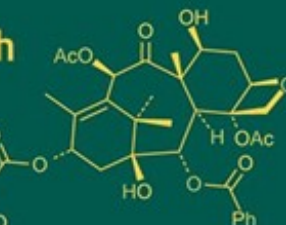


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Morphological plasticity of greengram (*Vigna radiata* L.) under different photovoltaic system

Pratiksha B Bhajanawale¹, Godawari S Pawar², Indra Mani Mishra³, Khizar S Baig⁴, Bhagvan V Asewar⁵, Vikram M Gholve⁶, Bhakti U Pune⁷, Shubhangi K Borkar⁸

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ABSTRACT

Agriphotovoltaic systems integrate photovoltaic (PV) infrastructure with crop production, creating modified light and thermal environments that can influence crop growth and productivity. The architectural characteristics of PV systems, particularly panel height, panel technology and crop position relative to the panels, may determine the extent of microclimatic modification and plant morphological adjustment. The present study evaluated the morphological and growth responses of greengram under different agriphotovoltaic configurations. A field experiment was conducted during the summer season of 2025 at the Agrivoltaics Research Field, Manwat, Parbhani, Maharashtra, under a collaborative research project between GIZ, Germany and Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani. The experiment comprised PV structures with panel heights of 1.75m, 3.75m and 1.25 m including monofacial and bifacial technologies, with greengram cultivated at horizontal distances of 0.5 and 1.5 m from the panels along with a Non PV System. The experiment was laid out in a randomized block design with seven treatments and three replications. Significant variation ($p < 0.05$) was observed in hypocotyl length, petiole length, stem thickness, leaf angle and total leaf area among the evaluated configurations. Plants growing beneath low-clearance PV structures showed stronger shade-avoidance responses, with maximum hypocotyl elongation (13.17 cm) and leaf angle (73.00°) recorded under T₁ (1.75m Monofacial panel with 0.5 m sowing distance away from panel). In contrast, the elevated bifacial configuration with adequate horizontal spacing (T₄; 3.75 m panel height and 1.5 m distance) promoted vegetative development, recording the highest total leaf area (78.66 cm²) and stem thickness (4.34 mm) compared with 50.97 cm² and 3.43 mm, respectively, in the Non PV System. Overall, the results indicate that PV system architecture substantially influences greengram morphological plasticity and elevated bifacial configurations combined with appropriate crop spacing can provide a more favourable growing environment by reducing excessive shade stress and supporting canopy development.

Keywords: Agriphotovoltaic systems, *Vigna radiata* L., Morphological plasticity, Shade Avoidance Syndrome, Bifacial technology

1. Introduction

Agriphotovoltaic systems (APV)- the simultaneous utilization of land for solar photovoltaic power generation and agricultural production-have emerged as a sustainable strategy to address land competition. However, overhead solar structures create heterogeneous spatial microclimates characterized by reduced Photosynthetically Active Radiation (PAR) and altered light quality. Crops under partial or intermittent shade exhibit distinct morpho-physiological responses, collectively known as the Shade Avoidance Syndrome (SAS). Key indicators of SAS include hypocotyl and stem elongation, petiole extension, leaf movements (steeper leaf angles). In pulse crops like greengram (*Vigna radiata* L.), canopy architecture directly regulates light interception efficiency, photosynthate partitioning and mechanical stability. Understanding how panel height, module technology (monofacial vs. bifacial) and spatial sowing distances influence canopy geometry is essential for designing crop-compatible APV installations.

2. Materials and Methods

2.1 Experimental site and treatment layout

The field investigation was conducted using a Randomized Block Design (RBD) with seven treatments replicated three times. The treatment details were as follows: T₁: 1.75m Monofacial panel with 0.5 m sowing distance away from panel. T₂: 1.75m Monofacial panel with 1.5m sowing distance away from panel. T₃: 3.75m Bifacial panel with 0.5m sowing distance away from panel. T₄: 3.75m Bifacial panel with 1.5m sowing distance away from panel. T₅: 1.25m Bifacial panel with 0.5m sowing distance away from panel base. T₆: 1.25m Bifacial panel with 1.5 m sowing distance away from panel base. T₇: Non-PV system. Seeds of

Corresponding Author:

