



RESEARCH ARTICLE

Enhancing light use efficiency and productivity of chickpea (*Cicer arietinum* L.) through optimisation of sowing windows

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Abstract

The field experiment was conducted during the rabi seasons of 2023–2024 and 2024–2025 at the Department of Agricultural Meteorology Farm, College of Agriculture, Pune, Maharashtra, India, using a split-split plot design. The gross and net plot sizes were (5.40×3.60) and (5.00×3.00) m², respectively, with 30×10 cm planting geometry. Sixteen treatment combinations were evaluated across three replications, comprising two protection levels- protected (P₁) (Flubendiamide 480 SC (39.35 % w/w) was applied at 0.4 mL L⁻¹) and unprotected (P₂) with two varieties Phule Vikram (V₁) and Vijay (V₂) and four sowing windows S₁- 41 MW, S₂- 43 MW, S₃- 45 MW, S₄- 47 MW. Dry matter accumulation at harvest improved under protection (26.33 and 26.23 g plant⁻¹). The V₁ also recorded higher dry matter accumulation (25.58 and 26.22 g plant⁻¹) compared with V₂ (25.54 and 24.30 g plant⁻¹). Radiation interception and light use efficiency were higher in P₁ (APAR 978 and 1035 $\mu\text{mol m}^{-2} \text{s}^{-1}$; LUE 1.07 and 0.99 g MJ⁻¹). Similarly, V₁ showed superior APAR (976 and 1037 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and LUE (1.04 and 1.05 g MJ⁻¹) compared to V₂. Early sowing significantly improved radiation interception and utilisation, with S₁ achieving the highest IPAR and LUE (1.15 g MJ⁻¹ m⁻² in 2023 and 1.10 g MJ⁻¹ m⁻² in 2024) (84 DAS), whereas S₄ recorded the lowest values. Overall, protected cultivation combined with early sowing and improved varietal performance enhanced biomass accumulation and radiation-use efficiency in chickpea.

Keywords: absorbed photosynthetically active radiation; biomass; chickpea; crop protection; light use efficiency; rabi season; sowing windows

Introduction

Chickpea (*Cicer arietinum* L.) occupies an important position among India's pulse crops, ranking first and contributing nearly 43 % to the total national pulse production (1). India dominates the global production scenario, accounting for approximately 69 % of the global cultivated area and 70 % of total production in 2023. However, the average productivity remains stagnant at 1049 kg ha⁻¹ (1). Beyond its agronomic significance, chickpea plays a pivotal role in alleviating protein-energy malnutrition. It is a rich repository of highly digestible dietary protein (18–22 %), essential minerals such as calcium and iron and vitamins (niacin (vitamin B3), thiamine (B1), riboflavin (B2), pyridoxine (B6) and folate (B9) and vitamin C), providing an energy density of roughly 396 kcal per 100 g.

Light use efficiency (LUE) is a critical determinant of crop productivity; however, limited information is available on the influence of sowing windows on radiation interception and its subsequent utilisation in chickpea under field conditions. Sowing

time governs crop exposure to prevailing environmental conditions, thereby affecting biomass accumulation and overall yield performance (2). It was hypothesised that optimising of sowing windows, in conjunction with suitable varietal selection and crop protection, would enhance radiation interception and improve LUE, ultimately leading to increased dry matter production. Therefore, the present study was undertaken to systematically evaluate the effects of different sowing windows, varieties and protection levels on radiation interception and LUE in chickpea.

Materials and Methods

Experimental site

The field experiment was conducted during the rabi seasons of 2023–2024 and 2024–2025 at the Department of Agricultural Meteorology Farm, Centre of Advanced Faculty Training (CAFT) in Agricultural Meteorology, College of Agriculture, Pune, Maharashtra State (India). The geographic location of the experimental site was 18°32' N latitude, 73°51' E longitude and

