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PHOTOSYNTHETICALLY ACTIVE RADIATION DYNAMICS IN PROTECTED CULTIVATION: A COMPARATIVE STUDY ON TOMATO CROP

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ABSTRACT

Photosynthetically Active Radiation (PAR), comprising red and blue wavelengths of the light spectrum, is a critical factor influencing photosynthesis and plant growth. Variations in PAR intensity can induce stress and photoinhibition, affecting crop performance. This research explores the dynamics of PAR and its impact on the growth and yield of tomato crops under four cultivation environments: agrivoltaic greenhouse (S_1), agrivoltaic system (S_2), poly-cum-nethouse (S_3) and open field (S_4, control). Additionally, two soil treatments were evaluated: silver-black plastic mulch (M_1) and no mulch (M_2). Climatic parameters, including PAR, temperature, and relative humidity, as well as crop performance, were monitored during the Rabi season. The poly-cum-nethouse (S_3) recorded the highest PAR intensity (500 μmol/m²/s) and temperature (34 °C) at noon time, while the agrivoltaic greenhouse (S_1) exhibited the lowest PAR (400 μmol/m²/s) and moderated microclimatic conditions, with relative humidity ranging from 44% to 88%. Tomato under agrivoltaic greenhouse with mulch achieved the highest yield (100.75 t/ha), highlighting the synergistic benefits of optimized microclimate regulation and soil management practices. This research underscores the potential of agrivoltaic greenhouses in enhancing sustainable crop production through improved resource use efficiency.

Key words : Agrivolatic, Greenhouse, Photosynthetically Active Radiation, Plastic Mulch, Tomato Cultivation.

Introduction

Photosynthetically Active Radiation (PAR), which spans the 400-700 nm spectral range, plays a pivotal role in plant growth and development by driving the process of photosynthesis. This portion of solar radiation is utilized by plants to convert solar energy into chemical energy, a process crucial for crop productivity and quality (Zhang *et al*., 2019). Despite only a small fraction (2-10%) of the incident PAR being effectively converted into chemical energy by photosynthetic organisms, optimizing its use is essential for enhancing agricultural output (Hussain *et al*., 2021). Controlled environments such as greenhouses, shade nets, and playhouses, the management of PAR becomes even more critical. These protected cultivation systems allow for precise control over environmental factors, fostering favorable conditions for crop growth (Jain *et al*., 2023). However, the intensity and distribution of PAR within these structures significantly influence plant photosynthesis, growth rates, and ultimately, the yield and quality of crops (Gruda *et al*., 2019). Tomato (*Solanum lycopersicum*), one of the most economically important and widely cultivated crops, is particularly sensitive to light conditions. Therefore, understanding how different levels and distribution of PAR affect tomato crops is critical for maximizing both their yield and nutritional value (Kimura and Sinha, 2008). The research thoroughly investigates the interaction between PAR, relative humidity and cumulative temperature in relation to tomato crop quality, highlighting the importance of both light and temperature in influencing crop development in controlled environments. One significant conclusion is that cumulative temperature, rather than PAR alone, is more influential in determining tomato quality. While shading treatments reduced PAR, their minimal impact on temperature variations within the greenhouse underscores the critical role of temperature management for optimal crop production (Riga *et al*., 2008).

Moreover, Klaring and Krumbein (2013) reported that reduced solar radiation intensity could lower photosynthesis and dry matter production, yet fruit quality remained unaffected. These findings suggest that the integration of energy generation and crop production in greenhouses could be a viable strategy with minimal negative effects on crop yield and quality. The study expands on findings from Crawford *et al*. (2020), who observed that severe shading reduced the growth and biomass of Texas wild rice, emphasizing the importance of light availability in crop growth and the restoration of endangered plant species. This reinforces the significance of PAR in maintaining healthy plant development and biodiversity. The research also explores how barley adapts to varying PAR levels through aquaporin activity and root morphological changes, as noted by Saini and Fricke (2020). High PAR was linked to increased water loss via transpiration, while lower PAR reduced root hydraulic conductivity, suggesting that PAR plays a critical role in regulating plant water uptake mechanisms. Further, studies by Cossu *et al*. (2018), Ezzaeri *et al*. (2018) and Ramani *et al*. (2023) suggests that integrating photovoltaics into greenhouse structures may not significantly affect crop yield or microclimate, offering valuable insights into sustainable greenhouse design. These findings support the notion that energy production and crop cultivation can coexist in a manner that does not compromise crop quality. In conclusion, this study provides an in-depth understanding of the complex dynamics between PAR, relative humidity and temperature, particularly for tomato production in protected cultivation systems. The findings emphasize the need for an integrated approach to manage light, temperature, and energy in order to optimize crop yield and quality while advancing sustainable agricultural practices.

