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Article

Keywords:

Posted Date: February 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8849552/v1

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on July 9th, 2026. See the published version at https://doi.org/10.1038/s41598-026-59115-4.

Phenology–soil moisture synchronisation and foliar boron regulate physiological resilience and yield stability of field pea (Pisum sativum L.) in rainfed rice-fallow systems

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Abstract

Rice-fallow agroecosystems across South and Southeast Asia represent a major opportunity for sustainable intensification, yet productivity of post-rice pulse crops remains limited by narrow sowing windows, rapid depletion of residual soil moisture, and micronutrient deficiencies. Field pea (*Pisum sativum* L.), a short-duration legume adapted to cool-season conditions, is well suited to these systems; however, yield stability under rainfed rice fallows is frequently constrained by terminal moisture stress and boron (B) deficiency. Here, we tested whether interactions between sowing phenology and foliar boron application regulate soil moisture dynamics, plant physiological responses, reproductive processes, and yield formation under rainfed conditions. A two-year field experiment (2017–2018 and 2018–2019) was conducted

using a split-plot design with four sowing dates (10 November, 20 November, 30 November, and 10 December) and four foliar boric acid concentrations (0, 0.1, 0.2, and 0.3%), applied at pre-flowering and pod initiation stages. Early sowing (10–20 November) maintained root-zone soil moisture above critical thresholds during flowering, extended crop duration by 14–17 days, and increased grain yield by 22–47% compared with late sowing. Delayed sowing accelerated soil moisture depletion, reduced plant water status (relative leaf water content and canopy temperature depression), and impaired photosynthetic capacity, leading to lower chlorophyll content, photosynthetic rate, leaf area index, and stomatal conductance. These physiological constraints were accompanied by reduced plant B concentration, pollen viability, and pollen germination, collectively contributing to yield decline. Foliar boron application at 0.2% enhanced relative leaf water content (3–6%), photosynthetic rate (8–15%), pollen viability (15–16%), and grain yield (~25%) relative to untreated controls, while responses plateaued at B application at 0.3%. Principal component analysis indicated that treatment responses were primarily structured along a physiological axis integrating soil moisture availability, plant water status, photosynthetic traits, and reproductive performance. Overall, sowing of field pea during 10-20 November combined with two foliar sprays of 0.2% boric acid is a practical and economically viable strategy for improving productivity of field pea in rainfed rice-fallow systems. Our findings demonstrate that synchronisation between crop phenology and residual soil moisture availability, combined with boron-mediated regulation of physiological and reproductive traits, governs yield stability of field pea in rainfed rice-fallow systems. These results provide mechanistic insights into crop adaptation strategies for water-limited environments and highlight management interactions that may enhance resilience across rainfed post-rice agroecosystems.

Introduction

Throughout South and Southeast Asia, more than 22 million hectares of fertile land remain uncultivated during the winter season after monsoon rice harvest; one of the largest underused agricultural resources in the world (Gumma et al., 2016[1]; Nath et al., 2024[2]). Despite their residual fertility, these rice-fallow areas face issues such as rapid soil moisture depletion, terminal drought, micro-nutrient deficiencies, and unpredictable weather, making their productive use both a challenge and an opportunity (Raju et al., 2020[3]). As global food and nutrition demand rise, sustainable intensification in this production ecology through short-duration and drought-tolerant legumes/pulse crops is gaining momentum (Pretty et al., 2018[4]). However, the yield improvements of post-rice season pulse crops have been modest due to

limited knowledge of location-specific agronomic management and scalable technologies. This highlights the need for integrated and region-focused research to address soil moisture stress, narrow planting windows, and nutrient deficiencies under rainfed rice-fallow systems (Nath et al., 2024[2]).

Besides Indian agro-ecologies, South and Southeast Asia, sub-Saharan Africa, and other rainfed post-rice systems facing shortening growing windows and terminal drought (Nath et al., 2024[2]). In South Asia, particularly in India, intensifying cropping systems is critical due to limited arable land, growing demand for pulses, and the need to meet the rising food grain requirements for a fast-growing population (Kumar et al., 2016[5]). Eastern India, largely dominated by monsoon-season rice cultivation, presents both challenges and opportunities for diversification with pulses, with 4.52 million hectares of rice-fallow land (Gumma et al., 2016[1]). Overall, India has around 11.7 million hectares of land lying fallow in each winter after rice harvest, representing a major opportunity to boost productivity and profitability (Pande et al., 2012[6]; Nath et al., 2024[2]). In West Bengal, rice fallows account for about 37% of the total rainy season rice area (1.72 million hectares), severely limiting regional agricultural performance (Kar and Kumar, 2009[7]). This persistence of rice fallows is linked to long-duration rice varieties that delay harvest, fast post-monsoon drying of soils, soil compaction from puddling, and erratic rainfall that hampers the establishment of subsequent crops (Subbarao et al., 2001[8]; Pal et al., 2023[9]).

Among potential crops, field pea (*Pisum sativum* L.) is particularly promising for rice-fallow regions due to its short growth cycle and ability to thrive in cool conditions while effectively using residual soil moisture through deep roots (Kumar et al., 2022[10]). As a legume, it fixes atmospheric nitrogen, improves soil fertility, and supports sustainable farming systems (Das et al., 2024[11]). Yet, productivity of field pea in rainfed rice-fallow systems remains substantially below its attainable potential due to sub-optimal agronomic management, uneven rainfall distribution, terminal drought stress, and delayed sowing. National statistics indicate that average field pea productivity in India is only about 0.8–1.0 t ha^{-1}, whereas attainable yields under improved agronomic practices and favourable environments range between 2.0 and 2.5 t ha^{-1}, reflecting a considerable yield gap of nearly 50–60% (Directorate of Economics and Statistics, 2023[12]). Sowing time is a key determinant of yield, influencing how crop growth aligns with soil moisture, temperature, and day length (Ghosh et al., 2016[13]; Tripathi et al., 2023[14]). Late sowing shortens growth duration, increases evapotranspiration, and intensifies drought and heat stress risks, while early sowing can expose seedlings to cold temperatures that harm germination and vigour (Saha et al., 2021[15]; Rathore et al., 2022[16]; Sharma et al.,

2023[17]). Research on optimizing sowing schedules in relation to changing climates and soil conditions remains limited (Bandyopadhyay et al., 2016[18]; Sharma et al., 2021[19]).

Alongside sowing time, proper micronutrient management, particularly boron (B), is vital for improving physiological processes, reproductive success, and yield in rice-fallow systems (Rathore et al., 2022[16]; Sharma et al., 2023[17]). Boron plays a crucial role in cell wall formation, membrane stability, carbohydrate transport, nitrogen metabolism, and pollen development (Goldbach et al., 2001[20]; Wimmer et al., 2015[21]; Das et al., 2024[11]). Boron deficiency is common in coarse, alkaline, and drought-prone soils, leading to poor reproductive success, reduced pollen viability, and flower abortion, resulting in lower yields (Reid, 2007[22]; Ahmed et al., 2021[23]). Studies in chickpea, lentil, and field pea showed that foliar boron sprays enhance pod filling, seed yield, and drought resilience (Kumar et al., 2022[10]). Despite advances in understanding sowing time and micronutrients separately, their combined influence on field pea productivity under moisture-limited rainfed rice-fallow conditions is poorly studied. Very few works have examined the combined effects of sowing windows and foliar B application on water status such includes relative leaf water content (RLWC), canopy temperature depression (CTD), stress indicators (proline, catalase), photosynthetic capacity (chlorophyll, stomatal conductance, photosynthetic rate, leaf area index), reproductive performance (pollen viability and germination) and grain yield of field pea in rice-fallow systems. Therefore, present study was undertaken to evaluate the interactive effects of sowing time and foliar boron application on field pea performance under rainfed rice-fallow conditions of Eastern India. In addition to conventional yield analysis, we used multivariate approaches (principal component analysis and principal component regression) to identify coordinated trait responses and quantify how integrated physiological and reproductive trait expression contributes to grain yield variation across sowing windows and B fertilization regimes.

We hypothesized that (i) sowing within an optimum window would synchronize field pea phenology with favourable soil moisture availability and thermal conditions, thereby improving physiological performance and reproductive success, and (ii) stage-specific foliar boric acid application would enhance plant B status, reproductive traits, and yield stability across sowing windows, with diminishing returns beyond an optimum concentration. The objectives were to: (i) evaluate the effects of sowing date on soil moisture dynamics, crop phenology, physiological and biochemical traits, and yield attributes under rainfed rice-fallow conditions; (ii) determine the influence of foliar boric acid concentrations on plant water status, photosynthetic traits, reproductive performance, and grain yield; and (iii) identify the most

effective sowing window × boron combination for maximizing grain yield and economic returns.

Materials and Methods

Experimental site information

The field investigation was carried out for two consecutive winter seasons, extending from November to March of 2017-18 and 2018-19, at the District Seed Farm (AB block) of Bidhan Chandra Krishi Viswavidyalaya, Kalyani, West Bengal, India (22°56′ N latitude and 88°32′ E longitude, with an elevation of about 13 m above mean sea level). The region falls under humid subtropical agro-climatic zone, which is characterized by a short and mild winter and a distinct monsoon pattern. The mean annual precipitation of the area is around 1450 mm, with nearly 85% occurring within June to September. All the weather-related data including minimum and maximum temperature, rainfall, recorded during the experimental periods of 2017-18 and 2018-19, are presented in Fig.1. The soil of the experimental site belongs to Aeric Haplaquept soil order (US Soil Taxonomy, Soil Survey Staff, 2003[24]), under a hyperthermic soil temperature regime and exhibit clay loam texture in the surface. The experimental soil is inherently low in organic carbon (5.5 g kg^{-1}), available nitrogen (123.5 kg ha^{-1}) and available boron (0.04-0.51 mg kg^{-1}), whereas, available phosphorus (37.3 kg ha^{-1}) and potassium (196.0 kg ha^{-1}) falls within medium range. The soil textual component, water holding capacity and key soil moisture constants (ield capacity (θ_{FC}), permanent wilting point (θ_{WP}), and critical soil moisture content (θ_C) are presented in Table 1.

Experimental details

The field experiment was arranged in a split plot design with three replications in both years. The main plot treatments comprised of four sowing dates: 10 November (S1), 20 November (S2), 30 November (S3), and 10 December (S4), and the subplot treatments included four foliar boric acid concentrations such as no spray (B1), 0.1% (B2), 0.2% (B3), and 0.3% (B4) applied at pre-flowering and pod-initiation stages. Each subplot measured 5 m × 4 m, with 1 m wide buffer zones separating the main plots and 0.75 m wide alleys maintained between replications to minimize treatment interference. After the harvest of a long duration rice crop (*Oryza sativa* L., cv. 'IET 5656') in the last week of October, pre-soaked field pea (*Pisum sativum* L., cv. 'VL 42') seeds were line sown according to the specified sowing dates. The recommended dose of fertilizers (RDF) was 20:40:40 kg N:P:K ha^{-1} and was uniformly applied as basal dose. Nitrogen was applied through urea (46% N), phosphorus as single super phosphate (16% P_2O_5) and potassium was applied through muriate of potash (60% K_2O). Weeding was done through a single hand weeding at 50-55 days after sowing (DAS). The foliar

application of B as boric acid was done twice: first at the pre-flowering stage and second at the pod-initiation stage, with the timing of sprays were adjusted to the phenological stages corresponding to each sowing date. The field pea was harvested between the end of March to the first week of April in both 2017-18 and 2018-19 cropping seasons, depending on the sowing time, with the crop duration ranging from 78-98 days.

Estimation of root zone soil moisture storage

Root zone soil moisture storage of field pea was monitored up to a depth of 450 mm, stratified into three layers: 0-150 mm, 150-300 mm and 300-450 mm, across five key phenological stages of field pea, namely: sowing, peak vegetative, 50% flowering, 50% pod formation, and harvest. Moisture measurements were taken using a profile soil moisture probe (PR2/4, Delta-T Devices Ltd., Cambridge, UK). The probe readings were calibrated against gravimetrically determined soil moisture values, demonstrating a strong positive relationship ($R^2 = 0.925$), thereby ensuring measurement reliability. The total available water (TAW) within each soil depth interval was computed as the difference between the volumetric water contents at field capacity and permanent wilting point, determined using a pressure plate/membrane apparatus following the method of Richards (1949) [25]. The TAW was calculated using the following equation:

$$TAW = (\theta_{FC} - \theta_{WP})\, Zr \quad \text{(eq. 1)}$$

where Zr represents effective rooting depth (mm); θ_{FC} and θ_{WP} denotes volumetric soil water content at field capacity ($mm^3\ mm^{-3}$) and permanent wilting point ($mm^3\ mm^{-3}$), respectively. The critical soil moisture content (θc) for each depth layer was estimated using the relation:

$$\theta c = (1 - p)(\theta_{FC} - \theta_{WP}) + \theta_{WP} \quad \text{(eq. 2)}$$

where, p denotes the fraction of TAW that can be depleted from the root zone before water stress occurs. A value of 0.5 was adopted for field pea, as recommended by Allen et al., (1998) [26].