Godawari S Pawar
 Department of Plant
 Physiology, College of
 Agriculture, Vasantrao
 Naik Marathwada Krishi
 Vidyapeeth, Parbhani,
 Maharashtra, India.

greengram (*Vigna radiata* L. Wilczek) variety 'BM 2003-2' were sown on March 2, 2025. BM 2003-2 is a prominent high-yielding cultivar developed by Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani,

2.2 Recording of data

Three plants were selected at random from each replication for recording morpho-architectural data at 60 DAS : Hypocotyl Length (cm) measured from the ground line to the cotyledonary node using a scale. Petiole Length (cm) measured from the nodal attachment point on the main stem to the leaflet base using a scale. Stem Thickness (mm) recorded at the middle of the second internode above ground level using a digital vernier caliper. Leaf Angle ($^{\circ}$) measured relative to the horizontal main axis using a protractor positioned along the central leaf vein. Leaf Area (cm^2) total leaf surface area per plant was determined using a portable leaf area meter.

3. Result and Discussion

3.1. Hypocotyl length (cm)

Marked differences in hypocotyl length were observed among the agriphotovoltaic treatments. The longest hypocotyl (13.17 cm) was recorded in T₁, comprising a 1.75 m monofacial panel height with a 0.5 m sowing distance, whereas the shortest hypocotyl (6.17 cm) was recorded in T₆, consisting of a 1.25 m bifacial panel height with a 1.5 m sowing distance. The difference between T₁ and T₆ (7.00 cm) was greater than the CD at 5% (1.49 cm), indicating a significant difference between these treatments. The greater elongation observed in T₁ associated with the lower light environment prevailing close to the PV structure. Under reduced irradiance, plants can modify their architecture by allocating relatively greater growth towards vertical elongation in an attempt to improve access to available light. The relatively shorter hypocotyl under T₆ suggests comparatively lower shade-induced elongation at the greater horizontal distance from the

panel. Similar shade-responsive elongation patterns have been reported under reduced light availability by Fan *et al.* (2019) [1]. Lyu *et al.* (2023) [2] observed that low-light stress induced rapid hypocotyl extension while suppressing internode expansion in the middle and upper main stem, ultimately decreasing mature plant height in greengram. (fig.1)

3.2. Petiole length (cm)

Petiole length differed significantly among the evaluated agriphotovoltaic treatments. The maximum petiole length (11.67 cm) was recorded in T₇ (Non-PV system) which was significantly superior to the other treatments, while the minimum value (2.13 cm) was observed in T₅, where greengram was cultivated beneath a 1.25 m bifacial panel height at a 0.5 m sowing distance. The difference of 9.54 cm between these treatments was substantially greater than the CD at 5% (1.50 cm), confirming a significant treatment effect. The greater petiole development under the Non-PV system related to the higher and more uniform availability of solar radiation, which favoured normal leaf and supporting-structure development. In contrast, the strongly modified light environment beneath the low-clearance PV structure have restricted petiole development. Differences in petiole morphology under contrasting irradiance regimes are consistent with the concept that plants adjust supporting tissues and leaf architecture according to their light environment (Niinemets *et al.*, 2002) [3] (fig.2).

3.3. Stem thickness (mm)

Stem thickness exhibited considerable variation among the agriphotovoltaic treatments. The thickest stem (4.34 mm) was recorded in T₄, representing the 3.75 m bifacial panel height with a 1.5 m sowing distance, whereas the thinnest stem (1.56 mm) occurred in T₁ under the 1.75 m monofacial panel height at a 0.5 m sowing distance. The difference between T₄ and T₁ was 2.78 mm, which exceeded the CD at 5% (0.65 mm), indicating a significant difference between the two treatments.