Materials and Methods

Location of the study

The research was carried out at the experimental field of the Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology (CAET), Junagadh Agricultural University (JAU), Junagadh, Gujarat, India.

Different Protected Structures

The research aimed to evaluate the dynamics of photosynthetically active radiation (PAR) and its impact on tomato cultivation under different protected cultivation structures, including agrivoltaic system, agrivoltaic greenhouse and poly-cum-nethouse.

JAU agrivoltaic system

The Junagadh Agricultural University (JAU) agrivoltaic system consisted of six rows of solar panels, with each row comprising 15 polycrystalline panels, resulting in a total installed capacity of 13.5 kW. The panels were arranged in a chessboard configuration to minimize shading effects, maximize land use efficiency, and ensure adequate sunlight penetration for crop growth.

Agrivoltaic greenhouse

The agrivoltaic greenhouse, designed for simultaneous crop cultivation and solar energy generation, featured a forced ventilation system and a checkerboard arrangement of photovoltaic (PV) panels. The structure contained four rows of PV modules, with eight panels per row, totaling an installed capacity of 4.8 kW. The greenhouse covered an area of 60 m² and utilized a UV-stabilized polyethylene sheet as the roof covering material. The design emphasized both light transmission for crop development and energy production efficiency.

Poly cum nethouse

The poly-cum-nethouse was a naturally ventilated structure with a gothic-arched roof covered with a UV-stabilized polyethylene film, while the sides were enclosed with 50% white mesh shade netting. The structure spanned a floor area of 45 m² and was oriented along the east-west ridge direction to optimize light distribution.

Climatic analysis

The performance of each protected structure was evaluated based on its ability to regulate key climatic parameters, including photosynthetically active radiation (PAR), relative humidity and air temperature. These parameters were continuously monitored at regular intervals during the crop growth period using an automatic mini weather station. The microclimatic data collected were analyzed to assess variations in light transmission and environmental conditions within the protected structures, providing insights into their impact on crop growth and productivity.

Crop cultivation

Tomato (*Solanum lycopersicum*), was cultivated under three different protected cultivation structures, as well as in open field conditions, which served as the control, during the Rabi season (December to March). Crop growth and yield parameters were monitored and recorded across multiple harvests to assess performance under the different treatments i.e protected structures and mulch treatments (silver-black mulch and no mulch).

Results and Discussion

Evaluation of Climatic Parameters

The variation in climatic parameters across protected cultivation structures demonstrates their influence on crop performance. The study analyzed major climatic parameters under various protected cultivation structures during the Rabi season to assess their impact on the microclimate and subsequent tomato crop growth. The parameters like; Photosynthetically Active Radiation (PAR), relative humidity (RH) and air temperature were measured at one-hour intervals throughout the crop period. Monthly averages were calculated to highlight the variations across different structures.

Effect of protected structures on photosynthetically active radiation (PAR)

The diurnal variation of PAR under different protected cultivation structures during the *Rabi* season provides valuable insights into how structural designs affect light availability for crop growth. As observed, PAR consistently peaked at 13:00 h in all structures, which is typical of diurnal light patterns, with the maximum light intensity occurring around midday (Riga *et al.*, 2008). Diurnal variation of mean PAR under various structures during the Rabi season depicted in Fig. 1.

