and advance harvesting by approximately 30-40 days compared with conventional open-field production (Serrano, 2023)^[8]. The principal objective of low-tunnel technology is therefore not merely to physically cover the crop but to create a more favourable microenvironment during periods when open-field conditions are unsuitable (Aruna *et al.*, 2010)^[9]. This makes the technology particularly relevant for early and off-season vegetable production. Earlier crop establishment and harvest may provide opportunities for growers to target high-value market windows and improve economic returns (Li *et al.*, 2013)^[10].

2.2. Importance of crop covers in capsicum production

Capsicum responds strongly to changes in the growing environment, and the nature of the covering material can influence important morphological and physiological traits. Plant height, branching, chlorophyll content, fruit set and fruit weight have been reported to vary under different shade colours and intensities (Rylski *et al.*, 1986)^[11]. Siwek and Libik (1999)^[12] reported differences in plant height under different coloured shade nets. Increased plant height was observed under white non-woven polypropylene and under green, red and blue shade nets compared with unshaded conditions. Similarly, Medany *et al.* (2009)^[13] reported that white non-woven polypropylene with a grammage of 25 GSM produced greater plant height in bell pepper than open-field cultivation.

The effects of shading intensity are also important. Masabni *et al.* (2016)^[14] showed that 50% and 70% shade level were significantly influenced the height and chlorophyll content of the sweet pepper plant. These findings illustrate that the response of capsicum to crop covers is not solely a function of cover versus no cover but rather the optical and physical properties of the covering material. Thus, the selection of an appropriate cover should consider its ability to regulate the amount and quality of radiation, modify temperature and humidity, and maintain suitable growing conditions throughout the crop cycle.

2.3. Modification of the light environment

Light is one of the major environmental factors governing photosynthesis, plant morphology and reproductive development. Crop-cover materials modify the quantity as well as the spectral composition of radiation reaching the crop canopy. Depending on their color, material and structure, covers may transmit, absorb or reflect different wavelengths of solar radiation (Chen *et al.*, 2004)^[15]. Changes in the spectral environment are particularly important because plants perceive specific wavelengths through photoreceptors that regulate several developmental processes. Blue and red wavelengths are associated with important physiological processes, while changes in the overall light environment can affect plant height, leaf expansion, chlorophyll formation, flowering and fruit set.

Consequently, photo-selective shade nets have increasingly been incorporated into protected vegetable production systems. Shahak *et al.* (2008)^[4] reported that photo-selective shade-net systems integrated with protective structures can modify the crop environment and improve vegetable production. Diaz-Perez and John (2019)^[16] also observed differences in chlorophyll content and crop morphology between low-tunnel treatments and unshaded conditions. These findings indicate that evaluation of crop-cover systems should extend beyond nominal shade percentage. The spectral transmission properties of a covering material may be equally important in determining plant responses (Chen *et al.*, 2004)^[15].

2.4. Modification of the crop microclimate

One of the principal functions of crop covers is modification of the microclimate surrounding the crop.

Low tunnels can influence air temperature, relative humidity, and soil moisture in the crop environment. These changes can result in more suitable conditions for crop establishment and early growth during low ambient temperature. But microclimate alteration can lead to positive and negative effects. In periods of strong solar radiation, heat buildup under a cover can lead to temperatures that are too high for crop growth. Effective ventilation is therefore essential for preventing heat stress (Casierra-Posada *et al.*, 2015)^[17].

Kumar *et al.* (2024)^[18] reported that temperatures beneath low plastic tunnels can become substantially higher than ambient temperatures during periods of peak solar radiation. Diaz-Perez and John (2019)^[16] similarly demonstrated differences in canopy temperature, relative humidity and soil moisture under row-cover treatments. Their observations indicated that 50% black shade nets maintained relatively higher canopy temperature and relative humidity, whereas 50% silver shade nets resulted in comparatively lower canopy temperature and relative humidity. These results highlight the fact that the influence of a crop cover layer is dependent on its optical properties and the environmental conditions. A material that is good for low temperature environment may be too hot for high radiation environment. Consequently, the technique of crop cover management needs to be flexible and tailored to the season, weather and crop growth stage.

2.5. Effects on plant growth and yield

Modification of the crop microclimate can influence vegetative growth and reproductive development and consequently affect yield. Shukla and Bhakar (2019)^[19] reported enhanced vegetative growth under protective crop-cover conditions. Kesumawati *et al.* (2020)^[20] observed significant differences in plant height and number of branches per plant under 35% and 50% green shade nets. The effects of crop-cover systems also extend to reproductive development and productivity. Ilić *et al.* (2017)^[21] reported improved fruit production and total yield under coloured shade nets, while Kaswan *et al.* (2022)^[22] documented increased sweet pepper yield under red shade nets compared with other coloured net treatments.

Evidence from several studies suggests that white non-woven polypropylene can provide favourable conditions for capsicum growth. Positive responses under white 25 GSM non-woven polypropylene were reported, including improvements in plant height, plant spread, branch number, fresh and dry root weight and yield-related parameters (Siwek *et al.*, 1999; Shukla *et al.*, 2019; Andhale *et al.*, 2014; Lang *et al.*, 2020)^[12, 19, 23, 24]. These responses may be associated with the combined effects of moderated temperature, altered radiation and improved protection from environmental stresses. The response, however, is not necessarily uniform across environments. Differences in cultivar, season, ambient weather, cover properties and management practices can modify the outcome of a particular covering treatment. Therefore, recommendations regarding specific cover materials should preferably be based on locally validated experiments.