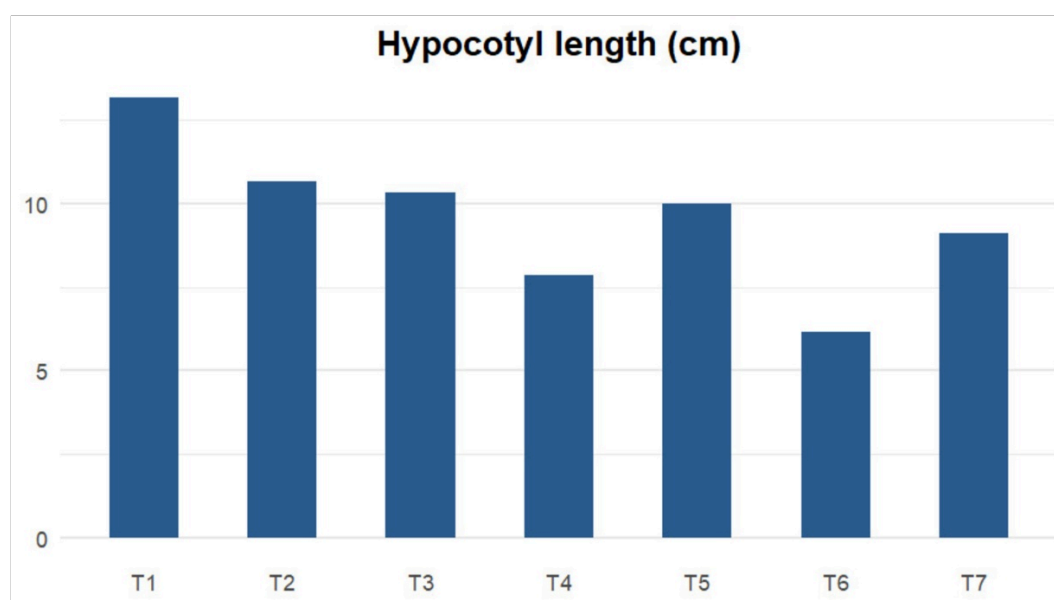


Figure 1. Hypocotyl Length at 60 DAS influenced by different PV systems

The reduced stem thickness under T₁ associated with shade-induced morphological adjustment, in which plants favour longitudinal extension to improve their position within the available light environment at the expense of radial stem development. Conversely, the greater stem thickness observed in T₄ indicates that the combination of greater panel clearance and increased horizontal distance provided a more favourable light environment for structural growth. Similar reductions in stem girth associated with shade-avoidance responses have been reported in crops grown under agriphotovoltaic or shaded conditions (Lee *et al.*, 2022) [4]. (fig.3)

3.4. Total leaf area (cm^2)

Significant differences in total leaf area per plant were observed among the agriphotovoltaic treatments. The greatest total leaf area (78.66 cm^2) was recorded under T₄, comprising a 3.75 m bifacial panel height with a 1.5 m sowing distance, whereas the lowest leaf area (11.9 cm^2) was recorded under T₅, where plants were grown at a 0.5 m distance from the 1.25 m bifacial panel height. The difference of 66.76 cm^2 was considerably greater than the CD at 5% (1.91 cm^2), demonstrating a significant treatment effect on leaf development.