The poly-cum-nethouse structure recorded the highest PAR value of 500 µmol/m²/s at noon, while the agrivoltaic greenhouse recorded the lowest value of 400 µmol/m²/s at the same time. These variations can be attributed to the differing structural materials and designs, particularly the shading effects introduced by photovoltaic modules in the agrivoltaic greenhouse. The poly-cum-nethouse, which uses a translucent polyethylene roof and 50% shade net, facilitates higher light transmission, thereby providing better conditions for photosynthesis during the day (Peet and Welles, 2005). This structure's light transmission efficiency supports its role in optimizing crop growth, especially in crops that require high light intensity for photosynthesis, such as tomatoes. However, while the poly-cum-nethouse maximizes PAR availability, the structure may be prone to higher internal temperatures, especially during midday peaks, potentially leading to thermal stress for crops (Gomez *et al.*, 2013). Thus, while light availability is crucial, temperature control in such structures becomes an essential factor in maintaining optimal crop conditions.

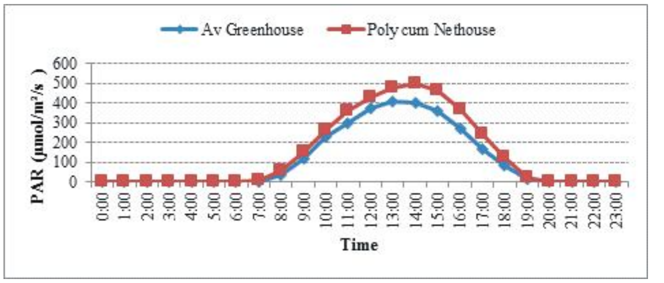

Fig. 1 : Diurnal variation of PAR under different protected structures.

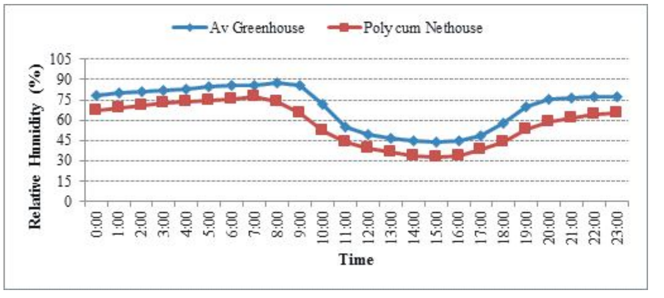

Fig. 2 : Diurnal variation of RH under protected different structures.

In contrast, the agrivoltaic greenhouse, which integrates solar panels into the design, recorded lower PAR values due to the shading effects caused by the panels. The checkerboard arrangement of the panels, while designed to minimize light obstruction, still causes partial shading that reduces the overall PAR inside the structure. This trade-off between light availability and renewable energy generation is inherent to agrivoltaic systems, which aim to balance energy production and crop productivity (Awasthi *et al.*, 2020). The reduced PAR levels in agrivoltaic greenhouses highlight the importance of optimizing panel configurations to minimize light loss while maximizing energy generation.

Effect of protected structures on relative humidity (RH)

The diurnal variation of mean relative humidity (RH) under different protected cultivation structures during the Rabi season, with corresponding trends illustrated in Fig. 2. The results indicate a clear distinction in the RH levels across the different structures. The highest RH of 88% was observed at 8:00 h across all structures, with the agrivoltaic greenhouse, while the poly-cum-net house recorded the lowest RH of 74% at the same time.

The observed higher RH in the agrivoltaic greenhouse can be attributed to its semi-enclosed design, which limits ventilation and allows for moisture retention within the structure. This finding is consistent with the work of Andrade *et al.* (2014), who noted that semi-enclosed systems, such as greenhouses with roof-mounted solar panels, tend to retain moisture more effectively, leading to higher RH levels compared to fully ventilated systems. In contrast, the poly-cum-net house, which relies on natural ventilation with open sides, exhibited greater air exchange, leading to lower RH levels. This is in line with the study by Garcia *et al*. (2017), who found that natural ventilation in structures like polyhouses results in more rapid moisture loss due to increased airflow, which can lower RH levels significantly during the day.

Throughout the *Rabi* season, the agrivoltaic greenhouse consistently maintained higher RH levels compared to other structures. This trend highlights the impact of the semi-enclosed design of the agrivoltaic greenhouse in limiting air circulation and enhancing moisture retention. This result aligns with findings by Rasool *et al*. (2019), who demonstrated that controlled environments such as agrivoltaic greenhouses help maintain stable microclimates, which is crucial for maintaining optimal conditions for crop growth.