Estimation of plant physiological parameters

The phenological development of field pea, such as: emergence, peak vegetative stage, flower initiation, 50% flowering, 50% pod formation and maturity was recorded through regular field observations at each growth phase. Canopy temperature was measured using a hand-held infrared thermometer (Model: Fluke- 59MAX+, USA). The field view of the thermometer was 4º and the instrument was held at an angle of 45º and at a 50 cm height from the crop canopy as to minimize the influence of background soil surface on canopy temperature measurement. About 5 measurements were taken from each plot on each day were taken at

each phenological stage. Canopy temperature depression (CTD) was calculated by subtracting the value of canopy temperature (T_c) from air temperature (T_a) Jackson *et al.,* 1981[27].

Relative leaf water content (RLWC) was determined following the procedure of Barrs and Weatherley (1962) [28] using fresh weight (F_w) and turgid weight (T_w) of leaf samples. The leaves were oven-dried at 80 ± 1°C, until a constant weight was reached to determine the dry weight (D_w). The RLWC (%) was computed as:

$$\text{RLWC} = \frac{F_w - D_w}{T_w - D_w} \times 100 \quad \text{(eq. 3)}$$

Leaf chlorophyll concentration was quantified using 10-15 fully expanded leaves, collected from each plot. Leaf pigments were extracted in 10 ml of 95% (v/v) ethanol, and the absorbance of the extract was measured at 645 nm and 663 nm using a spectrophotometer, following Arnon (1949) [29]. The total chlorophyll content (mg g^{-1} fresh weight) was calculated using:

$$\text{Leaf chlorophyll} = [(20.2 \times A_{645}) + (8.02 \times A_{663})] \times V/1000 \times W \quad \text{(eq. 4)}$$

where A denotes absorbance at the respective wavelengths, V is the final volume of chlorophyll extract in 95% (v/v) ethanol (ml), and W is the fresh weight of leaves (g). Leaf proline content was estimated following the aqueous sulfosalicylic acid extraction method described by Bates et al., (1973) [30]. Leaf area was measured using a leaf area meter (LI-3100C, LI-COR, USA), and the leaf area index (LAI) was calculated according to Daughtry (1990) [31] as:

$$\text{LAI} = \frac{(\text{Measured leafarea/plant}) \times \text{no.of plants}}{\text{Ground area (m2)}} \quad \text{(eq. 5)}$$

Catalase activity (CAT; EC 1.11.1.6) was assayed spectrophotometrically by monitoring the decomposition of hydrogen peroxide (H_2O_2) following the method of Aebi (1984) [32] with minor modifications. Briefly, fresh leaf tissue (0.5 g) was homogenized in 5 mL of ice-cold extraction buffer (50 mM potassium phosphate buffer, pH 7.0) containing 1 mM EDTA and 1% (w/v) polyvinylpyrrolidone (PVP). The homogenate was centrifuged at 12,000 × g for 15 min at 4°C and the supernatant was used as enzyme extract. The decrease in absorbance was recorded at 240 nm for 1 min. Catalase activity was calculated using the extinction coefficient of H_2O_2 (ε = 39.4 mM^{-1} cm^{-1}) and expressed as µmol H_2O_2 decomposed min^{-1} g^{-1} fresh weight. The photosynthetic rate (µmol m^{-2} s^{-1}) and stomatal conductance (mmol m^{-2} s^{-1}) were measured at different phenophases of field pea using a portable photosynthesis system (CI-340, CID Bio-Science Inc., USA). Observations were recorded on five uppermost fully expanded leaves per slot under clear sky conditions between 11.00 and 12.30 h, following the method of Syuhada et al., (2014) [33]. Pollen viability was assessed using acetocarmine staining, and the

proportion of viable pollen was expressed as a percentage. Pollen germination was evaluated in vitro following Niles and Quesenberry (1992) [34]. Freshly dehisced flowers (collected from 10 plants per plot between 06.00 and 07.00 h) were used. Pollen grains from five randomly selected flowers were dusted onto glass slides coated with germination medium. The slides were incubated at 24°C (ambient) and 32°C under dark conditions. A pollen grain was considered germinated when the pollen tube length equalled or exceeded the grain diameter. Random counts were made in three microscopic fields (10× magnification) at 30-minute intervals up to 90 minutes, when germination reached its maximum. The percentage pollen germination was calculated as:

$$\text{Germination (\%)} = \frac{\text{Number of germinated pollen per field}}{\text{Total number of pollen per field}} \times 100 \quad \text{(eq. 6)}$$

Boron concentration in plant tissues was analysed using the azomethine-H colorimetric method following dry ashing, as outlined by Berger and Troug (1939) [35].

Estimation of yield, yield attributes and economics

At physiological maturity of field pea, five representative plants were randomly selected from the net plot area in each treatment replicate. All pods present on each sampled plants were counted manually, and the mean number of pods per plant was computed and expressed as pods plant^{-1}. From the same sampled plants, a random sample of 20 pods was collected at harvest. The pods were manually opened and the number of seeds in each pod was counted. The average number of seeds per pod was calculated and expressed as seeds pod^{-1}. Grain yield was recorded from the net harvested plot area and standardized to 12% moisture content, expressed in kilograms per hectare (kg ha^{-1}). A comprehensive economic assessment of the management practices was undertaken to evaluate their profitability. The analysis considered the cost of cultivation, gross returns, net returns, and the benefit–cost (B:C) ratio for each treatment combination. The yield data (kg ha^{-1}) obtained from the experimental plots were used to estimate gross monetary returns, assuming a market price of ₹ 6,500 per quintal (₹ 65 per kg) for field pea. The base cost of cultivation, excluding foliar boron treatments, was estimated using prevailing regional production costs for field pea under Eastern Indian conditions. The total cost of cultivation for each treatment was computed by adding the base cost, the cost of boric acid (calculated according to concentration and spray volume), and the labour/application charges. Gross return was obtained by multiplying the yield with the market price, while net return was determined by subtracting the total cultivation cost from the gross return. Finally, the benefit–cost ratio (B:C) was calculated as:

$$\text{B:C ratio} = \frac{\text{Gross return}}{\text{Total cost of cultivation}} \quad \text{(eq. 7)}$$

Statistical analysis

Data were analysed for split-plot design, with sowing dates assigned to main plots and foliar boron treatments to subplots, using GenStat software (Version 16.0). The analysis of variance (ANOVA) was conducted to assess the main and interactive effects of sowing time and foliar boric acid application on various response parameters. Initially, individual-year ANOVA was performed to obtain the error mean squares (EMS) for each variable. The homogeneity of error variances between years was examined using an F-test. Subsequently, a combined mixed-model ANOVA was carried out, considering year as a random factor, while sowing date (S) and boron treatment (B) were treated as fixed factors. Data from both years were pooled and presented as overall means as described by Gomez and Gomez (1984) [36]. Treatment mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at 5% level of significance ($p < 0.05$). To explore multivariate relationships among physiological and yield attributes, principal component analysis (PCA) was computed using the correlation matrix. Trait loadings (factor loadings) and treatment scores were obtained for the first two components (PC1 and PC2). The proportion of total variance explained by each component was used to interpret the relative contribution of PC1 and PC2 in treatment discrimination and PC1-based ranking was used to compare overall treatment performance across sowing dates and boron levels. Principal component regression (PCR) was performed to predict grain yield using principal component scores derived from the standardized predictor traits. Grain yield (kg ha^{-1}) was used as the response variable, and PC scores were used as predictors. PCR model performance was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE). The significance of regression coefficients was tested at $p \leq 0.05$. Model adequacy was further assessed using an observed versus predicted yield plot. The PCA, PC1 ranking and PCR were performed using R statistical environment (Version 4.5.1).

Results

Soil moisture storage and crop phenology

Initially, the root zone soil moisture levels were below field capacity (132 mm) in both the cropping seasons, ranging from 122.2 mm (S1) to 94.2 mm (S4) in 2017-18, and 128.3 mm (S1) to 100.8 mm (S4) in 2018-19 (Fig. 2). Progressive decline in root zone soil moisture storage was observed with advancement of crop growth period. The total soil moisture depletion from sowing to 50% pod formation ranged from 45.5% (S1) to 40.8% (S4) in 2017-18; while in 2018-19, it ranged from 52.3% (S1) to 44.8% (S4). The most rapid depletion of

root zone soil moisture was observed between peak vegetative and peak flowering stage. The S1 and S2 maintained root zone soil moisture above critical moisture content ($\theta_C \approx 98$ mm) throughout the flowering stage, thereby avoiding mid-season soil moisture stress, whereas the root zone moisture content of S3 and S4 fall below θ_C, 15 days earlier and remained under soil moisture stress until harvest. The S3 and S4 consistently demonstrated faster and greater depletion of root zone soil moisture (~20-30% higher as compared to S1, S2), indicative of reduced water availability during critical growth phases. Foliar application of B in the form of boric acid did not exhibit any significant influence on root zone soil moisture storage.

The different phenophase durations of field pea in this study was significantly influenced by date of sowing across both 2017-18 and 2018-19, whereas the effect of foliar B application was minimal (Fig. 3 a-b). Early sowing (S1: 10 November and S2: 20 November) consistently maintained extended durations for each phenological stage and overall crop maturity as compared to delayed sowing (S3: 30 November and S4: 10 December). For instance, total crop duration from sowing to maturity ranged from 95-98 days for S1 and S2 2017-18 cropping season, while it ranged between 80-84 days for S3 and S4. Similarly, in 2018-19 cropping season, total crop duration varied from 94-97 days in early sowing to 78-83 days in case of delayed sowing. The reproductive phases (flower initiation, 50% flowering, 50% pod formation) also demonstrated an overall reduction by 5-7 days under delayed sown treatments compared to early sown treatments, across the two cropping seasons. Foliar B application twice (at pre-flowering and pod initiation), showed no significant effect on phenological progression of field pea across sowing dates and cropping seasons.

Plant water status and stress indicators

The plant water status and stress-related indicators of field pea, namely CTD, RLWC, proline content, and catalase activity were significantly influenced by date of sowing, crop growth stage and foliar boron application (Fig. 4.a-e). The extent of variation was consistently greater across sowing dates as compared to foliar boron levels, with reproductive stages exhibiting the strongest responses. The RLWC showed a clear decline with delayed sowing (Fig. 4.c). At peak vegetative stage, under early sowing (S1 and S2), RLWC ranged from 75-78%, while under delayed sowing (S3 and S4), it ranged from 67-70% (CI 95%). At 50% flowering stage, RLWC increased across all treatments, reaching 82-88% under S1 and S2, whereas delayed sowing maintained lower values (70-75% under S3 and 58-62% under S4) ($p < 0.05$). At 50% pod formation stage, RLWC declined sharply, particularly under delayed sowing, as S4 recorded ~20-25% decline as compared to S1. Foliar B application influenced RLWC, within each sowing date. Higher B levels (B3 and B4), consistently maintained 3-6%

higher RLWC as compared to B1 and B2, specifically at 50% flowering and 50% pod formation stage. The CTD also showed complementary trends to RLWC (Fig. 4. a-b). During peak vegetative period, CTD values were relatively small and negative across treatments, ranging from -0.3 to -0.8°C. At 50% flowering stage, CTD was markedly more negative, particularly under early sowing, with S1 and S2 recording values of -3.5 to -4.5°C, as compared to -2.0 to -2.8°C under S3 and -1.5 to -2.2°C under S4. These values represented a 35-45% reduction in canopy cooling under delayed sowing condition. Furthermore, at 50% pod formation stage, CTD values reached up to zero or became slightly positive under S3 and S4. Moreover, within each sowing date, foliar B application enhanced canopy cooling, with B3 and B4 recording nearly 0.4-0.8°C more negative CTD as compared to B1 and B2, specifically at 50% flowering and 50% pod formation stage.

Proline accumulation exhibited a significant increase with crop advancement as well as delayed sowing (Fig. 4.d). At peak vegetative stage, proline content remained low across treatments (≈1.2–1.5 μg g^{-1}). At 50% flowering, lowest proline levels were recorded in S1B3 and S1B4 treatments, whereas, the highest was recorded in case of S4B2 and S4B4, reflecting an overall increase of 28-30% under delayed sowing conditions. Although, foliar B application reduced proline accumulation under late sowing condition (~5.4% reduction under S3), S4 maintained elevated levels of proline content (~7.01–7.04 μg g^{-1}) across foliar B levels. Similarly, at 50% flowering and 50% pod formation stages, catalase activity was 40-60% ($p < 0.05$) higher under S3 and S4 as compared to S1 and S2 (Fig. 4.e). Foliar B application also significantly influenced catalase activity, with higher B levels (B3 and B4) consistently maintained 15-30% higher catalase activity as compared to B1 and B2, across all growth stages. Particularly under delayed sowing, stimulatory effect of B on catalase activity was more pronounced at 50% flowering and 50% pod formation stages.