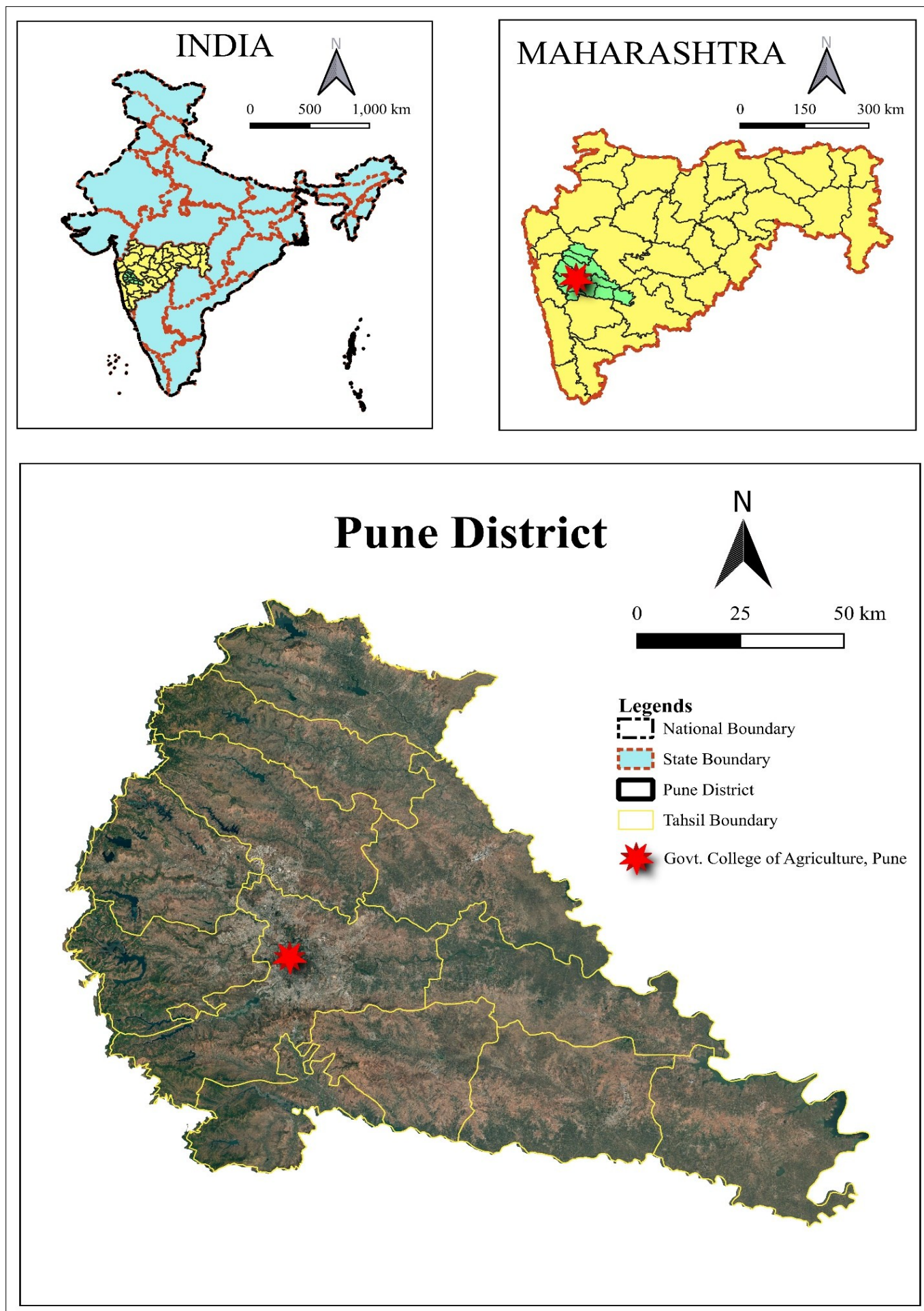


Fig. 1. Location of the study area.

Source: Survey of India (Government of India) online map portal.

557.7 m above mean sea level (Fig. 1).

Experimental design and treatments

The experiment was conducted using a split-split-plot design with three replications, comprising 16 treatment combinations. The main plot factor included two protection levels: P₁ (Protected) and P₂ (Unprotected). The sub-plot factor consisted of two chickpea varieties: V₁ (Phule Vikram) and V₂ (Vijay). The sub-subplot factor included four sowing windows: S₁ (41 MW: 08–14 Oct), S₂ (43 MW: 22–28 Oct), S₃ (45 MW: 05–11 Nov) and S₄ (47 MW: 19–25 Nov). The chickpea crop was sown on various sowing dates, viz. 41, 43, 45 and 47 MW in rabi, 2023 and rabi, 2024 by dibbling the seeds at 30 × 10 cm spacing. A basal dose of 20 N ha⁻¹ was applied through urea, 50 kg P₂O₅ ha⁻¹ through single super phosphate and 30 kg K ha⁻¹ through muriate of potash, applied before sowing. Observations for dry matter were recorded at 28, 56, 84 and at harvest.

Soil type

The soil of the experimental field (0–30 cm depth) was characterised as sandy clay loam, comprising 13.25 % coarse sand, 37.33 % fine sand, 23.54 % silt and 25.43 % clay. The soil reaction was slightly alkaline (pH 8.4) with low electrical conductivity (0.23 dS m⁻¹), indicating non-saline conditions. The organic carbon content was 0.45 %. The available nutrient status of the soil was 152.19 kg ha⁻¹ nitrogen, 19.62 kg ha⁻¹ phosphorus and 318.82 kg ha⁻¹ potassium.

Weather data

Daily weather data, including rainfall (mm), minimum and maximum temperatures (°C), were recorded at the Meteorological Observatory, College of Agriculture, Pune, Maharashtra.

Measurement of absorbed photosynthetically active radiation

The components of photosynthetically active radiation (PAR), including incident, transmitted and reflected fluxes, were recorded at 28-day intervals in the vicinity of local solar noon. All observations were conducted concurrently at mid-day, ensuring uniform illumination conditions across sampling dates. The absorbed radiations were calculated using the following equation, as given previously (3).

$$APAR = (PAR_0 + RPAR_s) - (TPAR + RPAR_c) \quad (\text{Eqn. 1})$$

Where, APAR = absorbed photosynthetically active radiation; PAR₀ = incident radiation; RPAR_s = reflected photosynthetically active radiation by soil; TPAR = transmitted photosynthetically active radiation; RPAR_c = reflected photosynthetically active radiation by canopy

Light use efficiency

With the help of cumulative absorbed radiation and vegetative plant growth, it is possible to estimate the light use efficiency of the plant per square metre.

Light use efficiency was determined as:

LUE =

$$\frac{\text{Amount of dry matter produced (g m}^{-2}\text{)}}{\text{Amount of cumulative PAR absorbed (MJ m}^{-2}\text{)}} \times 100 \quad (\text{Eqn. 2})$$

Incident radiation, transmitted radiation and reflected radiation were measured with the help of a line quantum sensor (LI-COR) and a Data logger (LI-COR 1000). Radiation was recorded in terms of $\mu\text{ mol m}^{-2} \text{ s}^{-1}$. But for estimation of LUE cumulated absorbed radiation was first estimated with the help of the above equations and then converted from $\mu\text{ mol m}^{-2} \text{ s}^{-1}$ to MJ m⁻² by

multiplication of the factor 0.0188.

Statistical analysis and interpretation of the data

The experimental data were analysed using analysis of variance (ANOVA) appropriate for a split-split plot design (4). The significance of treatment effects was tested at the 5 % level and when significant, mean comparisons were performed using the critical difference (CD) test. Standard error of mean (Sem $\pm$) was computed for all parameters. Pooled analysis over years was carried out following the procedure after testing the homogeneity of error variances using Bartlett's test (5). Regression analysis was performed to examine relationships among variables and stepwise backward elimination was applied to retain only significant predictors ($p \leq 0.05$). All statistical analyses were performed using IBM SPSS Statistics (version 29.0), while data organisation and preliminary analysis were conducted in Microsoft Excel. Graphs and figures were generated using RStudio (R version 4.5.1) with appropriate visualisation packages.

Results and Discussion

The results pertaining to the response of chickpea varieties Phule Vikram and Vijay to different sowing windows and protection treatments with respect to growth and yield attributes under rabi conditions are presented and discussed.

Dry matter accumulation g plant⁻¹

The data pertaining to mean dry matter accumulation g plant⁻¹ as influenced periodically by different treatments, during both the years recorded periodically, are presented in Table 1 and graphically depicted in Fig. 2. Throughout the crop's growth period, dry matter production followed a distinct pattern. It rose gradually up to 28 days after sowing (DAS), then accelerated rapidly between 56 and 84 DAS, marking the most active phase of biomass accumulation. After 84 DAS, the rate of increase declined as leaf senescence reduced photosynthetic activity. Maximum dry matter accumulation g plant⁻¹ was recorded at harvest 25.56 during 2023. The corresponding value for 2024 was 25.26 g plant⁻¹.