The consistent high RH levels in the agrivoltaic greenhouse are noteworthy because elevated RH can enhance water-use efficiency and reduce plant transpiration rates, which is particularly beneficial during the dry season. Similar studies, such as those by Masera *et al*. (2018), have shown that increased RH in controlled environments like greenhouses can help reduce water stress and enhance crop productivity, especially in regions prone to drought.

These findings suggest that protected cultivation structures, particularly the agrivoltaic greenhouse, play a significant role in modifying microclimatic conditions such as RH. By maintaining elevated RH levels, these structures create an environment that can be more favorable for crop growth, potentially enhancing productivity and reducing the need for irrigation. This underscores the value of agrivoltaic systems in sustainable agriculture, where water conservation and crop performance are paramount.

Effect of protected structures on temperature

The temperature dynamics within various protected cultivation structures were thoroughly analyzed to assess their impact on the tomato crop microclimate during the Rabi season. The data, as depicted in Fig. 3, highlight the diurnal variation in temperature across different structures. It was observed that temperature peaked at 14:00 h across all structures, which aligns closely with the diurnal pattern of solar radiation intensity.

The poly-cum-net house recorded the highest peak temperature of 34°C at 14:00 h. This can be explained by the combined effects of the polyethylene roof covering

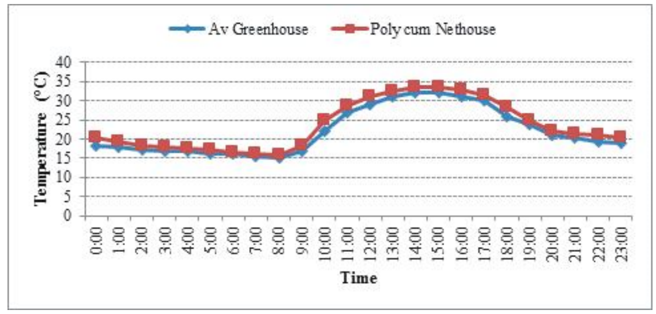

Fig. 3 : Diurnal variation of temperature under protected different structures.

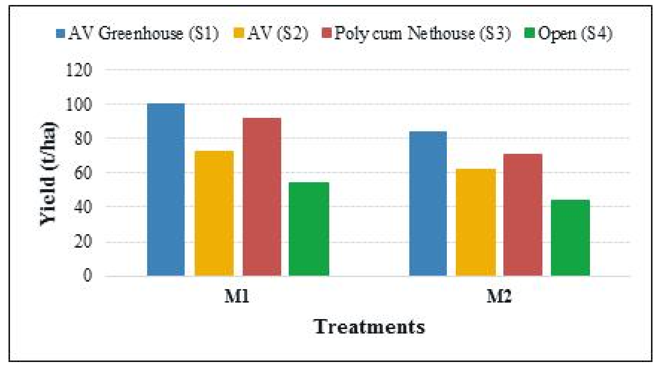

Fig. 4 : Effect of protected structures and mulch on tomato yield per hectare.

and shade net sides, which trap heat within the structure. Polyethylene, while effective in protecting crops from environmental factors, tends to have high thermal retention properties, leading to a noticeable rise in internal temperatures (Al-Helal *et al*., 2018). This suggests that, while the poly-cum-net house provides some protection against external environmental variables, its thermal insulation properties may contribute to temperature fluctuations within the greenhouse, especially under intense solar radiation conditions.

In contrast, the agrivoltaic greenhouse recorded a lower peak temperature of 32°C at 14:00 h. This can be attributed to the checkerboard arrangement of photovoltaic (PV) panels, which allowed for partial shading and reduced direct solar radiation exposure. The partial shading provided by the PV panels moderated the incoming solar radiation, leading to a cooler environment compared to the poly-cum-net house. Such structures have been shown to effectively reduce the internal temperature of protected environments, making them ideal for crops like tomatoes that require moderate thermal conditions for optimal growth (Zhao *et al*., 2019). This demonstrates the agrivoltaic greenhouse's efficiency in moderating temperature during the Rabi season, thereby creating a more favorable microclimate for tomato crop growth.