Photosynthetic traits

The extent of variation of photosynthetic capacity of field pea was consistently higher across sowing dates as compared to foliar B levels with strongest response was exhibited during the reproductive stages (Fig. 5. a-c). Across treatments, leaf chlorophyll content was lowest at peak vegetative stage and increased markedly at 50% flowering stage, followed by a steady decline at 50% pod formation stage (Fig. 5.a). Early sowing (S1 and S2) consistently recorded higher chlorophyll content than delayed sowing (S3 and S4) at all the growth stages. At 50% flowering, leaf chlorophyll content under S1 and S2 was roughly 15-25% higher as compared to S3 and nearly 25-35% higher as compared to S4. Foliar B application also enhanced leaf chlorophyll content within each sowing date, with B3 and B4 maintaining higher leaf

chlorophyll content as compared to B1 and B2 across all sowing dates, particularly at 50% flowering and 50% pod formation stages. Photosynthetic rate also exhibited similar pattern closely aligned with leaf chlorophyll content and growth stage (Fig. 5.a). Early sowing during 10-20 November (S1 and S2) recorded the highest photosynthetic rates, reaching nearly 14–16 μmol m^{-2} s^{-1} at 50% flowering. A reduction in photosynthetic rate was observed under delayed sowing (30-45% under S3 and 45-55% under S4). Foliar B application, within each sowing date, resulted in higher photosynthetic rate, with B3 and B4 maintaining 8-15% higher photosynthetic rate as compared to B1 and B2, particularly during 50% flowering stage. Under delayed sowing, foliar B application improved photosynthetic rate of field pea by 26.3-43.4%, as compared to their respective controls. In case of LAI, early sowing (S1 and S2) recorded significantly LAI, with maximum values reaching up to 1.3-1.5, observed during 50% pod formation stage (Fig. 5.b). On the contrary, delayed sowing resulted in 30-50% reduction in LAI relative to the early sown crop. Foliar B application increased LAI, with B3 and B4 consistently produced 5-12% higher LAI as compared to B1 and B2 across sowing dates and field pea growth stages ($p < 0.05$). Notably, B application increased 13-19% LAI (CI 95%) under delayed sowing as compared to their respective controls ($p < 0.05$). Stomatal conductance peaked at 50% flowering stage and progressively declined during 50% pod formation stage (Fig. 5.c), with early sowing (S1 and S2) maintained 25-40% higher stomatal conductance in comparison to delayed sowing (S3 and S4). Foliar B application significantly enhanced stomatal conductance, particularly at 50% flowering and 50% pod formation stages.

Reproductive traits

The reproductive performance of field pea was evaluated through pollen germination, pollen viability and plant B content (Table 2). Delayed sowing significantly reduced plant B content, across seasons. The S1 and S2 recorded the highest plant B content (4.05 ppm and 3.86 ppm, respectively), whereas S3 and S4 recorded significantly lower values (3.39 ppm and 2.93 ppm respectively), representing nearly 28% reduction in plant B content under S4 as compared to S1. Pollen viability was also strongly affected by sowing date, with 22% reduction in pollen viability with delayed sowing. Foliar B application also significantly improved pollen viability across sowing dates, with increasing from 72.3% under B1 to 83.2-83.1% under B3 and B4, resulting in an overall 15-16% increment. The non significance of sowing time × boron interaction for pollen viability indicating consistent B response across sowing dates. Similarly, early sowing (S1 and S2) recorded significantly higher pollen germination (89.2% and 88.7%, respectively), whereas delayed sowing resulted in significant decrease under S3 (78.1%) and S4 (64.6%). Pollen germination declined by approximately 27% under S4 as compared to S1.

Foliar B application significantly enhanced pollen germination, with pooled values increasing from 73.9% under B1 to 84.3-84.4% under B3 and B4, corresponding to an improvement of ~14%. Similarly to pollen viability, the interaction between sowing date and boron was also non-significant for pollen germination.

Yield and yield attributes

Delayed sowing caused a substantial decrease in yield attributes and grain yield. Pods plant^{-1} declined by 29-40% under S3 to S4 compared with S2. Also, seeds pod^{-1} decreased by 33% in S4 compared with S2. Consequently, grain yield declined with delayed sowing. The highest grain yield was recorded under S2 (1490 kg ha^{-1}), while yield decreased to 1159 kg ha^{-1} under S3 and 791 kg ha^{-1} under S4, corresponding to yield decrements of approximately 22% (S3) and 47% (S4) relative to S2. Foliar boron application significantly improved yield attributes and grain yield as compared to the control. Grain yield increased progressively from B1 to B3, with B3 recorded an approximate 25% yield advantage over B1.

Economics

Sowing time and foliar boron levels significantly influenced the economic performance of field pea, with a significant S × B interaction. The cost of cultivation increased slightly with boron application (₹45,000–48,450 ha^{-1}), but the enhanced returns offset the added cost. Gross return varied from ₹41,410 ha^{-1} under late sowing without B (S4B1) to ₹1,02,283 ha^{-1} under S2B3. Correspondingly, net return ranged from ₹3,591 to ₹53,983 ha^{-1}, and the B:C ratio from 0.92 to 2.12. Early sowing (S1 and S2) combined with 0.2% boron (B3) consistently achieved the highest profitability, with 25–40% greater returns than late sowings (S3 and S4). The S2B3 treatment recorded the highest economic efficiency (B:C, 2.12), while late sowing (S3 and S4) markedly reduced profitability due to lower yield and shorter crop duration.

Multivariate trait integration and yield prediction (PCA and PCR)

In PCA, the first two principal components explained 90.6% of the total variation among treatments, with PC1 accounting for 82.9% and PC2 for 7.7% (Fig. 6). In the biplot, soil moisture storage, RLWC, chlorophyll content, stomatal conductance, photosynthetic rate, LAI, plant B content, pollen viability, pollen germination, pods plant^{-1}, seeds pod^{-1} and grain yield showed vectors oriented in a similar direction along PC1, indicating their close association in explaining treatment-wise variation (Table 6). In contrast, CTD and catalase vectors were oriented in the opposite direction along PC1, reflecting an inverse pattern of variation relative to above trait group. Proline was primarily aligned with PC2, suggesting that it contributed mainly to the secondary axis of variation. Treatment scores were separated predominantly

along PC1, with early sowing treatments (S1 and S2) grouped towards the positive side of PC1, whereas delayed sowing treatments (S3 and S4) were shifted towards the negative side. Within each sowing window, higher boron levels (B3 and B4) were generally positioned closer to the positive PC1 direction compared with B1 and B2, indicating a consistent shift in multivariate trait expression under foliar B application.

Further, PC1 scores were also used to rank various sowing time and foliar B combination treatments (Fig. 7). The highest PC1 score were recorded under S2B4 (4.19) and S2B3(4.14), whereas all treatment combinations involving S3and S4 recorded negative PC1 scores, with the lowest values recorded under S4B1 (-6.12) and S4B2 (-5.66). Principal component regression was fitted with grain yield as the dependent variable and PC scores as predictors (Fig. 8; Table 5). In PCR model, PC1 was significant ($p<0.001$), while PC2 was non-significant. The fitted model produced $R^2 = 0.931$ with RMSE = 76.9 kg ha^{-1}. The observed versus predicted yield plot showed close correspondence of data points with the fitted regression line and the 1:1 reference line.

Discussions

Soil moisture dynamics and field pea physiological response under rice fallows

Root zone soil moisture storage is a key determinant of crop water availability under rainfed conditions. In Eastern India, the short winter growing season transitions rapidly into a hot, dry summer, leading to high evaporative demand and accelerated moisture loss (Ghosh et al., 2016[13]). Early sowing leverages higher initial soil moisture and extends the period of water availability, whereas delayed sowing suffers from low initial moisture and rapid depletion, limiting water supply during critical growth phases (Saha et al., 2021[15]). In this study, early sowing (10-20 November) maintained superior root zone soil moisture storage throughout the crop cycle, while delayed sowing (30 November to 10 December) experienced substantial losses, particularly during reproductive stages. Notably, in S4, root zone moisture fell below critical levels ($< \Theta_c$) well before flowering, signalling early onset of physiological stress that constrained vegetative growth and reproductive development. This aligns with observations by Allen et al., (1998) [26], who reported that in delayed sowing, moisture depletion often exceeds 50% of available water before peak flowering, critically limiting yield potential. In contrast, early sowing had more gradual depletion, supporting sustained growth and yield. It reinforces the recommendation for early sowing as a critical strategy to mitigate drought risk in rainfed ecologies (Gunes et al., 2007[37]; Bandyopadhyay et al., 2016[18]). Importantly, foliar B application in the form of boric acid had no significant impact on root zone soil moisture storage, indicating that while boron enhances physiological traits, it does not alter soil water

dynamics under field conditions. The negligible variation in soil moisture storage observed across B levels may be attributed to treatment-induced differences in crop canopy development and water use under favourable moisture availability (Kaya et al., 2009[38]). However, these differences were inconsequential compared to the dominant effect of sowing date on soil water availability. Early sowing (S1 and S2) increased the vegetative period and prolonged both flowering and pod-development stages, enlarging the window for biomass accumulation and reproductive success. Late sowing (S3 and S4) decreased these phases resulted in accelerated thermal accumulation and plant development, curtailing vegetative growth as well as reproductive duration (Rathore et al., 2022[16]; Sharma et al., 2023[39]). This truncation reduces the assimilate pool available for pod set and grain filling, thereby suppressing yield (Tripathi et al., 2023[14]). Early sown treatments (S1 and S2) experienced prolonged vegetative phase of approximately 25-30 days, as compared to 18-23 days under delayed sowing (S3 and S4). The reduction in crop duration due to delayed sowing was majorly attributed to shortening of vegetative phase (emergence to peak vegetative stage) as well as reproductive phase (flower initiation to pod maturity).

The RLWC declined significantly with delayed sowing, with the lowest values recorded in S4B1 (late sowing with no boric acid application). Late sowing (S3 and S4) exposed the crop to terminal moisture and thermal stress, resulting in a steep decline in RLWC (Sharma et al., 2023[39]). Foliar B application substantially improved RLWC across all sowing dates, with greater relative increases observed under late-sown conditions. The improvement in leaf water status under B application has also been reported earlier and is often attributed with improved membrane integrity and reduced stress-induced injury (Wimmer and Eichert, 2013[40]). Alongside RLWC, CTD also captures canopy thermal regulation under variable moisture availability. The canopy temperature-based indices have been widely accepted as integrative measure of actual crop water status as they reflect the combined influence of transpiration cooling and atmospheric evaporative demand under field conditions (Jackson *et al.,* 1981[27]; Blum, 2009[41]). The significant reduction in canopy cooling under delayed sowing coincided with lower RLWC and early crossing of the critical moisture threshold, showcasing the rapid progression of terminal stress during the reproductive phases in late sown field pea. This CTD response was also reflected in stomatal conductance, which declined sharply under delayed sowing condition, especially during reproductive stages of field pea. Reduced stomatal conductance under drought and heat stress is a common defence mechanism that impairs transpiration cooling and CO_2 diffusion, also contributing to reduced photosynthetic activity under stress environments (Flexas et al., 2004[42]). Foliar application of B, in this present study,

improved stomatal conductance, across sowing windows, likely through better maintenance of leaf physiological activity under stress (Wimmer and Eichert, 2013[40]). Thus, the combined response of RLWC, CTD and stomata conductance indicates that B application improved plant water status and sustained gas exchange, especially under stress-prone sowing windows (S3 and S4).

In present study, the osmotic and oxidative stress markers further clarified responses of field pea in various sowing windows induced terminal stress. For instance, proline content increased sharply under delayed sowing, reflecting higher osmotic stress under late-sown conditions (S3 and S4), as also reported by Ashraf and Foolad (2007) [43], who emphasized proline protective role in maintaining enzyme activity, stabilizing proteins, and scavenging free radicals during stress. Boron application led to a moderate yet consistent reduction in proline levels, particularly under late sowing. The applied B might down-regulate proline biosynthesis by maintaining NADPH balance and reducing reactive oxygen species (ROS) accumulation through enhanced antioxidant enzyme activities (Naeem et al., 2018[44]). Furthermore, catalase activity also showed marked increase with delayed sowing, while foliar B application at higher levels further enhanced catalase activity, particularly during 50% flowering and 50% pod formation stages. Catalase is a key antioxidant enzyme involved in scavenging H_2O_2, and its enhanced activity under delayed sowing is consistent with higher oxidative stress under terminal moisture stress (Gill and Tuteja, 2010[45], Hasanuzzaman et al., 2012[46]). The differential response under foliar B application indicating contrasting regulation of osmotic and antioxidative markers under stress. The increase in catalase activity with B supplementation suggests B-mediated strengthening of antioxidant defence pathways, consistent with earlier studies, that highlights B nutrition modulates antioxidant systems and improves cellular protection against oxidative damage under abiotic stress (Camacho-Cristóbal et al., 2008[47]). Thus, under delayed sowing condition, foliar B application simultaneously impaired excessive proline accumulation while stimulating catalase activity, contributing to better maintenance of physiological functioning, especially during reproductive stages.

The combined effects of water status, stomatal behaviour and antioxidative regulation were expressed through canopy development and photosynthetic capacity. In this study, LAI was significantly affected by sowing date, with early sowing (S1 and S2) promoting higher values across all stages. Whereas, the decline under delayed sowing is likely due to early onset of water stress, restricted cell expansion, and lower photosynthetic assimilation, all of which reduce canopy development (Flexas et al., 2004[42]). Chlorophyll content and photosynthetic rate, two interdependent physiological parameters, are central to carbon assimilation and crop

productivity. Early sowing (S1 and S2) supported higher chlorophyll concentrations and photosynthetic activity, whereas late sowing (S3 and S4) led to sharp declines in both, particularly during flowering and pod formation stages, as terminal soil water stress leads to degradation of synthesized chlorophyll and also inhibits the synthesis of new chlorophyll pigments (Mathobo et al., 2017[48]). The decline in photosynthetic rate under delayed sown condition, underlines the compounded effects of heat and moisture stress on stomatal conductance, chloroplast stability, and Rubisco activity. These findings align with earlier studies that documented similar impairments under late sowing and boron-deficient conditions (Nayyar and Gupta, 2006[49]; Mandal et al., 2021[50]). Foliar application of B significantly enhanced both chlorophyll content and photosynthetic rate under all sowing dates. This could be because of boron-mediated stabilization of thylakoid membranes, increased chlorophyll synthesis, and improved nutrient mobility resulting in higher functional integrity of photosystems under stress (Rerkasem and Jamjod, 2004[51]). It also facilitates phloem loading and carbohydrate translocation by forming borate–sugar complexes, which sustain photosynthetic activity by relieving feedback inhibition (Brown et al., 2002[52]). The improved photosynthetic performance under B application, particularly in stress-prone sowing windows, not only reflects enhanced physiological resilience but also directly translates into improved biomass accumulation and grain yield.