Effect of protection treatments

The mean dry matter accumulation g plant⁻¹ influenced by different treatments was significant at all stages of crop growth during both the years of 2023, 2024 and the pooled mean (Table 1). The mean dry matter accumulation g plant⁻¹ increased with advancement in the age of the chickpea.

Across both years, the protected treatment (P₁), where flubendiamide 480 SC (39.35 % w/w) was applied at 0.4 mL L⁻¹, recorded statistically significantly highest mean dry matter accumulation g plant⁻¹ (26.33 and 26.23 g) compared with the unprotected treatment (P₂), which showed comparatively lower values (24.80 and 24.29 g). The enhancement in dry matter accumulation under P₁ is attributed to the preservation of the photosynthetic source. By effectively managing pod borer (*Helicoverpa armigera*) and other defoliators, the P₁ treatment ensured higher leaf retention and functional leaf area. This luxuriant growth allowed for optimised light interception and gas exchange, ensuring that the metabolic energy was directed toward biomass consolidation rather than stress-induced tissue repair (6).

Effect of varieties

The mean dry matter accumulation g plant⁻¹ differences due to

Table 1. Periodical total dry matter accumulation g plant⁻¹ of chickpea as influenced by different treatments (2023, 2024 and pooled)

Treatment	Total dry matter accumulation g plant ⁻¹					
	28 DAS			56 DAS		
	2023	2024	Pooled	2023	2024	Pooled
A) Protection (P)						
P ₁ : Protected	2.79 ^a	2.82 ^a	2.81 ^a	13.27 ^a	13.62 ^a	13.44 ^a
P ₂ : Unprotected	2.78 ^a	2.79 ^a	2.79 ^a	12.68 ^b	13.52 ^a	13.10 ^b
S. Em. ±	0.01	0.02	0.01	0.01	0.07	0.06
C.D. at 5 %	NS	NS	NS	0.07	NS	0.25
B) Varieties (V)						
V ₁ : Phule Vikram	2.78 ^a	2.81 ^a	2.79 ^a	13.07 ^a	14.42 ^a	13.74 ^a
V ₂ : Vijay	2.79 ^a	2.81 ^a	2.80 ^a	12.88 ^b	12.72 ^b	12.80 ^b
S. Em. ±	0.01	0.02	0.02	0.04	0.06	0.06
C.D. at 5 %	NS	NS	NS	0.14	0.22	0.19
C) Sowing windows (S)						
S ₁ : 41 MW	2.87 ^a	2.94 ^a	2.91 ^a	13.78 ^a	14.63 ^a	14.21 ^a
S ₂ : 43 MW	2.81 ^a	2.81 ^a	2.81 ^a	13.28 ^b	14.01 ^b	13.64 ^b
S ₃ : 45 MW	2.76 ^a	2.76 ^a	2.76 ^a	12.69 ^c	13.28 ^c	12.99 ^c
S ₄ : 47 MW	2.70 ^a	2.72 ^a	2.71 ^a	12.14 ^d	12.36 ^d	12.25 ^d
S. Em. ±	0.06	0.08	0.07	0.04	0.04	0.05
C.D. at 5 %	NS	NS	NS	0.10	0.13	0.14
Interactions						
P × V						
S. Em. ±	0.02	0.03	0.03	0.05	0.08	0.08
C.D. at 5 %	NS	NS	NS	NS	NS	NS
P × S						
S. Em. ±	0.02	0.03	0.03	0.05	0.06	0.07
C.D. at 5 %	NS	NS	NS	NS	0.18	0.19
V × S						
S. Em. ±	0.02	0.03	0.03	0.05	0.06	0.07
C.D. at 5 %	NS	NS	NS	NS	NS	NS
P × V × S						
S. Em. ±	0.03	0.04	0.04	0.07	0.09	0.10
C.D. at 5 %	NS	NS	NS	NS	0.25	0.28
General mean	2.79	2.81	2.80	12.97	13.57	13.27

Treatment	Total dry matter accumulation g plant ⁻¹					
	84 DAS			At harvest		
	2023	2024	Pooled	2023	2024	Pooled
A) Protection (P)						
P ₁ : Protected	19.69 ^a	19.22 ^a	19.46 ^a	26.33 ^a	26.23 ^a	26.28 ^a
P ₂ : Unprotected	18.34 ^b	18.90 ^b	18.62 ^b	24.80 ^b	24.29 ^a	24.54 ^a
S. Em. ±	0.07	0.05	0.08	0.02	0.72	0.62
C.D. at 5 %	0.45	0.29	0.30	0.14	NS	NS
B) Varieties (V)						
V ₁ : Phule Vikram	19.04 ^a	20.33 ^a	19.69 ^a	25.58 ^a	26.22 ^a	25.90 ^a
V ₂ : Vijay	18.99 ^a	17.79 ^b	18.39 ^b	25.54 ^a	24.30 ^a	24.92 ^a
S. Em. ±	0.08	0.03	0.08	0.07	0.74	0.65
C.D. at 5 %	NS	0.14	0.25	NS	NS	NS
C) Sowing windows (S)						
S ₁ : 41 MW	20.33 ^a	20.66 ^a	20.49 ^a	27.35 ^a	27.17 ^a	27.26 ^a
S ₂ : 43 MW	19.29 ^b	19.87 ^b	19.58 ^b	26.12 ^b	25.89 ^b	26.01 ^b
S ₃ : 45 MW	18.64 ^c	18.54 ^c	18.59 ^c	24.95 ^c	24.71 ^{bc}	24.83 ^{bc}
S ₄ : 47 MW	17.80 ^d	17.17 ^d	17.49 ^d	23.83 ^d	23.26 ^c	23.55 ^c
S. Em. ±	0.07	0.08	0.07	0.07	0.13	0.13
C.D. at 5 %	0.20	0.23	0.21	0.21	0.38	0.36
Interactions						
P × V						
S. Em. ±	0.11	0.05	0.11	0.10	1.05	0.91
C.D. at 5 %	NS	NS	NS	NS	NS	NS
P × S						
S. Em. ±	0.08	0.07	0.08	0.10	0.18	0.18
C.D. at 5 %	0.23	0.21	0.22	NS	NS	NS
V × S						
S. Em. ±	0.08	0.07	0.08	0.10	0.18	0.18
C.D. at 5 %	0.23	0.21	0.22	NS	NS	NS
P × V × S						
S. Em. ±	0.11	0.10	0.11	0.14	0.26	0.26
C.D. at 5 %	0.32	0.30	0.31	NS	NS	NS
General mean	19.02	19.06	19.04	25.56	25.26	25.41

Means followed by the same lowercase letter(s) within a column are not significantly different at the 5 % level of significance ($p = 0.05$) as per the CD test. NS: Non-significant.