Over the entire Rabi season, the agrivoltaic greenhouse consistently maintained lower temperatures than the poly-cum-net house. The lower temperature in the agrivoltaic greenhouse is largely attributed to the partial shading effect of the PV panels, which reduce the intensity of solar radiation reaching the crop canopy. This finding supports previous studies that highlight the benefits of integrating photovoltaic panels in greenhouses, which can significantly enhance the energy efficiency and temperature regulation within the structure (Hernandez *et al*., 2018).

Discussion on climatic analysis

Temperature regulation in the agrivoltaic greenhouse is particularly important during periods of high external temperatures. The solar panels integrated into the system help to moderate excessive heat buildup within the greenhouse, ensuring that the temperature remains within a range conducive to healthy crop growth. As noted by Gomez *et al*. (2013), temperature extremes are a significant limiting factor for tomato growth, particularly in traditional greenhouses, where insufficient cooling mechanisms can lead to crop stress and reduced fruit quality. By moderating temperature fluctuations, the agrivoltaic greenhouse mitigates these stressors, which in turn reduces the potential for flower abortion, fruit cracking, and poor fruit set, as described by Peet and Welles (2005). Moreover, the agrivoltaic greenhouse structure allows for adequate PAR levels, which are critical for photosynthesis. A stable supply of PAR supports optimal plant growth, contributing to higher rates of photosynthesis and, consequently, improved crop productivity (Riga *et al*., 2008). In combination with the moderated temperature, this stable light environment helps to maintain favorable growing conditions throughout the cultivation cycle.

The high humidity levels within the agrivoltaic greenhouse further enhance the growth environment. According to recent studies, humidity is an important factor influencing plant transpiration and nutrient uptake, with optimal levels promoting better crop resilience and yield (Gomez *et al*., 2013). The ability of the agrivoltaic greenhouse to regulate both temperature and humidity levels places it at a distinct advantage over traditional greenhouse structures, such as poly-cum-net houses, which often suffer from greater exposure to temperature fluctuations and inadequate humidity control.

In comparison to the poly-cum-net house, the agrivoltaic greenhouse provides more consistent environmental conditions, leading to a reduction in crop stress. Poly-cum-net houses, while effective in providing basic shelter, do not offer the same level of temperature regulation, which can expose crops to more significant stress during periods of extreme heat. This stress not only reduces crop quality but also results in lower overall yields, as temperature fluctuations can impair the plant's metabolic processes (Peet and Welles, 2005). The stability of the microclimate within the agrivoltaic greenhouse is essential for promoting photosynthesis, reducing crop stress, and improving both the yield and quality of tomatoes. As evidenced in this study, the agrivoltaic greenhouse creates a more controlled and supportive environment than traditional structures, aligning with findings from recent literature that advocate for the benefits of integrated climate control systems in enhancing crop performance (Gomez *et al*., 2013).

Crop Performance analysis

This research evaluates the performance of tomato (*Solanum lycopersicum*) under various protected cultivation conditions and examines the influence of mulching on yield. The study compared four cultivation setups: agrivoltaic greenhouse (S_1), agrivoltaic structure (S_2), poly-cum-net house (S_3) and open field (S_4), combined with two soil treatments: mulched (M_1) and non-mulched (M_2). Statistical analysis was conducted to assess the effects of these treatments on crop growth, yield, and overall performance during the *Rabi* season.

Effect of protected structures on tomato yield per hectare

The results revealed a significant variation in tomato yield across the four protected structures. The agrivoltaic greenhouse (S_1) achieved the highest yield at 92.38 t/ha, compared to the open field (S_4), which yielded only 48.98 t/ha. This stark difference emphasizes the importance of controlled environments in enhancing crop productivity. Protected structures like the agrivoltaic greenhouse create favorable microclimatic conditions that promote plant growth by improving light diffusion, moderating temperature fluctuations, and minimizing environmental stressors. These findings align with previous studies, which suggest that greenhouse environments can significantly improve the yield of tomato crops by mitigating factors like extreme weather conditions and pest pressure (Riga *et al*., 2008; Peet and Welles, 2005). Moreover, the agrivoltaic system not only supports crop cultivation but also generates renewable energy, highlighting its potential as a sustainable agricultural practice (Gomez *et al*., 2013).