Reproductive physiology and sink formation

Pollen viability, a crucial determinant of reproductive success, was significantly reduced under delayed sowing (S3 and S4), likely due to high temperature and moisture stress during the critical gametogenesis phase. Drought and nutrient imbalances impair anther development, inhibit pollen formation, and reduce carbohydrate supply to reproductive tissues (Goldbach et al., 2001[20]). Boron supplementation in the form of boric acid, particularly at 0.2–0.3% foliar concentration, significantly improved pollen traits. This positive response is attributed to boron's role in pollen cell wall structure, callose deposition, pollen tube growth, and reproductive tissue integrity (Wimmer et al., 2015[21]). Boron also maintains plasma membrane stability and regulates Ca^{2+} flux, both of which are crucial for pollen tube guidance and fertilization. Moreover, boron facilitates the synthesis and translocation of sucrose and polyols by forming borate–sugar complexes, thereby improving carbohydrate allocation to anthers and developing pollen grains. This enhanced sugar availability ensures sufficient osmotic potential for pollen hydration and germination, improving pollen viability even under mild water stress (Stangoulis et al., 2010[53]; Saleem, 2011[54]). The observed strong correlations between plant B concentration and pollen viability ($R^2 = 0.74$, $p<0.001$, Fig. 9a) suggest a

physiological continuum wherein boron not only supports vegetative vigour but also reproductive precision. Consequently, B-treated plants sustain higher pollen germination rates, efficient fertilization, and better pod set under stress-prone sowing environments. Plant boron content also varied markedly with both sowing date and foliar application level of boric acid. Early sowing promoted greater boron uptake due to longer growth duration, better root development, and higher soil moisture availability during initial growth stages. In contrast, late sowing led to significant reductions in tissue B content (as low as 2.93 ppm in S4), likely due to limited boron mobility in dry soils and shortened uptake windows (Goldbach et al., 2001[20]).

Improved pollen viability and germination under boron supply were also accompanied by significant increase in yield components, particularly pods plant^{-1} and seed pod^{-1}, which together represent key sink establishment traits in grain legumes. In case of field pea, pod number is widely recognized as the most plastic yield component and is substantially influenced by reproductive success and stress exposure during flowering, while seed pod^{-1} is mainly governed by fertilization efficiency and early seed development (Sadras 2007[55]). Under delayed sowing (S3 and S4), decline in pollen viability and germination combined with terminal moisture stress coincided with significant reductions in pods plant^{-1} and seed pod^{-1} resulting in a marked yield penalty. Similar reductions in pod set and seed number under late sowing or terminal moisture stress condition have also been reported in pea and other cool season legumes, where stress during flowering significantly increased pod abortion and ultimately reduces seed set (Siddique et al., 2001[56]). Foliar B application significantly improved sink formation associated with improved pollen traits, across sowing windows. Notably, the response in pods plant^{-1} and seed pod^{-1} showed a plateau at higher levels, with B3 (0.2%) and B4 (0.3%) remains statistically at par, indicating that boron requirement for reproductive improvement was largely met at the B3 (0.2%) level under the present condition. Overall, these results demonstrate that timely sowing combined with appropriate boron supplementation improves reproductive functioning and sink establishment in field pea under rice-fallow environments, primarily through improved pollen performance and better realization of yield components, particularly pod number and seed set.

Yield, economics and multivariate trait integration

Early sowing, particularly on 20th November (S2)**,** produced the highest seed yield (up to 1574 kg ha^{-1} in S2B3), while delayed sowing (S3 and S4) resulted in reductions of 20–46%. This decline was primarily attributed to reduced soil moisture availability, shorter reproductive duration, and higher physiological stress during critical growth stages, conditions that impaired assimilate production and translocation (Tripathi et al., 2023[14]; Slafer et al., 2014[57]). However,

foliar boron application, especially boric acid 0.2% (B3), significantly enhanced biomass production by supporting photosynthetic efficiency, leaf area development, and overall plant vigour under stress-prone conditions (Ahmed et al., 2021[23]; Sharma et al., 2021[19]). Regression analysis further confirmed that seed yield was strongly influenced by pollen viability (R^2 = 0.8725, $p<0.001$) (Fig. 9b)**;** traits sensitive to both boron nutrition and environmental conditions (Kumar et al., 2022[10]; Tripathi et al., 2023[14]). The multivariate structure of trait variation was effectively captured through PCA, providing an integrated understanding of treatment-wise performance. The PCA biplot revealed a clear separation of treatments mainly along PC1, indicating that the primary driver of the majority of variation among date of sowing × boron combinations was coordinated shifts in physiological and reproductive traits. Traits such as RLWC, stomatal conductance, soil moisture storage, chlorophyll, photosynthetic rate, LAI, pollen viability, pollen germination, plant boron content, pods plant^{-1}, and seeds pod^{-1} were positioned along the same direction of PC1, reflecting their positive association (positive factor loading in PC1, Table 6) and synchronized enhancement under favourable management combinations. On the contrary, catalase and proline content were oriented in the opposite direction along PC1, showing a contrasting pattern as compared to the above-mentioned productivity-linked traits. Treatment positioning in PCA space clearly differentiated high-performing and low-performing combinations. Treatments belonging to S1 and S2 clustered on the positive side of PC1, whereas treatments under S3 and S4 were shifted towards the negative PC1 space, reflecting overall reduction in physiological and reproductive trait expression under delayed sowing. Foliar B application also produced a consistent shift in the treatment positions in the PCA biplot, with treatments having higher B levels (B3 and B4) moving towards the positive PC1 region. This shift indicated the closer relationship between foliar B nutrition and the yield linked trait cluster. The PC1 score-based ranking further supported this separation (Fig. 7), with the top-ranked treatments being S2B4 (PC1 = 4.19) and S2B3 (PC1 = 4.14), followed by S1B4 (PC1 = 3.83) and S1B3 (PC1 = 3.64). This PC1-based ordering provides a quantitative multivariate index of treatment performance, indicating that optimum sowing combined with foliar B supplementation consistently maximized the coordinated expression of key traits. To further link multivariate trait behaviour with yield, principal component regression was used to predict grain yield from PC scores (Fig. 8). The PCR model (grain yield = 1213.46 + 88.88×PC1) showed that PC1 was highly significant ($p<0.001$), conforming that yield variation across treatments was primarily driven by the trait complex represented along PC1. The model explained a large proportion of yield variability (R^2 = 0.931), and the observed versus predicted yield relationship showed strong agreement, indicating high predictive

reliability of the PC-based yield framework. Collectively, PCA and PCR demonstrate that treatment differences in yield were strongly aligned with PC1-driven multivariate shifts in water status, photosynthetic capacity, reproductive traits, and plant boron content, rather than isolated changes in individual traits.

Although most physiological parameters including RLWC, LAI, chlorophyll content, and photosynthetic rate; were either superior or statistically at par in both early sowing treatments (S1 and S2), seed yield was consistently higher in S2 across both years. This suggests that while S1 benefitted from higher initial soil moisture, the phenological alignment of S2 (20 November) with favourable temperature and moisture regimes during the reproductive stages likely enhanced assimilate partitioning and reproductive efficiency, resulting in superior yield performance. These observations align with the findings of Tripathi et al., (2023) [14] and Sharma et al., (2021) [19], who emphasized the importance of phenological synchronization in optimizing pulse crop productivity under rainfed conditions. Furthermore, in PCA, although the highest PC1 score was recorded in S2B4, closely followed by S2B3, yield and key physiological traits did not significantly differ between B3 (boric acid 0.2%) and B4 (boric acid 0.3%) treatments. This indicates a response plateau beyond 0.2% boric acid application, corroborating earlier reports that emphasize the sufficiency of 0.2% boric acid application for optimizing physiological and reproductive processes in legumes (Wimmer et al., 2015[21]). Early sowing not only maximized productivity but also economic efficiency, primarily due to better resource utilization and higher marketable yield. In contrast, late sowing (S4) coupled with no boron application (S4B1) resulted in the lowest economic returns (net return INR 3591 ha^{-1}) and B:C ratio below unity (0.92), indicating economic non-viability. Even with B application, late sowing treatments failed to break even, highlighting the inefficiency of delayed sowing under rainfed rice-fallow systems. Across boron levels, 0.2% boric acid (B3) consistently provided the best economic returns, suggesting that it is the most cost-effective dose. While 0.3% boric acid (B4) yielded comparable productivity, the slightly higher input cost did not result in a proportional gain in return, confirming a diminishing marginal return beyond the 0.2% threshold. Thus, from both agronomic and economic standpoints, sowing on 20 November coupled with foliar B application 0.2% (S2B3) as boric acid emerges as the optimal strategy for enhancing field pea productivity and profitability under rainfed rice fallows.

Conclusions

The present study demonstrates that interactions between sowing phenology and foliar boron application regulate physiological performance, reproductive processes, and grain yield formation of field pea under rainfed rice-fallow conditions. Early sowing, particularly around

mid-November (20 November), maintained higher root-zone soil moisture availability during critical developmental stages, which supported improved plant water status (RLWC and canopy temperature depression) and enhanced photosynthetic capacity, including higher chlorophyll content, photosynthetic rate, leaf area index, and stomatal conductance. These physiological advantages translated into improved reproductive competence, reflected in increased pollen viability and germination, and ultimately greater yield stability. Foliar boron application applied at pre-flowering and pod initiation stages further strengthened these responses by enhancing plant boron status and supporting reproductive functioning. The response plateau observed beyond 0.2% boric acid suggests that moderate foliar boron levels are sufficient to maximise physiological and reproductive benefits under the studied conditions. Multivariate analysis indicated that treatment differences were primarily structured along a physiological axis integrating soil moisture availability, plant water relations, photosynthetic traits, and reproductive performance, highlighting the coordinated nature of trait responses governing yield outcomes. The integrated management option S2B3 (20 November sowing + 0.2% boric acid) recorded the highest grain yield and profitability (net return ₹53,983 ha^{-1}; B:C ratio 2.12), and was consistently ranked among the best treatments in PC1-based multivariate performance. Thus, sowing field pea around 20 November with 0.2% foliar boric acid at pre-flowering and pod initiation optimizes water use, reproductive success, yield, and profitability under rainfed rice-fallow systems. Collectively, these findings suggest that synchronisation between crop phenology and residual soil moisture dynamics, combined with boron-mediated regulation of physiological and reproductive traits, plays a central role in determining productivity of field pea in water-limited rice-fallow environments. While the results are specific to the experimental site and seasons, they provide broader insight into how management-driven phenological alignment and micronutrient regulation can influence crop resilience in rainfed systems. Future research should evaluate multi-location and long-term responses, varietal interactions, and integration with additional climate-adaptive management strategies to further refine understanding of crop performance under variable environmental conditions.

Authorship contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Arpita Nalia, Subham Mukherjee, Ananya Ghosh, Hasim Reza and Rajib Nath. The first draft of the manuscript was written by Arpita Nalia and

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The datasets used and/or analysed during the current study available from the First and Corresponding authors on reasonable request.

Funding Information

The study was conducted as part of academic research activities at Bidhan Chandra Krishi Viswavidyalaya (BCKV) without external financial support.