DAS: Days after sowing; P: Protection (P₁: Protected, P₂: Unprotected); V: Variety (V₁: Phule Vikram, V₂: Vijay); S: Sowing windows; MW: Meteorological week; S.Em. ±: Standard error of mean; CD: Critical difference.

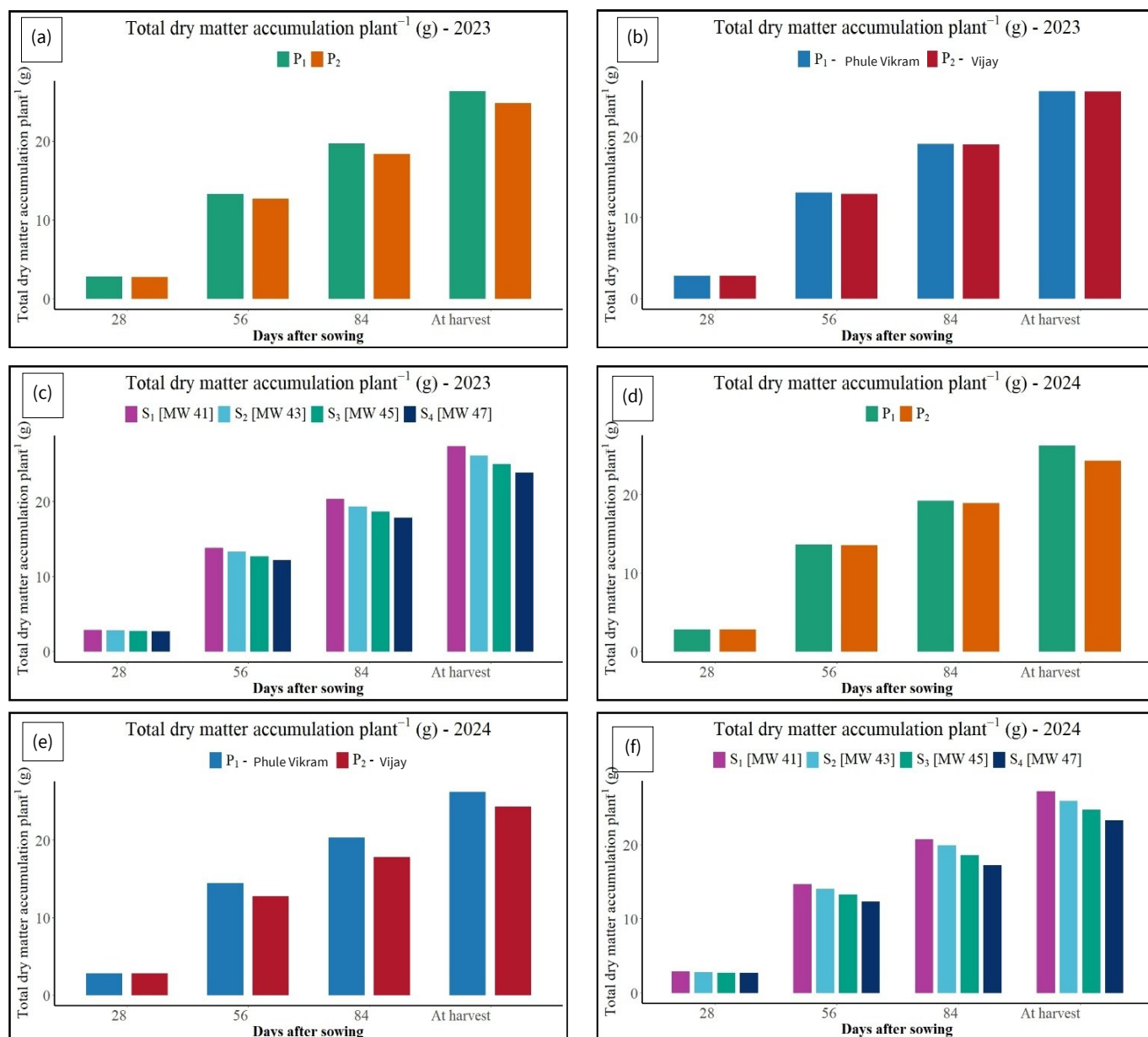


Fig. 2. Periodical total dry matter accumulation (g plant^{-1}) of chickpea as influenced by different treatments (2023 and 2024).

varieties were significant from 56 DAS onwards during both the years of 2023 and 2024, while no significant differences were observed at 28 DAS. Phule Vikram (V_1) consistently outperformed Vijay (V_2), reaching a maximum DMA of 26.22 g at harvest in 2024 (Table 1).

While both varieties shared a similar "grand growth" window (28–84 DAS), V_1 exhibited superior biomass partitioning efficiency. This variation is primarily governed by the inherent genetic constitution and canopy architecture of the genotype rather than external variables. The higher accumulation in Phule Vikram suggests a more robust genetic potential for resource acquisition, allowing it to translate available environmental inputs into structural dry matter more effectively than the variety Vijay (7–10).

Effect of sowing windows

Sowing windows significantly influenced dry matter accumulation throughout the crop growth period. Dry matter accumulation g plant^{-1} increased progressively with crop age, reaching its maximum at maturity (Table 1). At 28 DAS, differences among sowing windows were not significant, while from 56 DAS onwards, significant differences were observed.

The highest dry matter accumulation g plant^{-1} of chickpea was observed in the $S_1(41\text{MW})$ at 56, 84 DAS and at harvest during both years, which was significantly superior over the rest of the sowing dates except at 28 DAS. The significantly lower dry matter accumulation g plant^{-1} of chickpea was recorded at $S_4(47\text{MW})$. At all the stages of growth, the dry matter weight g plant^{-1} showed a decreasing trend with late sowings (S_1 – S_4). The superiority of the S_1 window is linked to favourable environmental-phenological alignment. Plants sown in MW 41 were exposed to optimal thermal regimes and photoperiods during their most active growth phases. This early establishment facilitated higher LUE and a prolonged vegetative duration, resulting in a higher net photosynthetic rate. Conversely, delayed sowing S_4 caused phenological compression, where restricted vegetative growth and suboptimal temperatures limited the crop's ability to accumulate dry matter before maturity (9, 11).