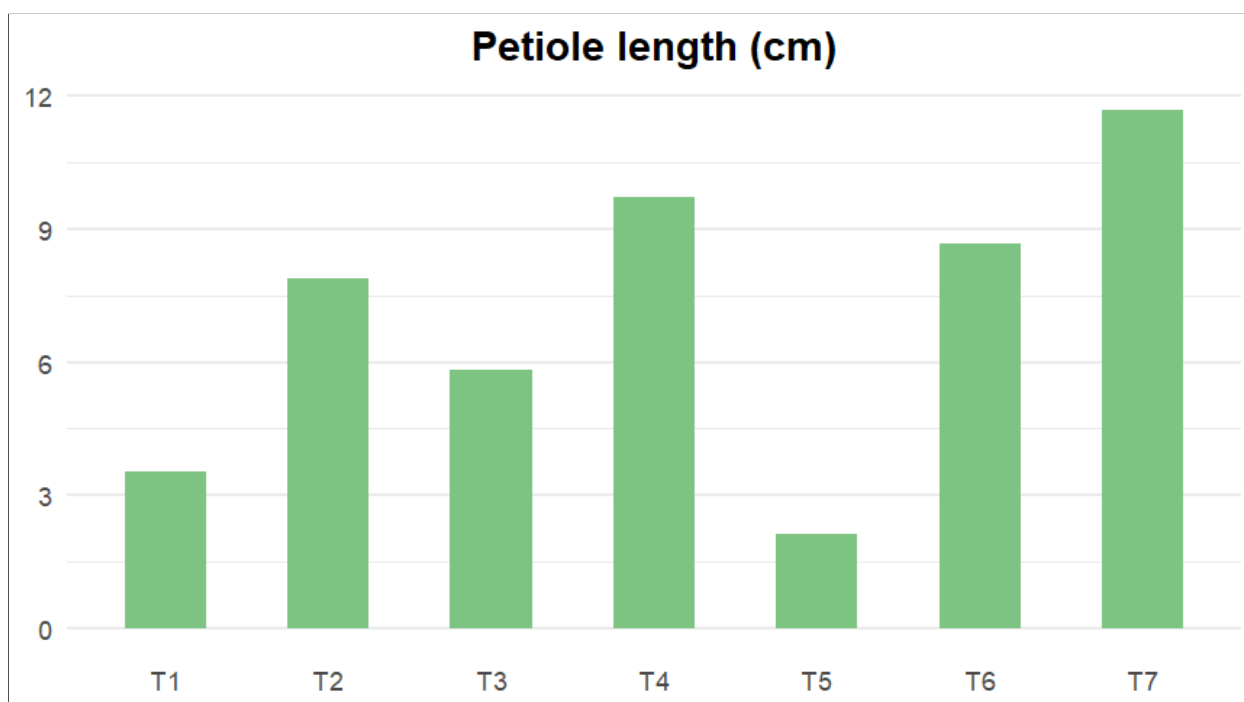


Figure 2. Petiole Length (cm) at 60 DAS influenced by different PV system

The comparatively larger canopy development under T₄ suggested that the greater panel clearance and horizontal spacing created a more favourable light environment for leaf production and expansion. Although plants frequently respond to shade by increasing individual leaf expansion as an acclimation mechanism for improving light interception, severe or prolonged shading can restrict overall canopy de-

velopment when carbon assimilation becomes limiting. The reduced total leaf area under T₅ may therefore reflect the stronger shading imposed by the low horizontal clearance from the PV structure. Comparable responses of leaf development to altered light environments have been reported by Yang *et al.* (2014) [5] and Wu *et al.* (2017) [6]. (fig.4)

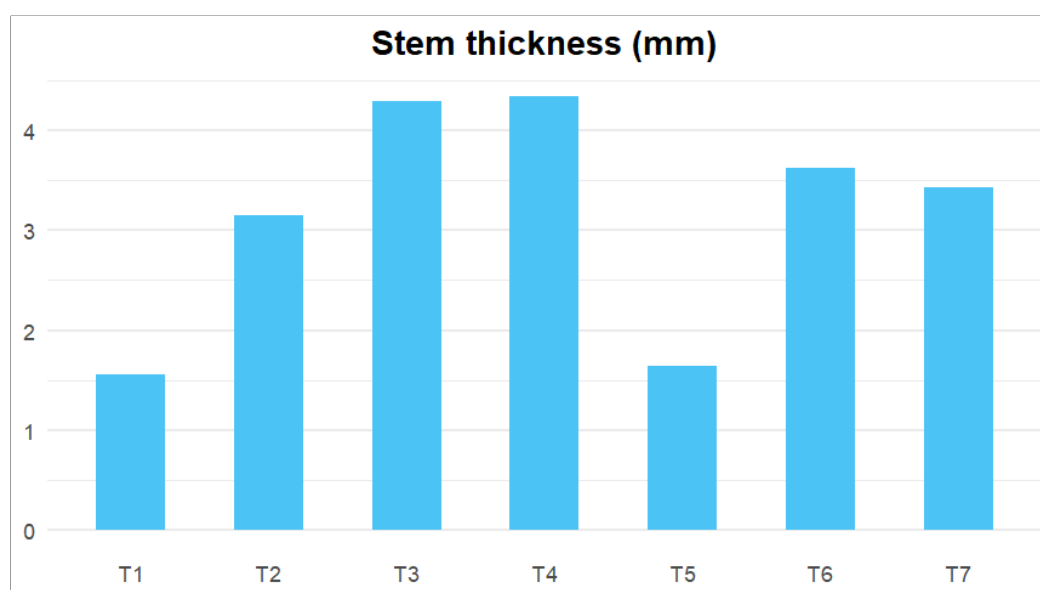


Figure 3. Stem Thickness (mm) at 60 DAS influenced by different PV systems

3.5. Leaf angle (°)

Leaf angle differed significantly among the treatments. The maximum leaf angle was recorded in T₁ (73.00°), whereas the minimum was observed in T₄ (41.00°). The difference of 32.00° between T₁ and T₄ was substantially greater than the CD at 5% (1.75°), indicating a significant difference. However, T₄ (41.00°) was statistically at par with T₃ (41.11°), as the difference between these treatments was only 0.11° which was lower than the CD at 5%. The greater leaf angle under T₁ indicates a pronounced alteration in canopy architecture under the more restricted light environment. Modification of leaf orientation