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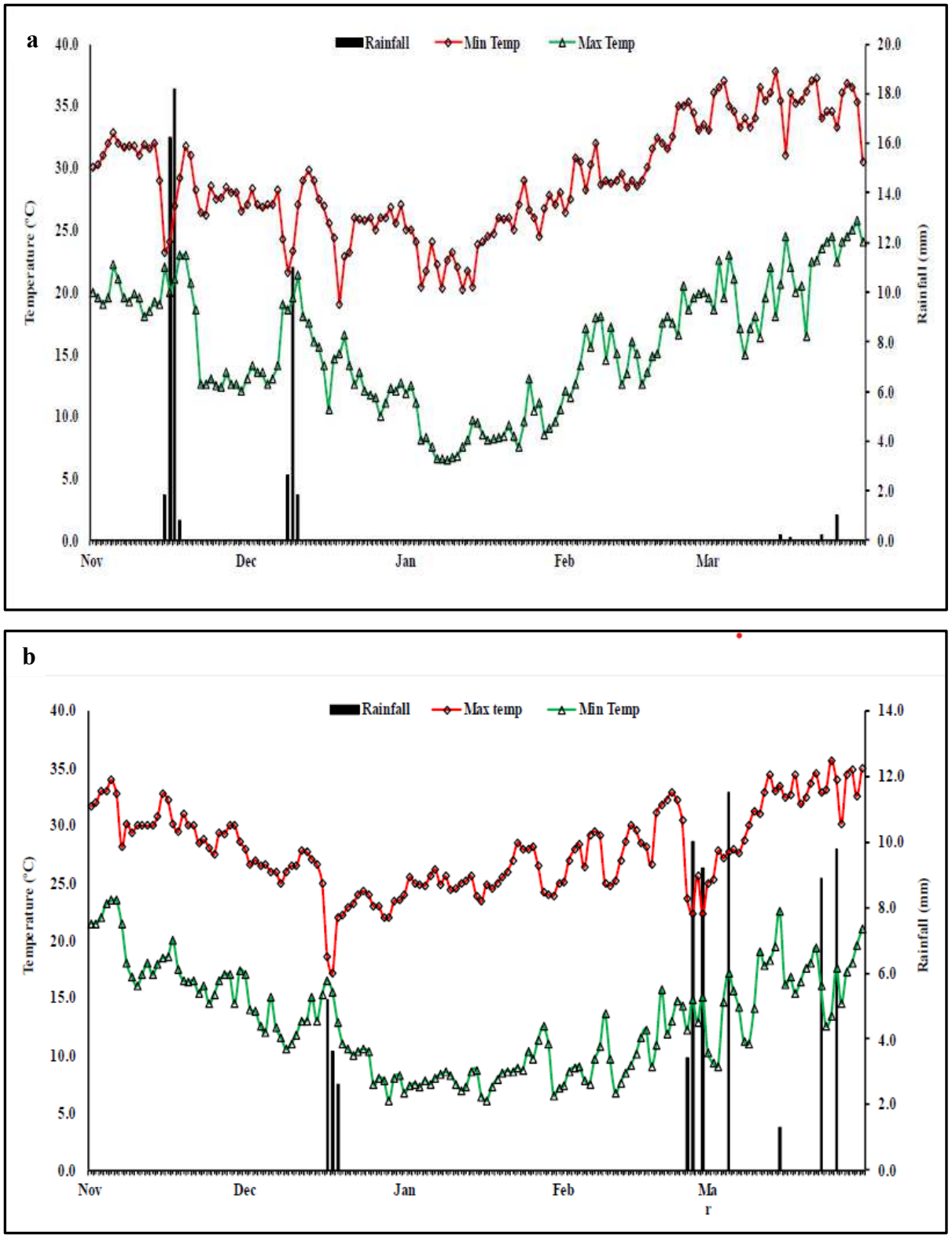


Fig. 1. Daily distribution of maximum, minimum temperature (ºC), and rainfall (mm) during the study periods of field pea growing seasons in 2017–18 (a) and 2018–19 (b).

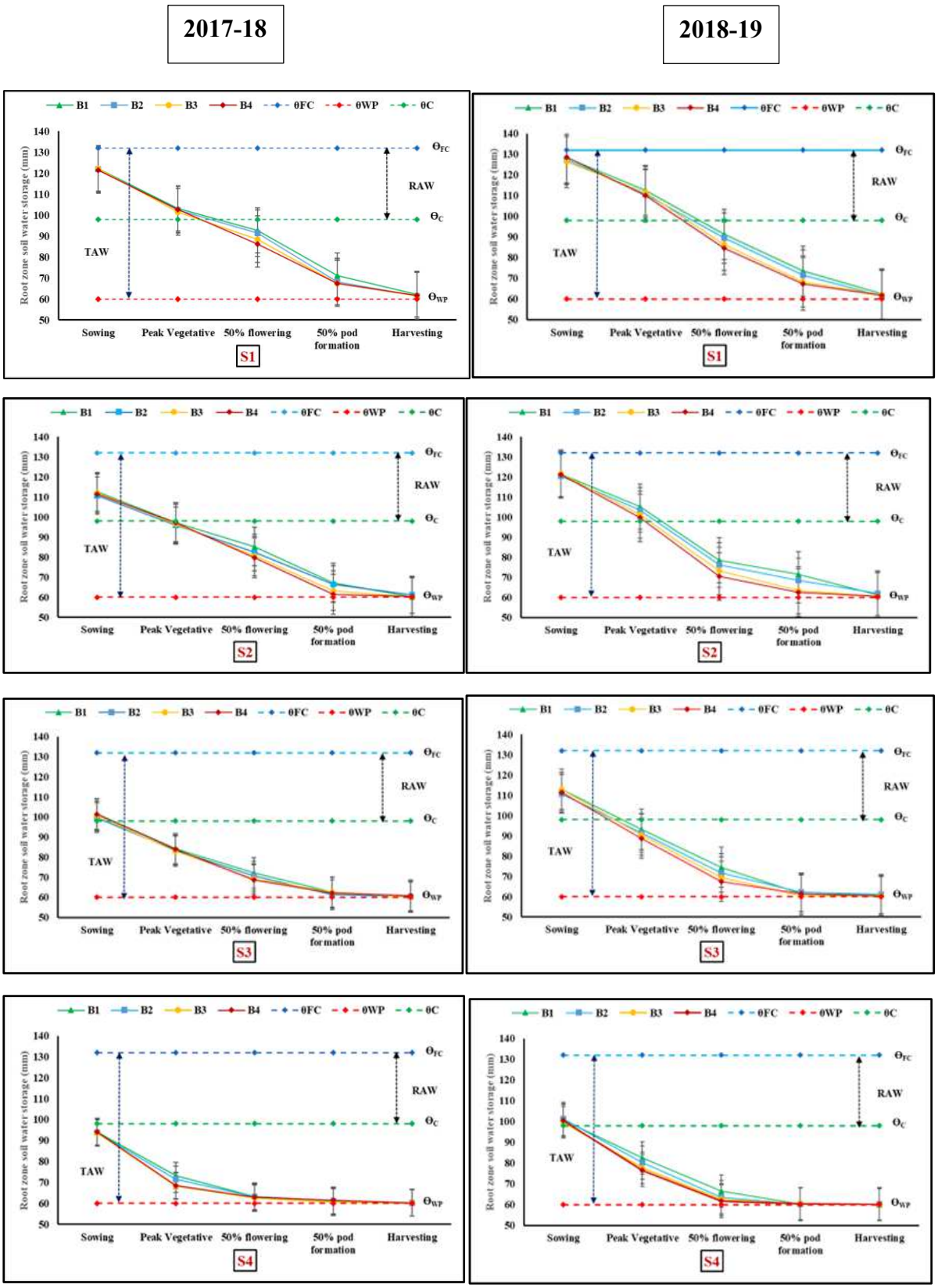


Fig. 2. Periodical soil moisture storage at different growth stages of field pea under different sowing time (S1, S2, S3 and S4) and foliar boron applications (B1, B2, B3 and B4) during the study period of 2017–18 and 2018–19; θ_{FC} = moisture storage (mm) at field capacity; θ_{WP} = moisture storage (mm) at wilting point; θ_C = critical soil moisture content; RAW = readily available water; TAW = total available water; S1 = 10 November, S2 = 20 November, S3 = 30 November and S4 = 10 December; B_1 = no boron spray, B_2 = 0.1% boric acid, B_3 = 0.2% boric acid, B_4 = 0.3% boric acid spray. Error bars represent standard error of mean.

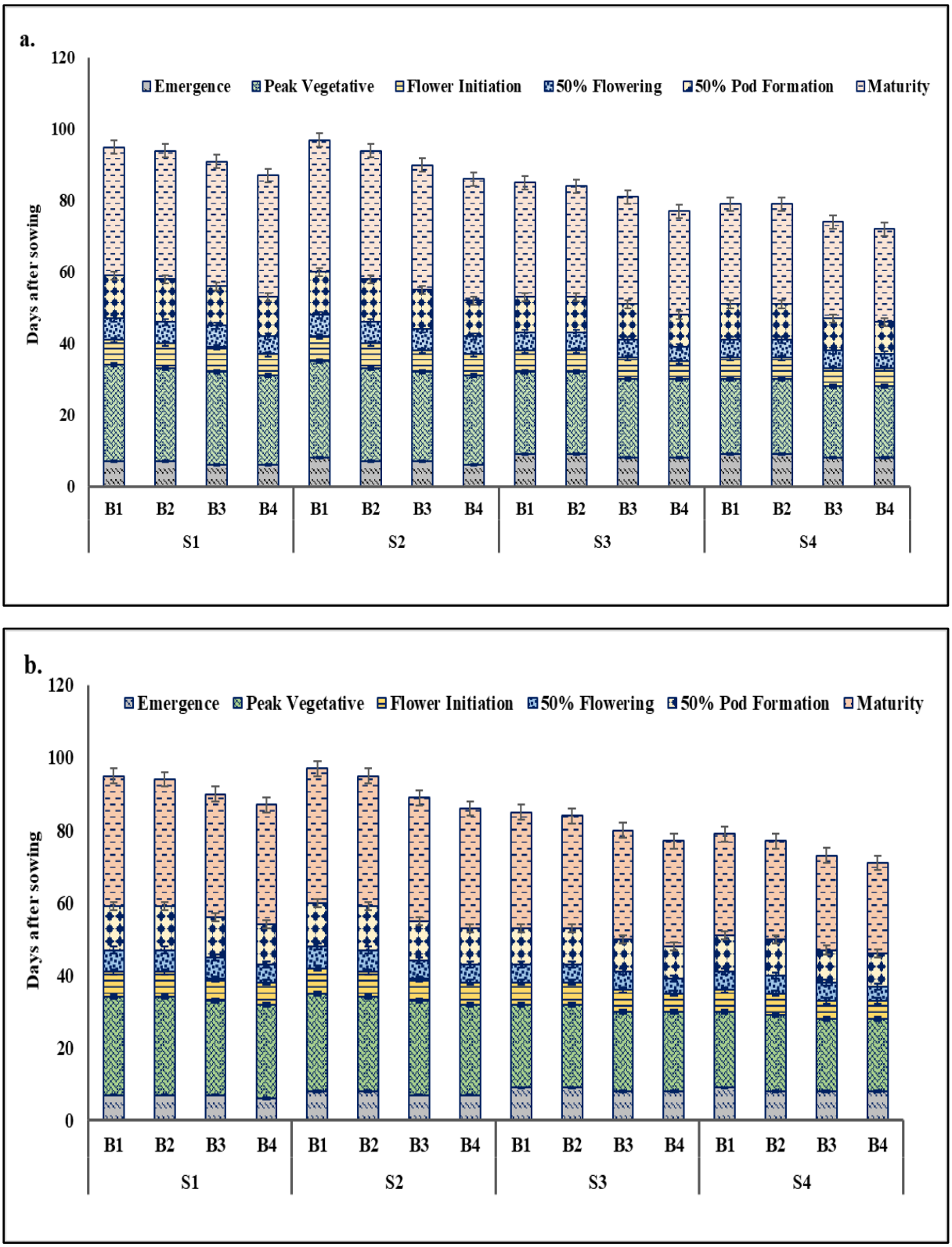
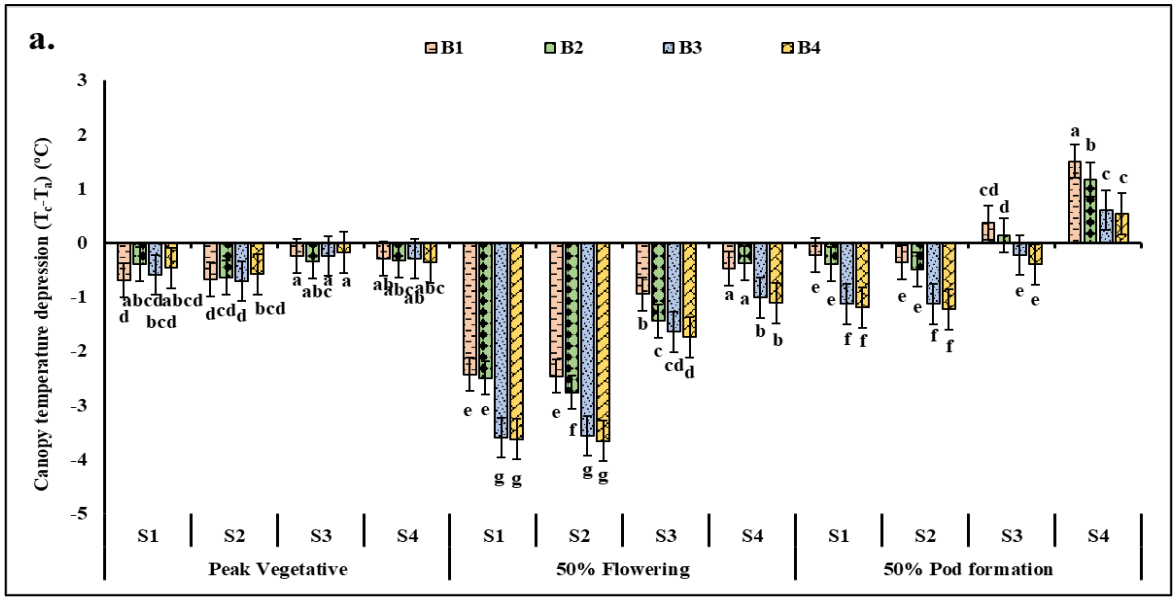
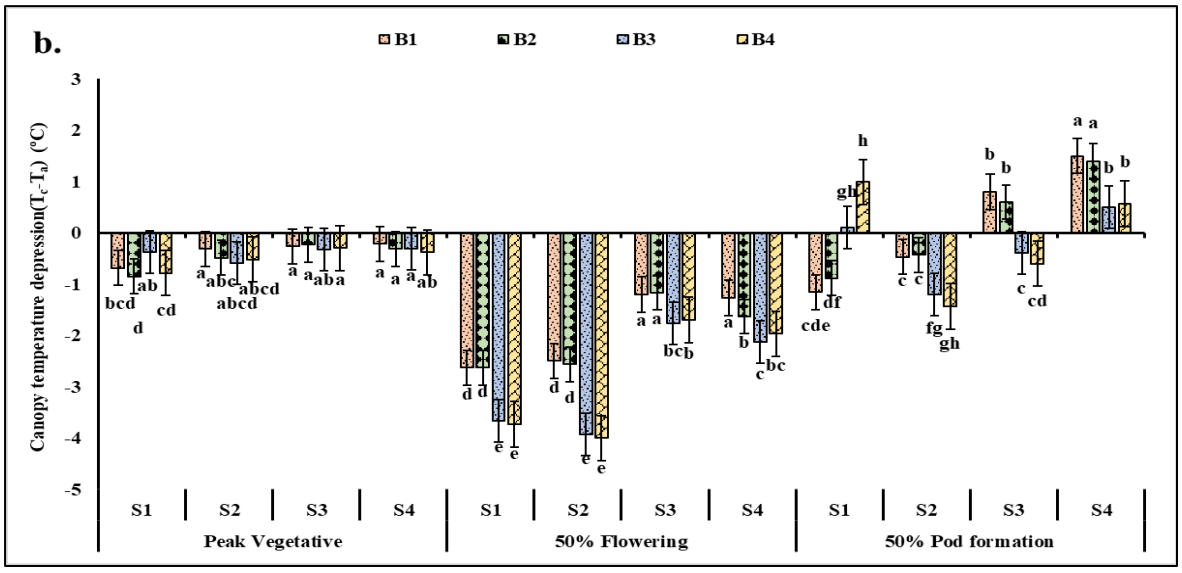
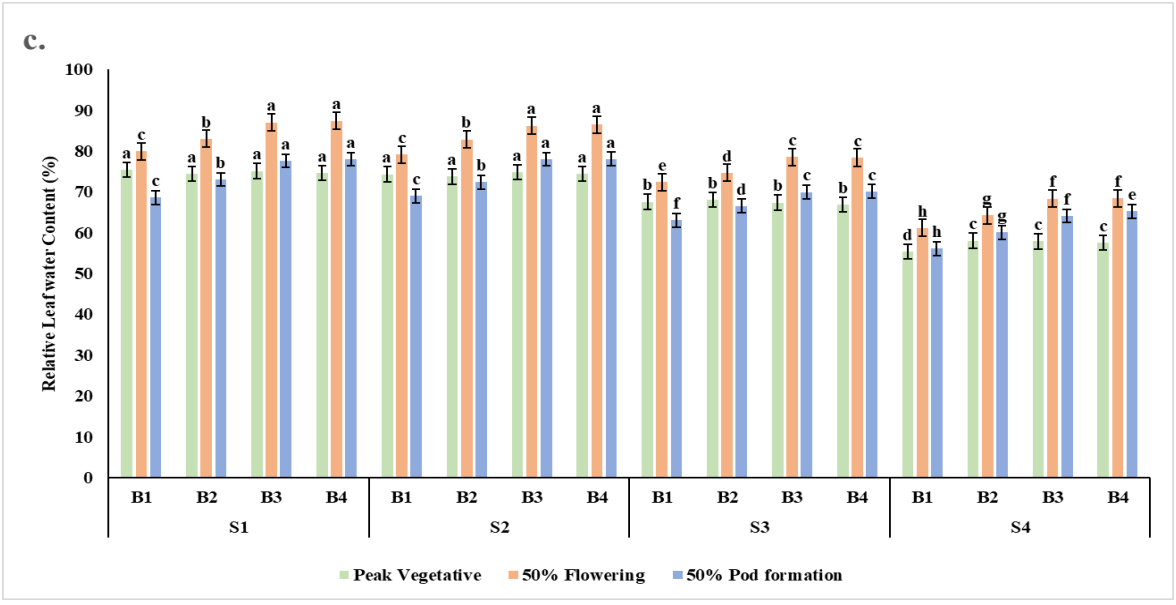