Effect of interaction

Interaction effects between protection treatments, varieties and sowing windows had a significant influence on dry matter accumulation g plant^{-1} of chickpea at 56, 84 DAS and at harvest.

During 2023, 2024 and for the pooled mean, the interaction effects of protection treatment with sowing windows (Table 2), varieties with sowing windows (Table 3), as well as the three-way interaction among protection, varieties and sowing windows were found to be significant (Table 4). Significantly higher dry matter accumulation per plant was observed for the combinations of protection treatment P_1 with sowing window S_1 (41 MW) (P_1S_1), variety Phule Vikram (V_1) with S_1 (41 MW) (V_1S_1) and the combined effect of protection treatment P_1 , variety Phule Vikram and S_1 ($P_1V_1S_1$), which were all superior over the other treatment combinations.

Absorbed photosynthetically active radiation

Absorbed photosynthetically active radiation (APAR) is defined as the amount of PAR captured by the crop canopy and available for photosynthesis. The data regarding absorbed PAR (APAR) are presented in Table 5 and graphically depicted in Fig. 3.

Effect of protection treatments

The application of flubendiamide 480 SC (P_1) showed statistically marginal differences in APAR compared to unprotected plots (P_2). In 2023, peak APAR at 84 DAS reached $978 \mu \text{mol m}^{-2} \text{s}^{-1}$ in P_1 versus $1033 \mu \text{mol m}^{-2} \text{s}^{-1}$ in P_2 . A similar trend was observed during 2024 (Table 5).

Table 2. Periodical total dry matter accumulation of chickpea as influenced by interaction between protection and sowing windows at 56 and 84 DAS (2023, 2024 and pooled)

Treatments		Total dry matter accumulation g plant ⁻¹							
sowing windows	Protection	56 DAS				84 DAS			
		2024		Pooled		2023		2024	
		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
S_1 : 41 MW		14.65 ^a	14.62 ^a	14.39 ^a	14.03 ^b	21.03 ^a	19.62 ^b	20.77 ^a	20.54 ^a
S_2 : 43 MW		13.85 ^c	14.17 ^b	13.69 ^c	13.60 ^c	19.82 ^b	18.77 ^d	19.88 ^b	19.86 ^b
S_3 : 45 MW		13.39 ^d	13.16 ^d	13.19 ^d	12.78 ^e	19.32 ^c	17.97 ^f	18.71 ^c	18.37 ^c
S_4 : 47 MW		12.58 ^e	12.13 ^f	12.51 ^f	11.99 ^g	18.61 ^d	16.99 ^e	17.51 ^d	16.84 ^e
S. Em. $\pm$		0.06		0.07		0.08		0.07	
C.D. at 5 %		0.18		0.19		0.23		0.21	

Means followed by the same lowercase letter(s) within each column are not significantly different at $p = 0.05$ as per the CD test.

DAS: Days after sowing; P: Protection (P_1 : Protected, P_2 : Unprotected); S: Sowing windows; MW: Meteorological week; S.Em. $\pm$: Standard error of mean; CD: Critical difference.

Table 3. Periodical total dry matter accumulation of chickpea as influenced by interaction between varieties and sowing windows at 84 DAS (2023, 2024 and pooled)

Treatments		Total dry matter accumulation g plant ⁻¹					
Sowing windows	Variety	84 DAS					
		2023		2024		Pooled	
		V_1	V_2	V_1	V_2	V_1	V_2
S_1 : 41 MW		20.51 ^a	20.15 ^b	22.07 ^a	19.24 ^d	21.29 ^a	19.69 ^c
S_2 : 43 MW		19.42 ^c	19.17 ^c	21.10 ^b	18.64 ^e	20.26 ^b	18.90 ^e
S_3 : 45 MW		18.66 ^d	18.63 ^d	19.81 ^c	17.27 ^f	19.23 ^d	17.95 ^f
S_4 : 47 MW		17.58 ^f	18.02 ^e	18.35 ^e	16.00 ^g	17.96 ^f	17.01 ^g
S. Em. $\pm$		0.08		0.07		0.08	
C.D. at 5 %		0.23		0.21		0.22	

Means followed by the same lowercase letter(s) within each column are not significantly different at $p = 0.05$ as per the CD test.

DAS: Days after sowing; V: Variety (V_1 : Phule Vikram, V_2 : Vijay); S: Sowing windows; MW: Meteorological week; S.Em. $\pm$: Standard error of mean; CD: Critical difference.

Table 4. Periodical total dry matter accumulation of chickpea as influenced by interaction between protection, varieties and sowing windows at 56 and 84 DAS (2023, 2024 and pooled)

Treatments		Total dry matter accumulation g plant ⁻¹							
$P \times V \times S$		56 DAS				84 DAS			
		2023		Pooled		2023		2024	
		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
		P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
V_1S_1		15.68 ^a	15.37 ^a	14.88 ^a	14.49 ^b	21.12 ^a	19.89 ^b	22.50 ^a	21.65 ^b
V_1S_2		14.83 ^a	14.91 ^a	14.19 ^b	14.12 ^b	20.01 ^b	18.83 ^c	21.24 ^b	20.97 ^b
V_1S_3		14.13 ^b	14.14 ^b	13.52 ^c	13.41 ^c	19.28 ^b	18.04 ^c	19.80 ^c	19.82 ^c
V_1S_4		13.16 ^b	13.13 ^b	12.75 ^d	12.58 ^e	18.22 ^c	16.95 ^e	18.36 ^e	18.33 ^e
V_1S_1		13.61 ^b	13.88 ^b	13.90 ^b	13.57 ^c	20.94 ^a	19.35 ^b	19.04 ^d	19.43 ^c
V_1S_2		12.87 ^c	13.42 ^b	13.20 ^c	13.07 ^d	19.63 ^b	18.71 ^c	18.53 ^e	18.75 ^d
V_1S_3		12.65 ^c	12.19 ^c	12.85 ^d	12.16 ^e	19.36 ^b	17.90 ^d	17.61 ^f	16.93 ^g
V_1S_4		12.01 ^c	11.13 ^d	12.27 ^e	11.39 ^f	19.00 ^c	17.04 ^e	16.65 ^g	15.35 ^h
S. Em. $\pm$		0.09		0.10		0.11		0.10	
C.D. at 5 %		0.25		0.28		0.32		0.30	

Means followed by the same lowercase letter(s) within each column are not significantly different at $p = 0.05$ as per the CD test.