is an important mechanism through which plants regulate light interception within the canopy. Under contrasting radiation conditions, leaves can alter their orientation to balance light capture, radiation penetration and thermal load. The relatively lower leaf angles observed under T₃ and T₄ suggest a more favourable canopy arrangement under the elevated bifacial configuration, potentially allowing efficient interception of available radiation without excessive vertical orientation. Such plasticity in leaf orientation represents an important component of plant acclimation to changes in the light environment (Taiz *et al.*, 2015) [7]. (fig.5)

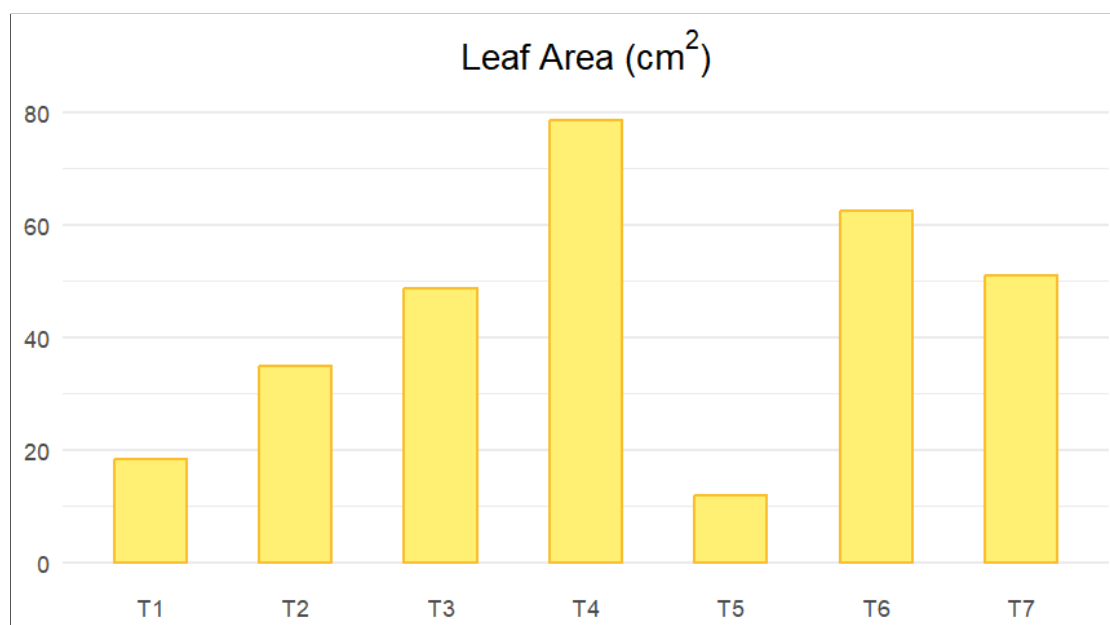


Figure 4. Leaf Area (cm²) at 60 DAS influenced by different PV system

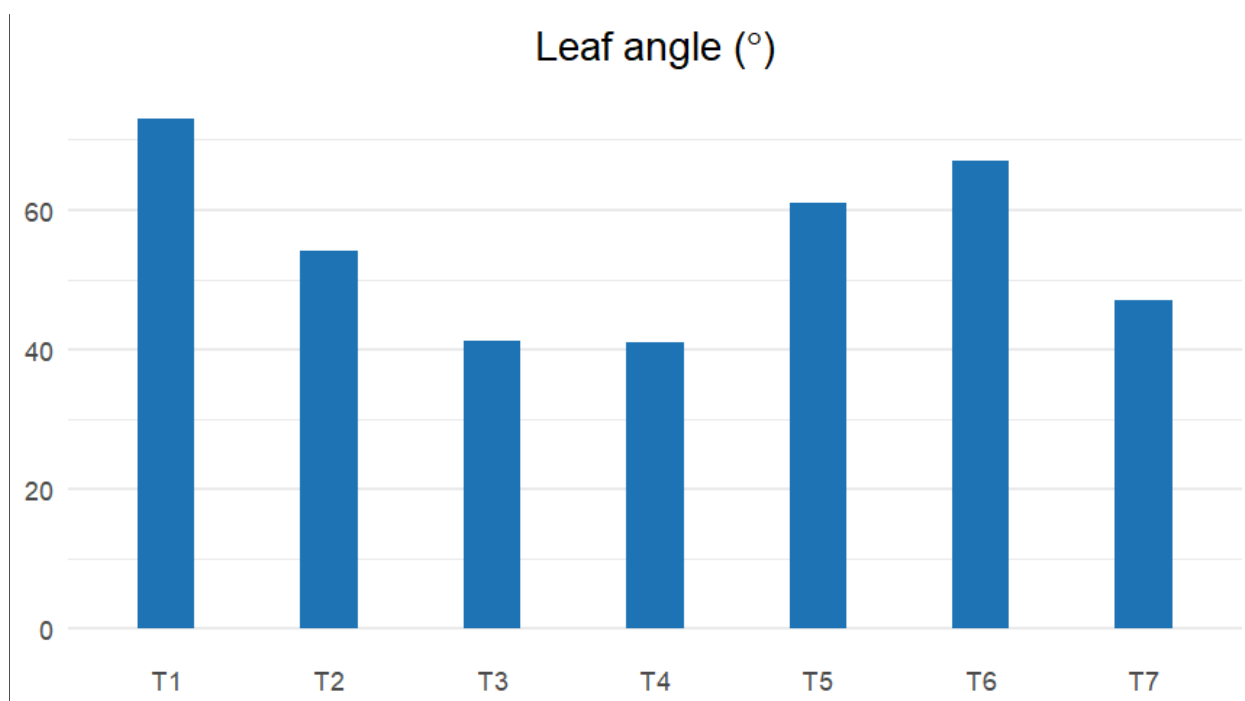


Figure 5. Leaf angle (°) at 60 DAS influenced by different PV systems

Conclusion

The study demonstrated that agriphotovoltaic system architecture substantially influenced the morphological development and architectural plasticity of greengram. Variations in panel height, PV technology and sowing distance resulted in significant differences in hypocotyl length, petiole length, stem thickness, total leaf area and leaf angle. The low-clearance configuration with closer sowing distance, particularly T₁ (1.75 m monofacial panel height at 0.5 m distance), induced stronger morphological responses associated with reduced light availability, including greater hypocotyl elongation and steeper leaf orientation while stem thickening and overall leaf development were comparatively restricted. In contrast, T₄, comprising a 3.75 m bifacial panel height with a 1.5 m sowing distance, produced the greatest stem thickness and total leaf area indicating a more favourable growing environment for vegetative development. Overall, the findings suggest that panel clearance and crop position are critical determinants of crop response in agriphotovoltaic systems and that elevated bifacial configurations combined with adequate horizontal spacing can reduce

excessive shading and support more balanced crop canopy development. Thus, appropriate PV structural design is essential for achieving compatibility between solar-energy generation and agricultural productivity.

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Disclaimer The opinions expressed in this publication are solely those of the authors and do not necessarily represent the official position of their affiliated organizations. Although reasonable steps were taken to guarantee the accuracy and completeness of the data presented, the authors disclaim all liability for any direct or indirect consequences arising from its application.

Conflict of Interest

The authors report no financial, commercial, or personal relationships that could be construed as a potential conflict of interest. The funding entities played no role in designing the experiment, gathering or analyzing the dataset, preparing the manuscript, or deciding to submit the paper for publication.

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Authors**Pratiksha B Bhajanawale**

Department of Plant Physiology, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Godawari S Pawar

Department of Plant Physiology, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Indra Mani Mishra

Hon. Vice-Chancellor, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Khizar S Baig

Directorate of research, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Bhagvan V Asewar

Department of Agronomy, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Vikram M Gholve

Department of Plant Pathology, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Bhakti U Pune

Department of Plant Physiology, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.

Shubhangi K Borkar

Department of Plant Physiology, College of Agriculture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India.