Fig. 3. Duration of different phenological phases of field pea under variable sowing time (S1, S2, S3 and S4) and foliar boron applications (B1, B2, B3 and B4) during the study period of 2017–18 (a) and 2018–19 (b). S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray. Error bars represent standard error.


a.
B1
B2
B3
B4
Canopy temperature depression (Tc-Ta) (°C)
S1
S2
S3
S4
Peak Vegetative
50% Flowering
50% Pod formation


b.
B1
B2
B3
B4
Canopy temperature depression(Tc-Ta) (°C)
S1
S2
S3
S4
Peak Vegetative
50% Flowering
50% Pod formation


c.
Relative Leaf water Content (%)
B1
B2
B3
B4
S1
S2
S3
S4
Peak Vegetative
50% Flowering
50% Pod formation

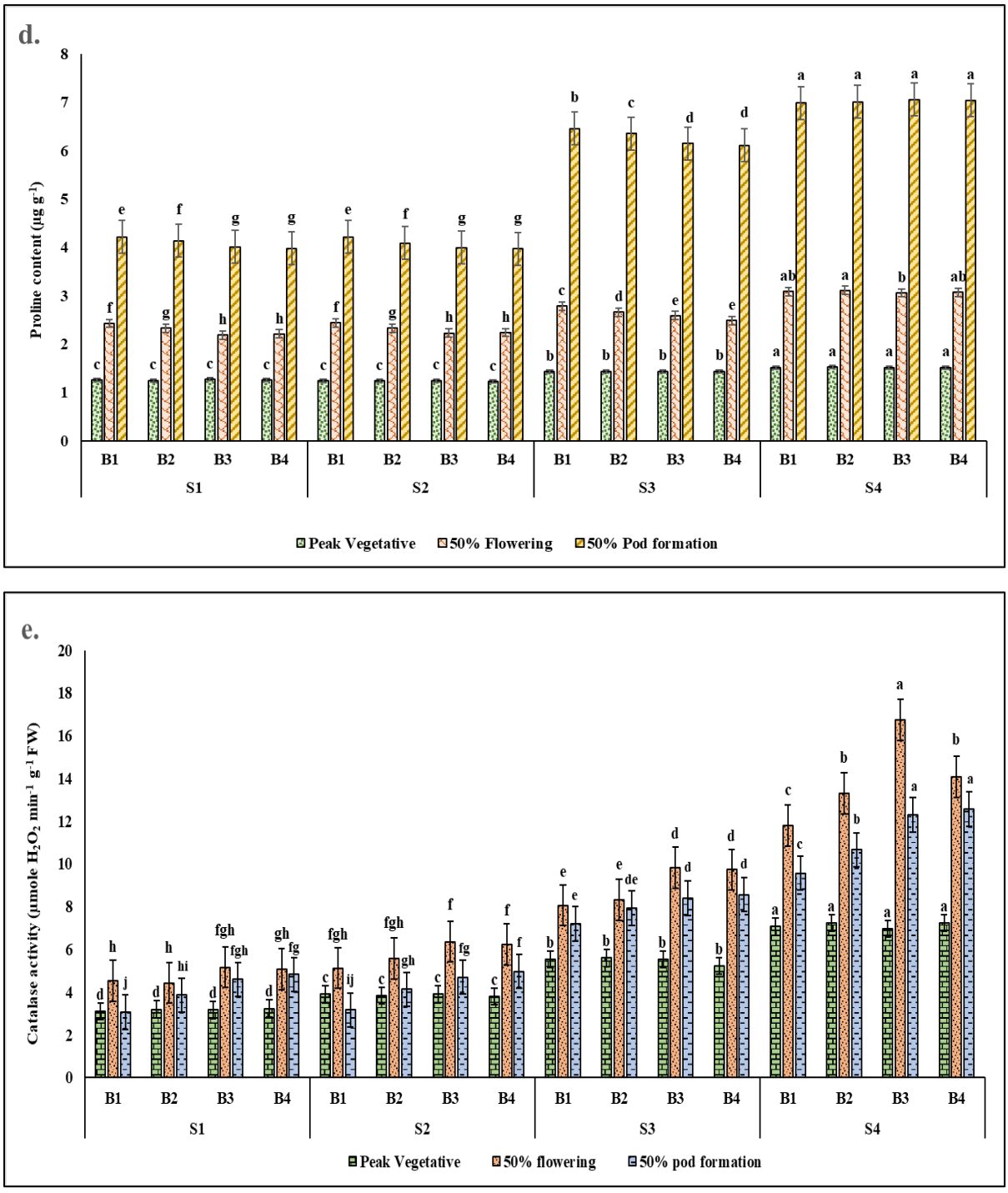
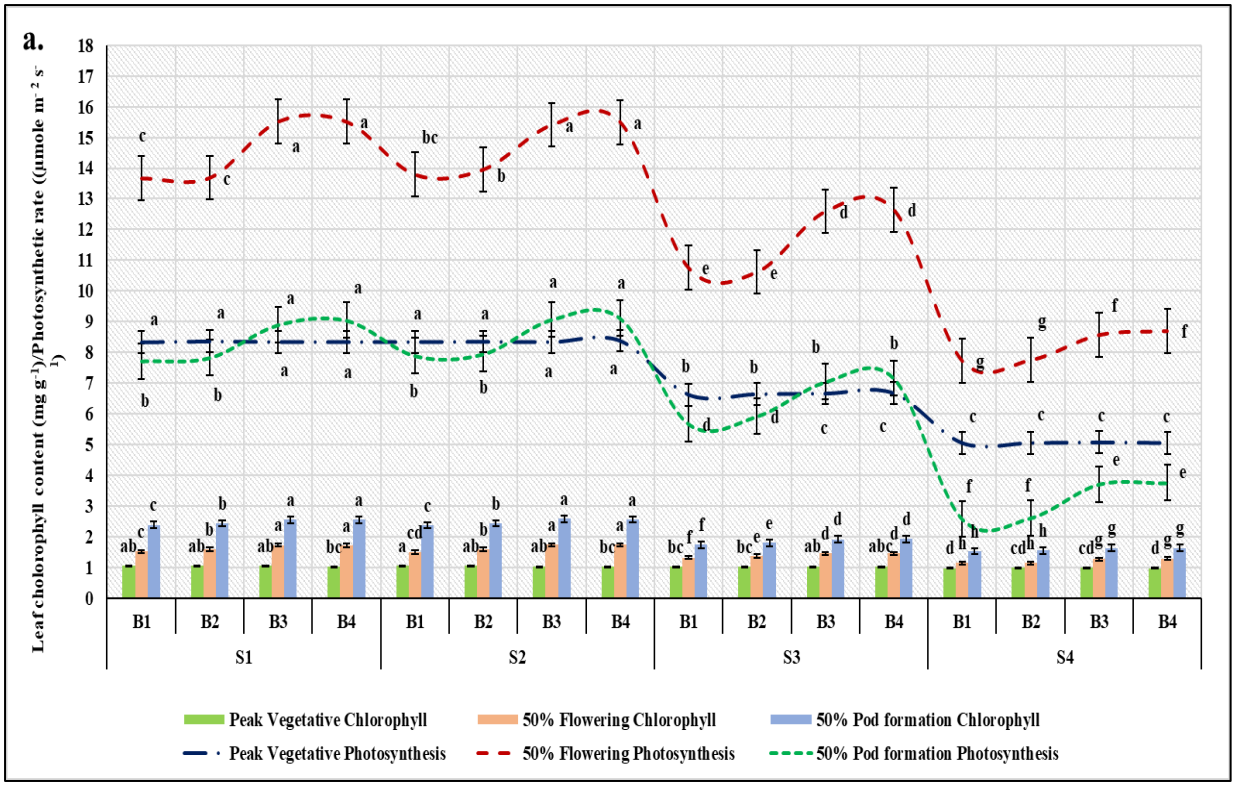
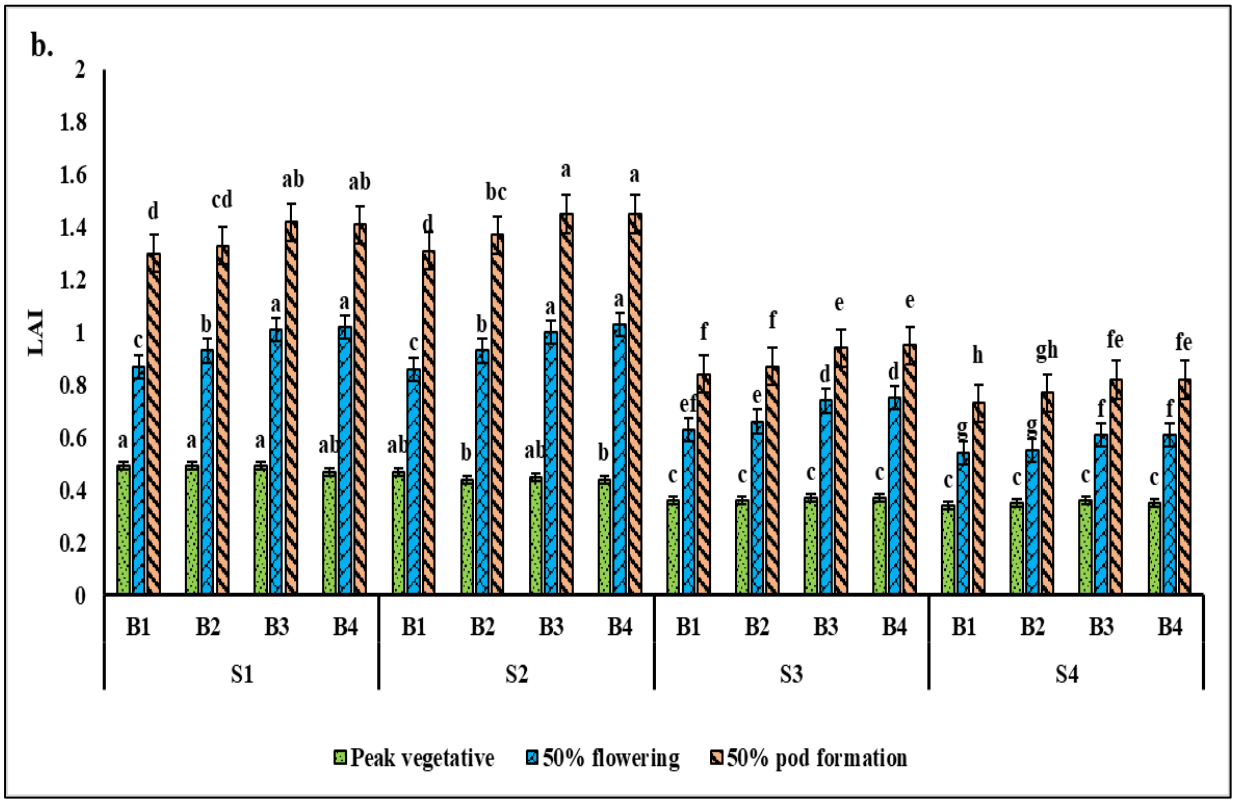