DAS: Days after sowing; P: Protection (P_1 : Protected, P_2 : Unprotected); V: Variety (V_1 : Phule Vikram, V_2 : Vijay); S: Sowing windows (S_1 : 41 MW, S_2 : 43 MW, S_3 : 45 MW, S_4 : 47 MW); MW: Meteorological week; S.Em. $\pm$: Standard error of mean; CD: Critical difference.

Table 5. Mean absorbed photosynthetically active radiation (PAR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$) across various phenophases of chickpea as influenced by different treatments (2023 and 2024)

Treatment	APAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$)							
	28 DAS		56 DAS		84 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
A) Protection (P)								
P ₁ : Protected	550	507	897	904	978	1035	697	718
P ₂ : Unprotected	550	506	891	900	976	1033	691	706
B) Varieties (V)								
V ₁ : Phule Vikram	555	511	898	907	976	1037	686	720
V ₂ : Vijay	545	502	890	898	978	1031	701	703
C) Sowing windows (S)								
S ₁ : 41 MW	602	522	867	884	939	998	737	731
S ₂ : 43 MW	563	517	891	906	972	1030	699	721
S ₃ : 45 MW	538	504	907	912	994	1048	688	715
S ₄ : 47 MW	498	483	911	907	1004	1059	652	680
General mean	550	507	894	902	977	1034	694	712

APAR: Absorbed photosynthetically active radiation; DAS: Days after sowing; MW: Meteorological week.

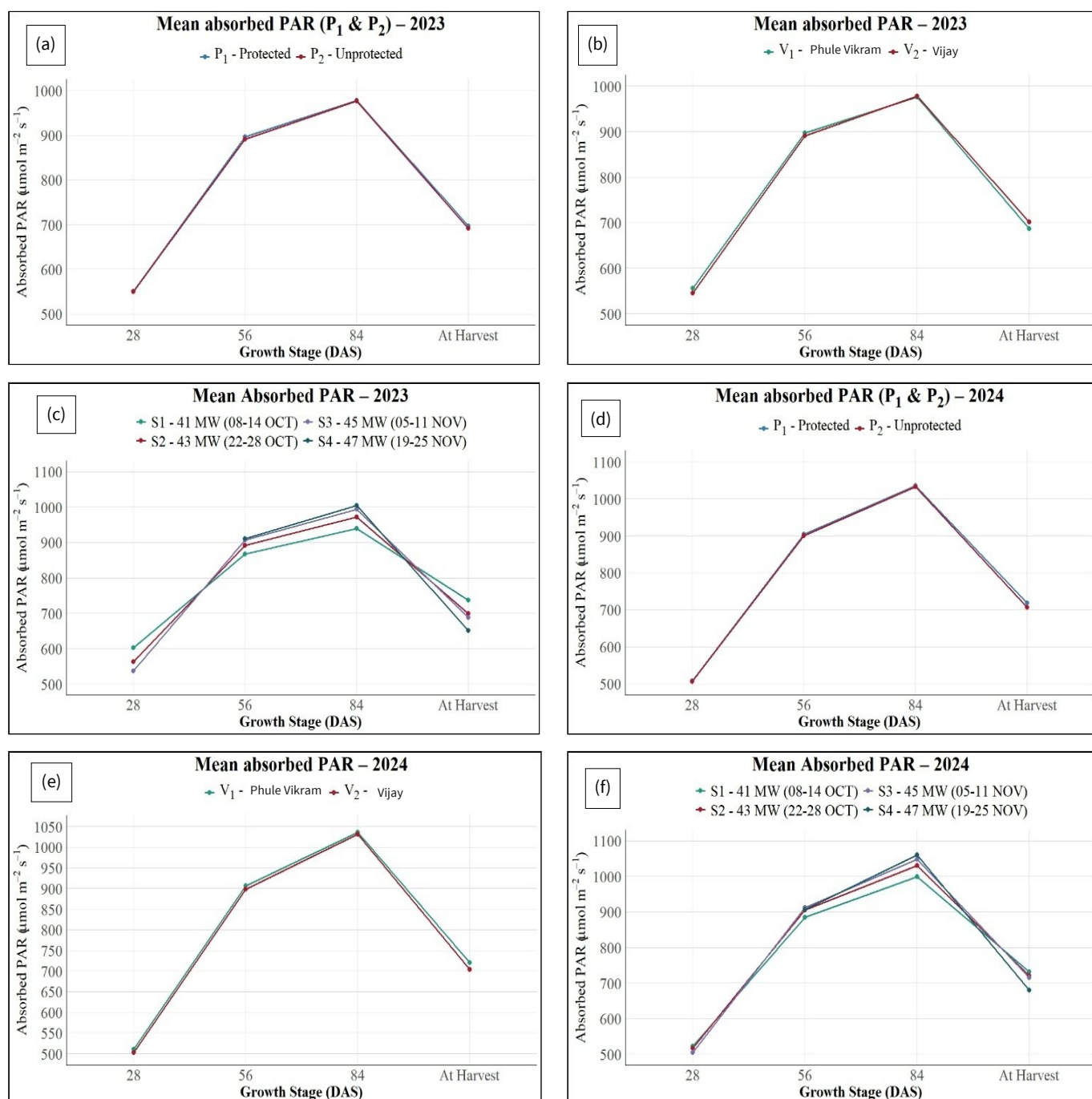


Fig. 3. Mean absorbed PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$) as influenced by protection, varieties and sowing windows during 2023 and 2024.

These observations suggest that the protective treatment (Flubendiamide 480 SC (39.35 % w/w)) exerted minimal influence on APAR in this experiment, likely because the canopy development remained similar under both protected and unprotected conditions. While protection significantly benefits LUE, it appears to have a limited impact on APAR (the quantity of light captured), likely because the leaf canopy remained relatively comparable between the 2 treatments during the vegetative phase (3).