Effect of mulch on tomato yield per hectare

The impact of mulching on tomato yield was also

(A). Agrivoltaic greenhouse (S_1)

(B). Agrivoltaic (S_2)

(C). Poly cum nethouse (S_3)

(D). Open field (S_4)

Fig. 5 : Tomato cultivation across various protected structures.

Table 1 : Effect of protected structures and mulch on tomato yield (t/ha).

Treatment	Protected structure				
	S_1	S_2	S_3	S_4	Mean
Mulch (M_1)	100.75	72.54	91.22	54.25	**79.69**
No Mulch (M_2)	84.01	61.69	70.51	43.71	**64.98**
Mean	**92.38**	**67.11**	**80.86**	**48.98**	

	Protected structure (S)	Mulch (M)	Interaction (S x M)
S.Em. ±	1.19	0.57	1.68
C.D. at (5 %)	3.53	2.55	4.87
C.V. (%)	7.24		

statistically significant, with the mulch treatment (M_1) resulting in higher yields (79.69 t/ha) compared to the no-mulch treatment (M_2), which produced 64.98 t/ha (Table 1). Mulching likely facilitated improved soil moisture retention, reduced weed growth, and stabilized soil temperatures, all of which are crucial for optimal tomato growth. The benefits of mulching on crop yield are well-documented, with several studies highlighting that mulching improves water availability and temperature regulation in the root zone, leading to better plant health and higher productivity (Zhao *et al.*, 2019; Mor *et al.*, 2020).

Interaction effect of protected structures and mulch on tomato yield per hectare

The interaction between protected structures and mulch treatments was found to be statistically significant, suggesting that the combination of both factors maximized tomato yield. The agrivoltaic greenhouse with mulch (S_1M_1) recorded the highest yield of 100.75 t/ha, while the open field without mulch (S_4M_2) had the lowest yield at 43.71 t/ha (Fig. 5). This finding underscores the synergistic effect of using advanced protected structures along with soil mulching. The agrivoltaic greenhouse provides a stable environment with moderated temperature and light conditions, which, when combined with mulch, further enhances soil moisture retention and temperature regulation, resulting in optimal growing conditions for tomatoes.

The findings from this study demonstrate that both protected cultivation structures and mulching practices significantly influence tomato yield, with the agrivoltaic greenhouse in combination with mulch yielding the highest results. Research has shown that protected environments, such as greenhouses, can help mitigate environmental stresses like high temperatures, which are often detrimental to tomato production, particularly in open field conditions (Peet ad Welles, 2005). Additionally, mulching has been shown to reduce soil evaporation, control soil temperature, and suppress weed growth, all of which contribute to improved tomato yield (Mor *et al*., 2020).

These findings highlight the importance of an integrated approach to crop management, where both environmental control (through protected structures) and soil management (through mulching) work together to enhance productivity.

Conclusion

This study highlights the significant impact of protected cultivation structures and soil management practices on photosynthetically active radiation (PAR) dynamics, microclimatic conditions, and tomato crop performance during the *Rabi* season. Among the evaluated structures, the agrivoltaic greenhouse demonstrated superior performance in creating an optimal microclimate by effectively moderating PAR, relative humidity (RH) and temperature. The checkerboard arrangement of photovoltaic panels in the agrivoltaic greenhouse not only provided partial shading to reduce excessive heat but also ensured sufficient light diffusion, benefiting photosynthesis and reducing crop stress. The results revealed that the agrivoltaic greenhouse (S1) consistently recorded the highest tomato yield of 92.38 t/ha, significantly outperforming the poly-cum-net house (S_3) and open field (S_4). This was further enhanced by the use of mulch, which improved soil moisture retention, stabilized soil temperatures, and suppressed weed growth. The combination of agrivoltaic greenhouse with mulch (S_1M_1) achieved the highest yield of 100.75 t/ha, demonstrating the synergistic effects of advanced protected cultivation and soil management practices.

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