Fig.4. Canopy temperature depression (ºC**)** (2017-18 **(a.)** and 2018-19 **(b.)**, Relative leaf water content (%) **(c.)**, Proline content (µg g^{-1}) **(d.)** and Catalase activity (µmole H_2O_2 min^{-1} g^{-1} FW**) (e.)** at critical growth stages of field pea under different sowing dates and foliar boric acid application [pooled data of 2017–18 and 2018–19 cropping seasons except canopy temperature depression]. S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray. Different lowercase letters in every growing stage are significantly different at $p < 0.05$ according to Duncan multiple range test. Error bars represent standard error.


a.
Leaf cholorophyll content (mg g-1)/Photosynthetic rate ((µmole m-2 s-1)
B1
B2
B3
B4
S1
S2
S3
S4
Peak Vegetative Chlorophyll
50% Flowering Chlorophyll
50% Pod formation Chlorophyll
Peak Vegetative Photosynthesis
50% Flowering Photosynthesis
50% Pod formation Photosynthesis


b.
LAI
B1
B2
B3
B4
S1
S2
S3
S4
Peak vegetative
50% flowering
50% pod formation

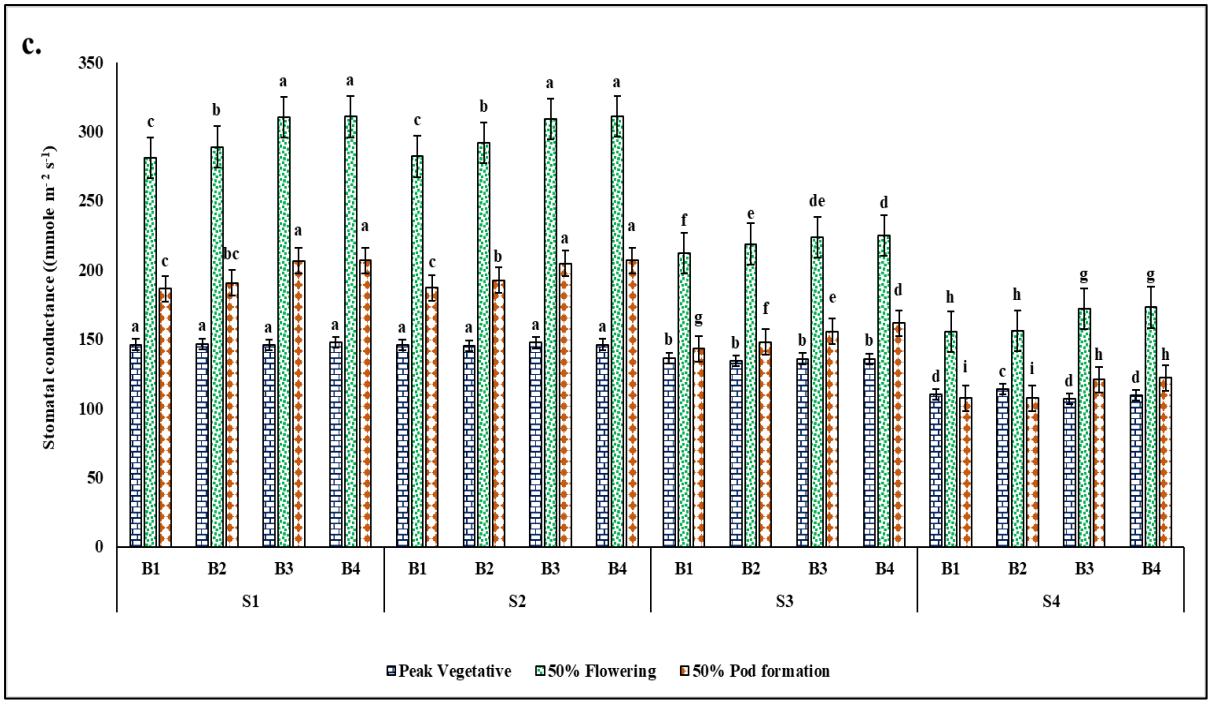


Fig.5. Leaf chlorophyll content (mg g^{-1}**)** and photosynthetic rate (µmole m^{-2} s^{-1}) (**a.**), Leaf area index (**b.**) and Stomatal conductance (mmole m^{-2} s^{-1}**) (c.)** at critical growth stages of field pea under different sowing dates and foliar boric acid application [pooled data of 2017–18 and 2018–19 cropping seasons]. S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray. Different lowercase letters in every growing stage are significantly different at $p < 0.05$ according to Duncan multiple range test. Error bars represent standard error.

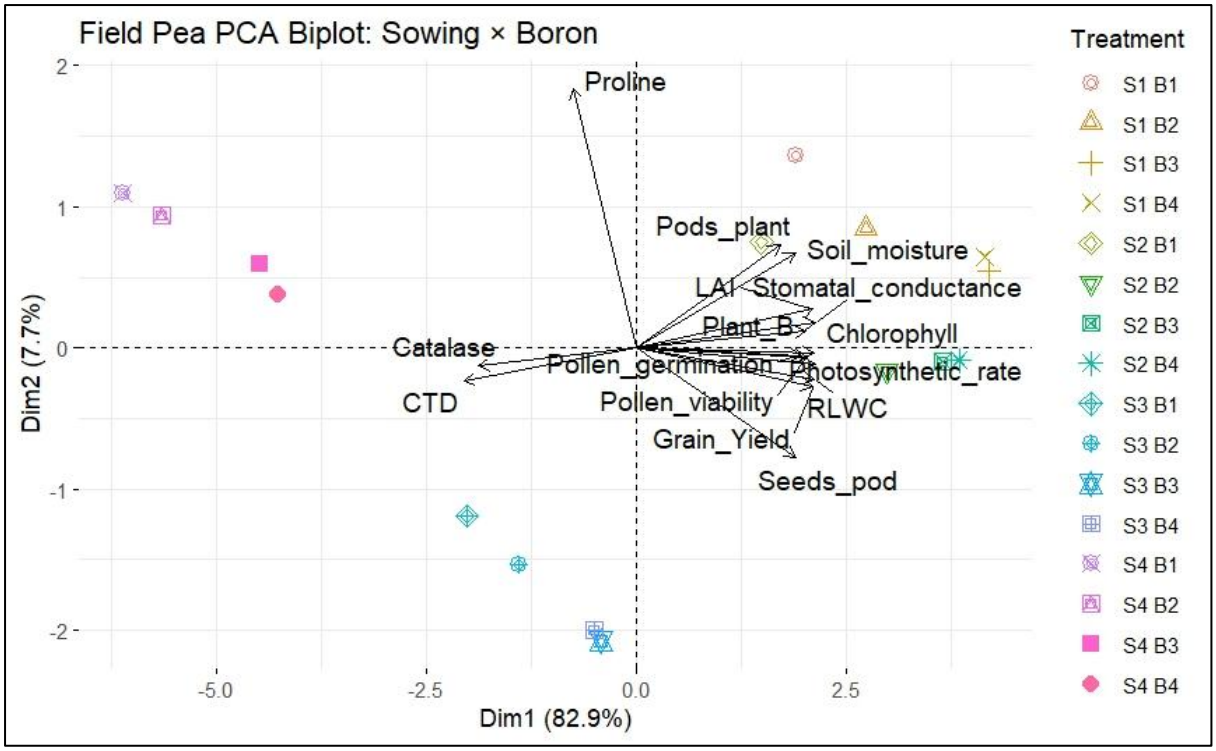


Fig.6. Principal component biplot illustrating integrated physiological and reproductive responses of field pea to sowing date × boron application. S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray.

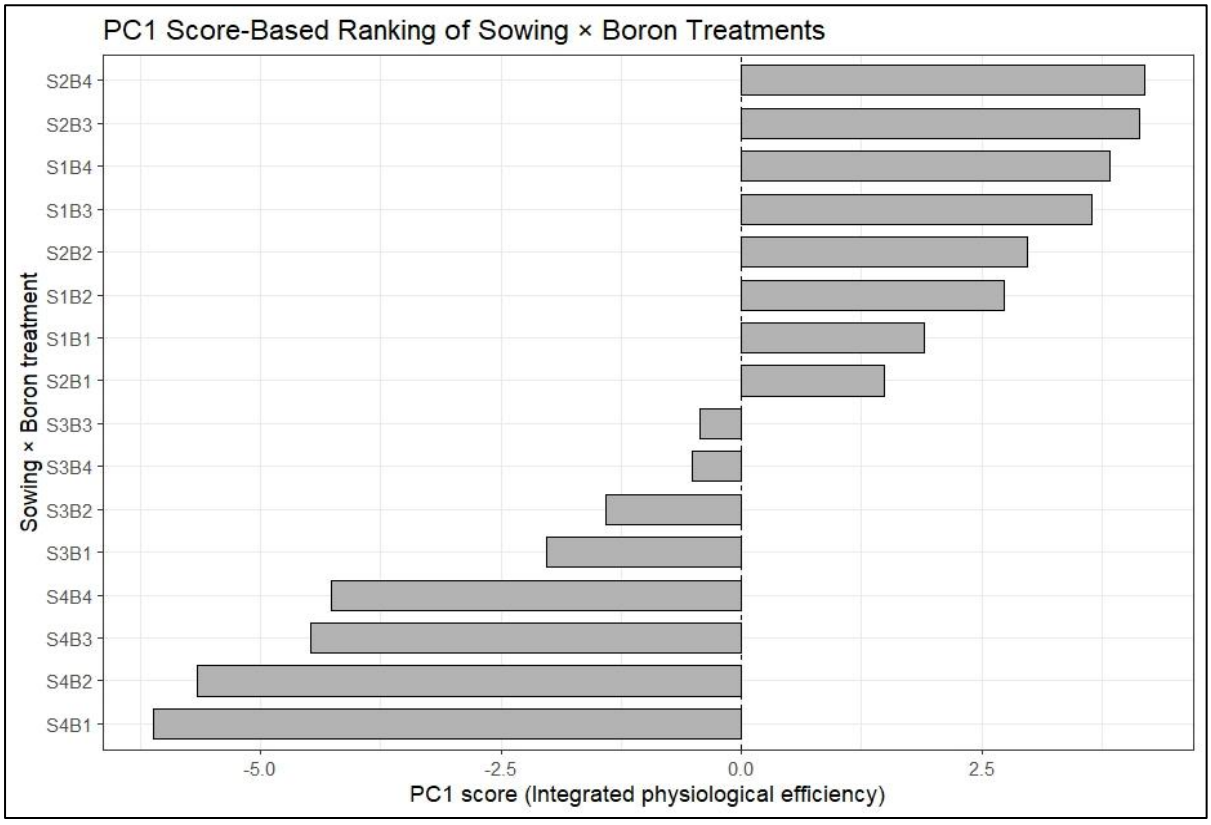


Fig.7. PC1-based ranking of sowing date × boron treatments reflecting integrated physiological efficiency in field pea. S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray.