Effect of varieties

The varietal differences between Phule Vikram (V_1) and Vijay (V_2) were evident across both years. V_1 generally maintained higher APAR values, reaching 978 and 1037 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 84 DAS during the 2023 and 2024 seasons (Table 5).

In both years, APAR values were increased with an increase in crop age and canopy development. It increases up to 84 DAS and then decreases thereafter, due to senescence of leaves, drying of pods and branches changing their colour. The variation in light absorption is primarily a function of genotypic canopy geometry. Phule Vikram's inherent growth habit facilitates a more rapid establishment of green cover, maximising the cumulative radiation intercepted during the vegetative and early reproductive stages. The synchronisation of peak APAR with the flowering and pod-set stage (84 DAS) is critical for ensuring that radiation capture is maximised when the plant's energy requirement for biomass partitioning is highest (6, 12).

Effect of sowing windows

Sowing dates significantly modulated the APAR profile throughout the crop cycle during both years. The early sowing window (S_1 - MW 41) consistently demonstrated higher APAR during the initial and peak growth stages compared to the late-sown crop (S_4 - MW 47) (Table 5).

The superiority of S_1 is attributed to the optimal environmental conditions that promote profuse vegetative growth and rapid canopy closure. This early vigour results in a larger cumulative intercepted radiation load compared to late-sown crops, which experience constrained growth. In S_4 , the lower APAR values in early stages reflect a restricted canopy footprint. Although some late-sown plots showed high instantaneous APAR at 84 DAS due to delayed phenology, the overall cumulative energy capture was reduced by phenological compression and early senescence (13, 14).

Strategic early sowing (MW 41) ensures that the peak of

solar radiation availability is effectively utilised by a well-developed canopy, thereby stabilising the crop's energy balance in fluctuating thermal regimes.

Light use efficiency

Radiation interception parameters were interpreted based on mean values, as statistical analysis was not performed. The data regarding LUE as influenced by different treatments are presented in Table 6 and graphically depicted in Fig. 4.

Effect of protection treatments

The LUE of chickpea exhibited a temporal increase with crop age, peaking at 84 DAS before declining at maturity. During 2023, the protected treatment (P_1), using flubendiamide 480 SC, achieved a maximum LUE of 1.07 $\text{g MJ}^{-1} \text{m}^{-2}$, compared to 1.00 $\text{g MJ}^{-1} \text{m}^{-2}$ in unprotected plots (P_2). A similar trend was observed in 2024, with P_1 reaching 0.99 $\text{g MJ}^{-1} \text{m}^{-2}$ versus 0.98 $\text{g MJ}^{-1} \text{m}^{-2}$ in P_2 .

The consistently higher LUE under protected conditions, though marginal, indicates that mitigating biotic stress is essential for maintaining photosynthetic integrity. By reducing pest-induced defoliation, the P_1 treatment sustains a greater leaf area and functional chlorophyll density. This prevents the plant from diverting metabolic energy toward tissue repair, allowing for more efficient conversion of intercepted radiation into biomass. These results align with previous findings that pest and disease pressure act as "efficiency reducers" (15). Maintaining a healthy canopy through the reproductive phase (84 DAS) ensures the crop operates at its maximum radiation use potential, which is critical for climate-resilient yield stability.

Effect of varieties

Significant variations in LUE were observed between the two chickpea varieties, Phule Vikram (V_1) and Vijay (V_2), across both years. In 2023, V_1 recorded peak LUE values of 1.04 $\text{g MJ}^{-1} \text{m}^{-2}$ at 84 DAS, compared to 1.03 $\text{g MJ}^{-1} \text{m}^{-2}$ for V_2 . The difference was more pronounced in 2024, where V_1 reached 1.05 $\text{g MJ}^{-1} \text{m}^{-2}$, significantly outperforming V_2 at 0.92 $\text{g MJ}^{-1} \text{m}^{-2}$.

The superior LUE of Phule Vikram is primarily attributed to its optimised canopy architecture and growth habit. Phule Vikram's canopy facilitates more efficient light penetration into deeper leaf layers. By maintaining a higher APAR at the critical reproductive phase (84 DAS), V_1 sustains a robust "source" to meet the "sink" demand of pod formation (12, 16). The ability of V_1 to achieve early canopy closure and maintain high LUE during the

Table 6. Light use efficiency ($\text{g MJ}^{-1} \text{m}^{-2}$) across various phenophase of chickpea as influenced by different treatments (2023 and 2024)

Treatment	Light use efficiency ($\text{g MJ}^{-1} \text{m}^{-2}$)							
	28 DAS		56 DAS		84 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
A) Protection (P)								
P_1 : Protected	0.27	0.30	0.79	0.80	1.07	0.99	0.57	0.59
P_2 : Unprotected	0.25	0.30	0.76	0.80	1.00	0.98	0.54	0.55
B) Varieties (V)								
V_1 : Phule Vikram	0.26	0.31	0.78	0.85	1.04	1.05	0.56	0.59
V_2 : Vijay	0.25	0.28	0.77	0.75	1.03	0.92	0.55	0.55
C) Sowing windows (S)								
S_1 : 41 MW	0.26	0.32	0.85	0.88	1.15	1.10	0.63	0.64
S_2 : 43 MW	0.26	0.31	0.79	0.82	1.06	1.03	0.57	0.58
S_3 : 45 MW	0.25	0.29	0.74	0.77	1.00	0.94	0.54	0.55
S_4 : 47 MW	0.25	0.27	0.71	0.72	0.94	0.86	0.49	0.51
General mean	0.26	0.30	0.77	0.80	1.04	0.98	0.56	0.57

DAS: Days after sowing; MW: Meteorological week.