Figure 1. Schematic representation of a row-cover low tunnel system for capsicum

3. Bed preparation and installation of hoops

Successful low-tunnel production starts with crop bed preparation. The beds must be prepared in such a way that the resultant soil is loose, well-drained and conducive to rapid root growth. Under drip-irrigated production systems, bed dimensions should be compatible with the selected crop spacing and irrigation layout. Flexible galvanized iron (GI) hoops are commonly used to support the covering material. The hoops are installed over the beds before or around the time of transplanting. Kumar *et al.* (2024)^[18] reported hoop spacing of approximately 1.5-2.5 m along the bed, with a distance of approximately 40-60 cm between the insertion points of each hoop and an arch height of about 40-60 cm above the bed surface. *Capsicum* seedlings are generally transplanted in a single row on prepared beds. A planting arrangement of approximately 50 cm within the row and 1.5-1.6 m between beds has been reported for low-tunnel capsicum production (Thakur *et al.*, 2013)^[25]. Accurate hoop placement is important because inadequate spacing or insufficient structural support may result in sagging of the covering material, poor ventilation and physical contact between the cover and crop canopy.

3.1. Installation and securing of covering materials

After installation of the support structure, the selected covering material is stretched over the hoops to enclose the crop canopy. The material should be firmly secured along the edges and ends to prevent displacement caused by wind and to maintain a relatively stable internal microenvironment. Improperly installed covers may move excessively and come into direct contact with young leaves, potentially causing mechanical injury. In addition, gaps or loose edges may reduce the effectiveness of the protected environment and allow greater exposure to adverse weather conditions (Serrano, 2023)^[8]. The selection of the covering material should therefore be based on the intended production season, expected weather conditions and desired degree of modification of light and temperature.

3.2. Ventilation and removal of crop cover

Ventilation is a critical element of the management practices in low tunnel production. Although covering materials can conserve heat during cool periods, solar radiation can rapidly increase the temperature inside the tunnel during clear days. Excessive temperature and humidity may adversely affect crop growth and increase the risk of physiological disorders and disease development (Arthurs *et al.*, 2013)^[26]. Kumar *et al.* (2024)^[18] recommended the provision of small ventilation openings of approximately 3-4 cm along the sides of plastic tunnels. These openings can be progressively enlarged as ex-

ternal temperatures increase. Complete removal of the covering material can subsequently be undertaken when ambient conditions become favourable for normal crop growth.

The duration of cover retention should not be considered a fixed management period. Instead, it should be determined by the season, crop growth stage, material characteristics and prevailing environmental conditions. Diaz-Perez *et al.* (2024)^[27] reported that extended coverage without proper ventilation in high radiation conditions can lead to high temperature and relative humidity. Therefore, the main purpose of management should be to maintain a favourable microclimate in the canopy rather than to ensure the crop is under physical cover all the time.

4. Role of low tunnels in vegetable production

Low tunnels have considerable potential for advancing vegetable production and enabling production during periods when open-field environmental conditions are unfavourable. They can support rapid seedling establishment, improve transplant survival, advance flowering and harvest and provide protection against adverse weather conditions (Kalloo *et al.*, 2002)^[28]. Protected cultivation systems can create favourable microclimatic conditions during periods unsuitable for open-field production and may consequently contribute to improvements in fruit quality, productivity and economic returns (Shahak *et al.*, 2008)^[4]. An additional advantage of row covers is their potential to function as physical barriers against insect pests. Non-woven polypropylene materials can reduce insect access to the crop and consequently reduce feeding injury and the incidence of pest infestation (Imran *et al.*, 2006)^[29].

In contrast to large polyhouses or high-tunnel structures, low tunnels involve a moderate financial outlay and can be put up or taken down with some ease. As such, Kumar *et al.* (2024)^[18] underlined their potential applicability for small and marginal farmers who are in pursuit of relatively cost-effective protected cultivation technologies. However, the economic and agronomic advantages of low tunnels are also subject to proper material selection and management. The cost of covering material, labour for installation and removal, ventilation needs and the number of years that the material can be effectively used are all factors in determining the overall economic viability of the technology.

5. Conclusion

Crop-cover systems and low tunnels are potential techniques for enhancing capsicum growth, productivity and resilience through altering the crop microenvironment. The quality of the covering material, its

optical and physical properties, season, level of shading, ventilation and crop-management practices are major determinants of their effectiveness. However, further research is needed to establish clear relationships between cover characteristics, microclimatic changes and plant physiological responses. Future studies should integrate microclimate monitoring, pest and disease assessment, water-use efficiency and economic analysis, supported by multi-season and multi-location validation. Such research will facilitate the development of site- and season-specific crop-cover strategies for sustainable and economically viable capsicum production.

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How to cite this article: Thube HB, Kshirsagar S, Agale M, Shinde G. Effects of crop cover systems on microclimate, growth, yield and quality of *Capsicum*. *International Journal of Advanced Biochemistry Research*. 2026;SP-10(10):995-998. doi: <https://www.doi.org/10.33545/26174693.2026.v10.i10SI.10413>