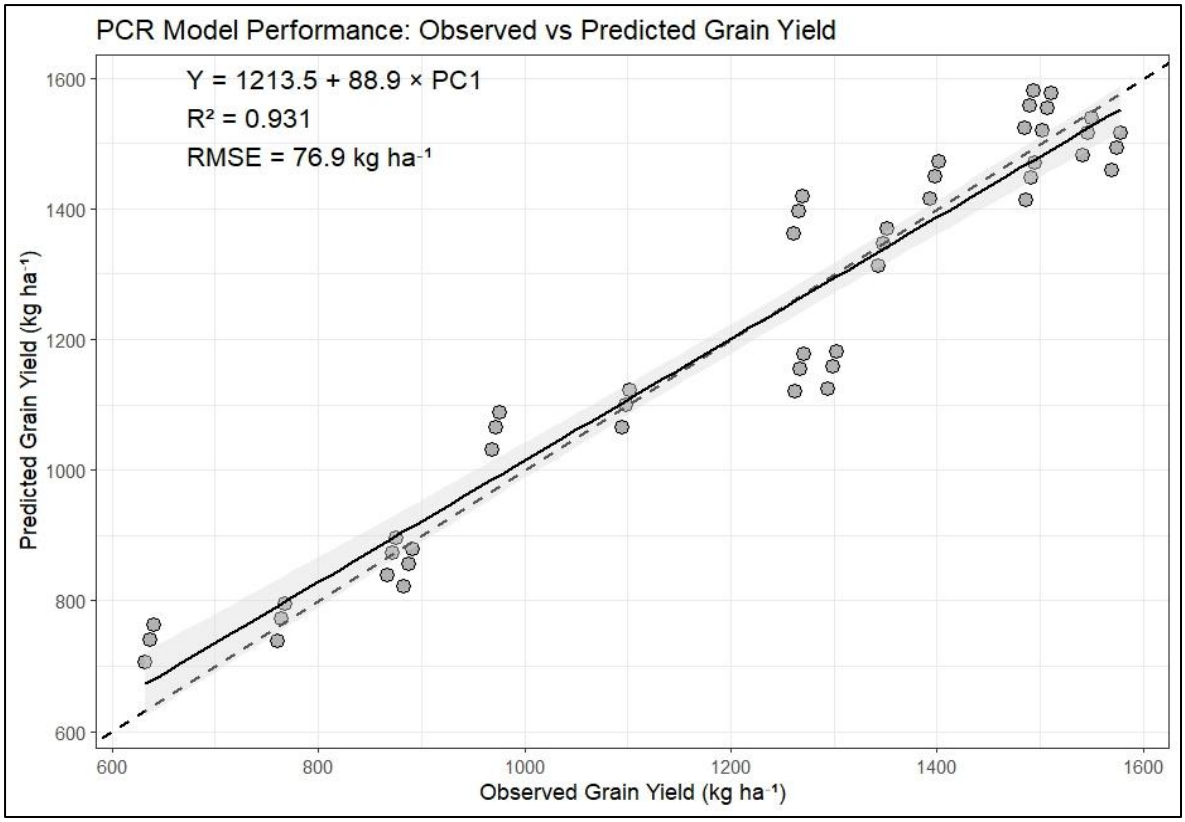


Fig.8. Performance of principal component regression (PCR) in predicting grain yield of field pea

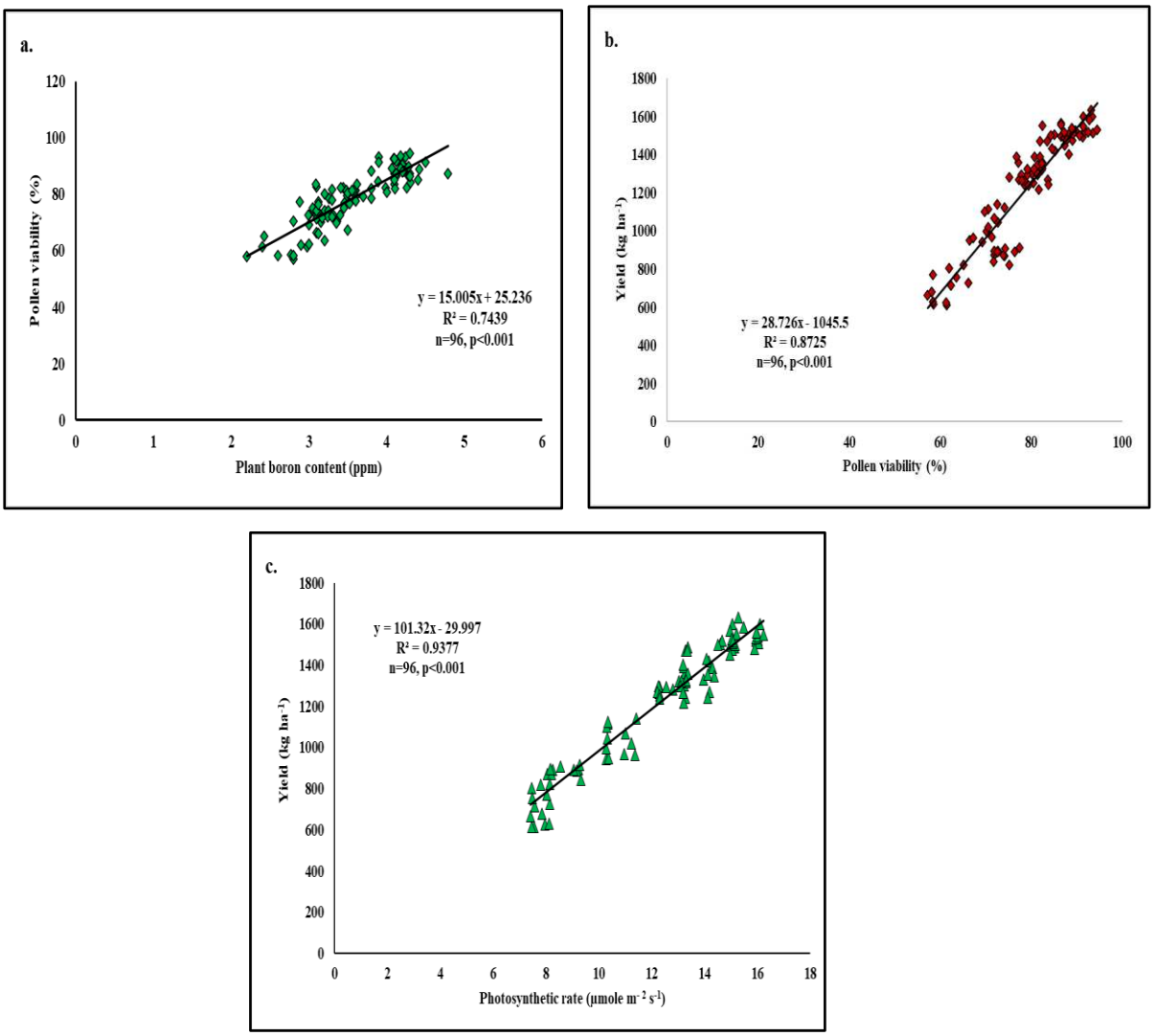


Fig.9. Relation between pollen viability (%) vs plant boron content (ppm) (a); Yield (kg ha^{-1}) vs pollen viability (%) (b) and Yield (kg ha-1) vs photosynthetic rate (µmole m^{-2} s^{-1})**.**

Table 1.

Textural class, maximum water holding capacity (WHC, %), moisture content at field capacity (Θ_{FC}, %V/V), permanent wilting point (Θ_{WP}, %V/V), critical moisture content (Θ_{C}, %V/V) of the different horizons of the soil profile of the experimental site.

Properties	0-15 cm	15-30 cm	30-45 cm
Sand (%)	39	37	33
Silt (%)	28	26	24
Clay (%)	33	37	43
Textural class	Clay loam	Clay	Clay
WHC (%)	48	51	61
Θ_{FC}, %V/V	35	42	55
Θ_{WP}, %V/V	12	16	32
Θ_{C}, %V/V	23.5	31	43.5

Table 2.

Effect of different dates of sowing and foliar boron application on plant boron content (ppm), pollen germination (%) and pollen viability (%) of field pea during 2017-18 and 2018-19 cropping season.

	Plant B (ppm)			Pollen viability (%)			Pollen germination (%)		
	2017-18	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**
S1	4.01a	4.09a	4.05a	85.31a	86.67a	85.99a	88.95a	89.46a	89.20a
S2	3.89b	3.84b	3.86b	85.61a	86.77a	86.19a	89.10a	88.84a	88.97a
S3	3.41c	3.37c	3.39c	75.12b	74.98b	75.05b	78.78b	77.55b	78.17b
S4	3.02d	2.84d	2.93d	67.10c	67.62c	67.36c	64.57c	64.79c	64.68c
B1	3.16c	3.04b	3.09c	72.01c	72.58c	72.30c	73.94c	73.94c	73.94c
B2	3.60b	3.63a	3.62b	75.42b	76.38b	75.90b	78.46b	78.25b	78.36b
B3	3.80a	3.79a	3.79a	82.57a	83.91a	83.24a	84.54a	84.08a	84.31a
B4	3.78a	3.68a	3.73a	83.15a	83.18a	83.17a	84.45a	84.36a	84.41a
S	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
B	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
S×B	<0.05	<0.001	<0.001	NS	NS	NS	NS	NS	NS

S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray; Different lower-case letters within same columns are significantly different at $p<0.05$ according to Duncan multiple range test; ns = non-significant.

Table 3.

Effect of different dates of sowing and foliar boron application yield (kg ha-1) and yield attributing characters of field pea during 2017-18 and 2018-19 cropping season.

	Pods/plant			Seeds/pod			Yield (kg ha^{-1})		
	2017-18	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**
S1	12.89a	13.15a	13.26a	4.09b	4.14b	4.12b	1400b	1431b	1415b
S2	13.09a	13.43a	13.02a	4.33a	4.39a	4.36a	1474a	1506a	1490a
S3	9.19b	9.35b	9.27b	3.94b	3.99b	3.97b	1147c	1172c	1159c
S4	7.74c	7.95c	7.84c	2.93c	2.96c	2.94c	782d	799d	791d
B1	8.95c	9.15c	9.05c	3.43b	3.48b	3.46b	1045c	1067c	1056c
B2	9.85b	9.99b	9.92b	3.91a	3.96a	3.93a	1176b	1201b	1188b
B3	12.11a	12.47a	12.29a	4.02a	4.07a	4.05a	1303a	1331a	1317a
B4	12.00a	12.27a	12.14a	3.93a	3.98a	3.96a	1280a	1308a	1294a
S	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
B	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
S×B	<0.05	<0.001	<0.001	<0.05	<0.05	<0.05	<0.001	<0.001	<0.001

S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray; Different lower-case letters within same columns are significantly different at $p<0.05$ according to Duncan multiple range test; ns = non-significant.

Table 4.

Economic analysis (Cost of cultivation, Gross return, Net return, benefit-cost ratio of field pea production under different sowing time and foliar boric acid application.

	Cost of cultivation	**Gross return**	**Net return**	**B:C ratio**
S1 B1	45000	82314^{f}	37314^{e}	1.83^{f}
S1 B1	48150	90887^{d}	42737^{d}	1.89^{ef}
S1 B3	48300	97958^{bc}	49658^{bc}	2.03^{bc}
S1 B4	48450	96870^{c}	48420^{c}	2.00^{cd}
S2 B1	45000	87639^{e}	42639^{d}	1.95^{de}
S2 B2	48150	96943^{c}	48793^{bc}	2.01^{bcd}
S2 B3	48300	102283^{a}	53983^{a}	2.12^{a}
S2 B4	48450	100470^{ab}	52020^{ab}	2.07^{ab}
S3 B1	45000	63221^{h}	18221^{h}	1.41^{i}
S3 B2	48150	71421^{g}	23271^{g}	1.48^{h}
S3 B3	48300	84429^{f}	36129^{ef}	1.75^{g}
S3 B4	48450	82358^{f}	33908^{f}	1.70^{g}
S4 B1	45000	41410^{k}	-3591^{k}	0.92^{l}
S4 B2	48150	49737^{j}	1587^{j}	1.03^{k}
S4 B3	48300	57697^{i}	9397^{i}	1.19^{j}
S4 B4	48450	56705^{i}	8255^{i}	1.17^{j}
S		<0.001	<0.001	<0.001
B		<0.001	<0.001	<0.001
S×B		<0.05	<0.05	<0.05

S1=10 November, S2=20 November, S3=30 November and S4=10 December; B_1: no spray, B_2: 0.1% boric acid, B_3: 0.2% boric acid B_4: 0.3% boric acid spray. Different lower-case letters within same columns are significantly different at $p<0.05$ according to Duncan multiple range test; ns = non-significant.

Table 5.

Principal component regression (PCR) coefficients for grain yield of field pea.

Term	Estimate	Std. Error	t value	p value
Intercept	1213.46	11.46	105.87	<0.001
PC1	88.88	3.61	24.64	<0.001
PC2	7.57	8.41	0.90	0.373

Table 6.

Factor loadings of physiological, reproductive, and yield-related traits on the first two principal components (PC1 and PC2) in field pea

Trait	PC1 (82.9%)	PC2 (7.7%)
Soil moisture storage	0.88	0.27
Canopy temperature depression (CTD)	−0.93	0.18
Relative leaf water content (RLWC)	0.96	0.12
Chlorophyll	0.70	−0.65
Proline	−0.36	0.61
Catalase	−0.87	−0.22
Photosynthetic rate	0.86	0.43
Stomatal conductance	0.99	0.09
Leaf area index (LAI)	0.82	0.53
Pollen germination	0.92	−0.02
Pollen viability	0.92	0.09
Pods per plant	0.81	−0.06
Seeds per pod	0.75	−0.62
Plant boron content	0.92	−0.16

Supplementary Files

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- Supplementary.docx