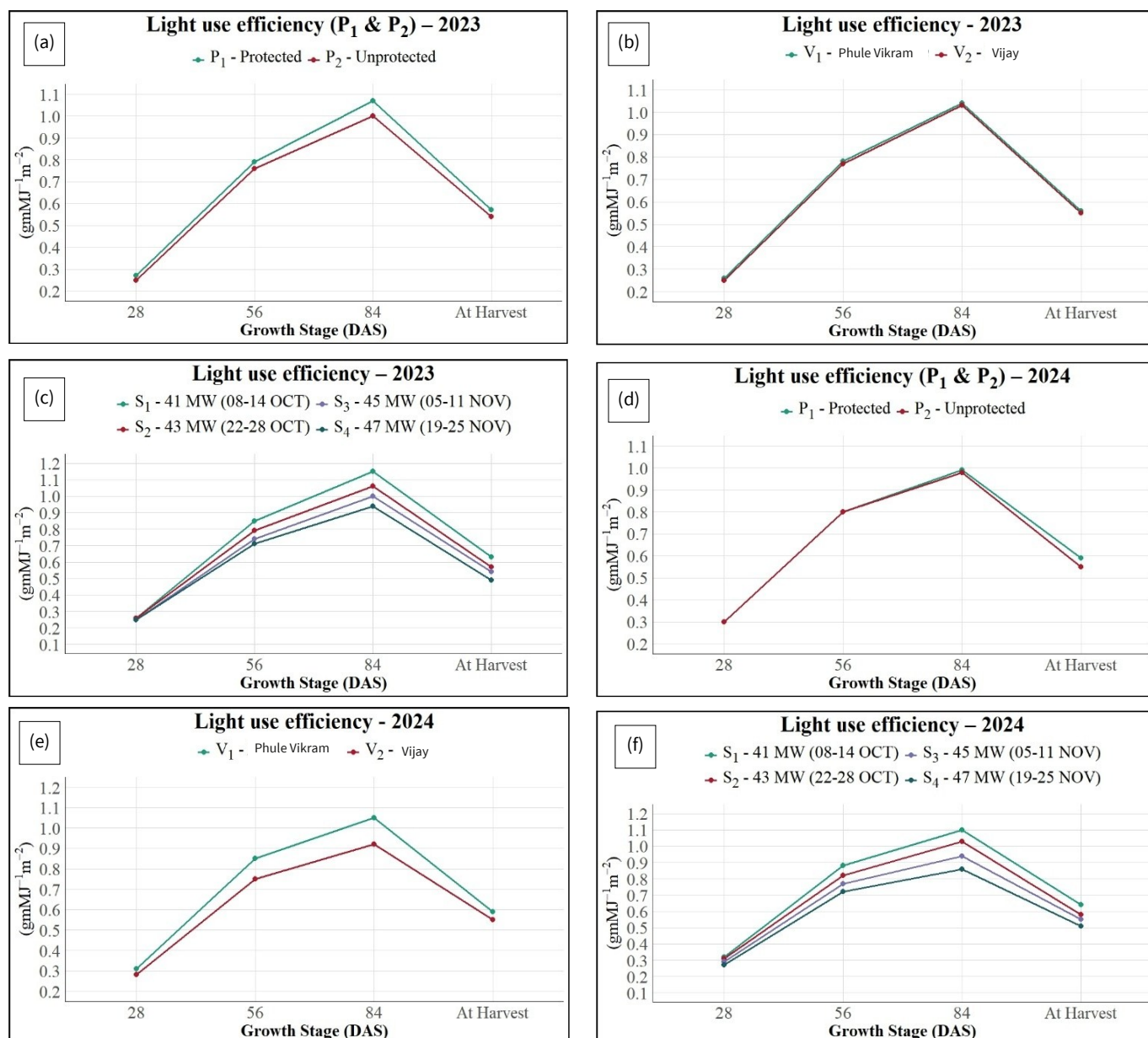


Fig. 4. Light use efficiency ($\text{g MJ}^{-1} \text{m}^2$) as influenced by protection, varieties and sowing windows during 2023 and 2024.

reproductive phase (6, 17) suggests it is a more radiation-efficient genotype. This makes it better suited for maximising biomass in environments where light interception is the primary driver of productivity.

Effect of sowing windows

The sowing window was the most influential factor driving variations in LUE. In 2023, the earliest sowing (S_1 - MW 41) achieved a peak LUE of $1.15 \text{ g MJ}^{-1} \text{m}^2$, whereas the late sowing (S_4 - MW 47) dropped to $0.94 \text{ g MJ}^{-1} \text{m}^2$ at 84 DAS. A similar decline was recorded in 2024, with S_1 reaching $1.10 \text{ g MJ}^{-1} \text{m}^2$ compared to $0.86 \text{ g MJ}^{-1} \text{m}^2$ in S_4 .

The drastic reduction in LUE with delayed sowing is a result of phenological compression and environmental forcing. Early sowing (S_1) provides an optimal thermal window and adequate soil moisture, promoting rapid canopy closure. This ensures that peak radiation interception coincides with the maximum photosynthate demand during pod formation (18, 19). In S_4 , restricted vegetative growth and higher temperatures during later stages accelerate leaf senescence. The reduction in LUE observed with delayed sowing (S_4) is primarily due to a significant contraction of the photosynthetic duration (canopy functional longevity) (14, 20). This

phenological compression, driven by rising ambient temperatures, accelerates leaf senescence and reduces the time available for biomass accumulation. Consequently, the crop's efficiency in converting intercepted radiation into dry matter is compromised, as the curtailed vegetative phase limits the development of a robust source-to-sink relationship (13, 15, 21). These findings highlight that early sowing (S_1 : MW 41) is a critical climate-smart strategy. It buffers the crop against terminal heat stress, ensuring high LUE by aligning the crop's most active growth phase with favourable environmental conditions.

Conclusion

Dry matter accumulation, absorbed photosynthetically active radiation and light use efficiency consistently demonstrated the superiority of P_1 and V_1 over P_2 and V_2 across both rabi seasons, indicating improved radiation utilisation and biomass production efficiency. The earliest sowing window (S_1 : MW 41) markedly increased biomass production and radiation conversion efficiency, with peak LUE values observed at 84 DAS in both years. In contrast, delayed sowing (S_4 : MW 47) reduced dry matter production and LUE, underscoring the sensitivity of chickpea productivity to

sowing time. Collectively, these findings highlight that optimised planting schedules coupled with favourable phenological and physiological traits substantially strengthen biomass accumulation and light-use efficiency in chickpea.

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Authors' contributions

ODR conceptualised the study, drafted the original manuscript, conducted the formal analysis and integrated the primary data interpretations into the scientific framework of the study. PUR and SVB contributed to the refinement of the methodology, critically reviewed the analytical procedures and assisted in structuring the manuscript during the review and editing phases. NDT and SKR played pivotal roles in validating the methodological approach and ensuring scientific coherence through detailed manuscript review and editing. VAS and JDJ provided overall project administration, technical supervision and intellectual oversight throughout the research process. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and Gemini to improve language clarity, correct grammar and assist in refining the overall structure of the manuscript. After using this tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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