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Response of Terminal Drought and High Temperature Stress on *Pheno*-phases and its Consequence on Yield and Yield Contributing Traits in Lentil (*Lens culinaris* Medik)

Ananya Baidya[1,2], Subhasis Mondal[1], Rajeev Kumar[3], Ranjit Singh Gujjar[3], Santanu Banerjee[4] Kousik Atta[5], Nurnabi Meharul Alam[6]

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ABSTRACT

Background: In eastern India, lentil (*Lens culinaris* Medikus) is largely grown as a rice-fallow crop under residual soil moisture. Delayed rice harvesting frequently causes delayed lentil sowing, exposing crops to sub-optimal climatic conditions during critical phenophases and inducing terminal heat and drought stress that reduce growth, development and yield.

Methods: A field experiment was conducted with five lentil genotypes (WBL-58, PRECOZ, WBL-77, ILL-10893 and L-13-123) sown on 15th November, 30th November and 15th December to assess phenology, physiology, yield attributes and seed quality under delayed sowing.

Result: Delayed sowing significantly reduced seed-filling duration, yield components, dry matter partitioning, seed size, micronutrient concentration and seed germination. Flowering time, pollen quality, chlorophyll content, relative leaf water content and proline accumulation were adversely affected across genotypes. WBL-58 performed best under low soil moisture (-0.885 to -1.665 MPa) and high temperature (30-32°C), whereas L-13-123 showed severe yield loss.

Key words: Lentil, Micronutrient, *Pheno*-phase, Pollen, Terminal drought.

INTRODUCTION

Lentil (*Lens culinaris* Medikus) is a self-pollinated diploid (2n=14) cool-season pulse crop widely cultivated in the Southwest Asia and North Africa (SWANA) region and India and it ranks fifth in global pulse production after common bean, dry pea, chickpea and cowpea (FAOSTAT, 2022). Globally, lentil occupies about 3 million hectares with a production of 5.8 million tonnes and an average productivity of 3 t ha^{-1} (Choukri *et al.*, 2022). In India, lentil contributes nearly one-third of global production and is the second most important pulse in the Indo-Gangetic Plains, valued for its high protein content (~25%) (Malik *et al.*, 2022; Zeroual *et al.*, 2022). In eastern India, including West Bengal, lentil is predominantly grown as a rice-fallow crop under residual soil moisture due to limited irrigation coverage. Delayed transplanting of *kharif* rice caused by erratic rainfall often leads to delayed lentil sowing, disrupting the synchronization between crop phenology and climatic conditions.

Abiotic stresses, particularly terminal heat and drought, severely constrain lentil productivity by impairing reproductive development, especially pollen viability (Prasad *et al.*, 2019). Climate change-induced increases in temperature and moisture stress trigger transcriptional and physiological disruptions affecting crop growth and phenology (Sehgal *et al.*, 2017). Delayed sowing exposes lentil to cumulative heat units, shortened day length, cold stress during early growth and terminal heat and drought during reproductive stages (Rather *et al.*, 2022; Baidya *et al.*, 2021). The optimum temperature for lentil growth ranges from 10-30°C; even a 1°C rise during reproduction can reduce yield by 11-13%, while temperatures above 30-32°C impair flowering and pod filling (Venugopalan *et al.*, 2021). Shortened seed-filling duration under late sowing results in reduced seed size and quality (Liu *et al.*, 2021). Despite these

[1]Department of Plant Physiology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia-741 252, West Bengal, India.
[2]ICAR-Central Soil Salinity Research Institute, Karnal-132 001, Haryana, India.
[3]ICAR-Indian Institute of Sugarcane Research, Lucknow-226 002, Uttar Pradesh, India.
[4]Department of soil and water systems, University of Idaho-Boise, Boise, Idaho, USA.
[5]Faculty of Agricultural Sciences, GLA University, Mathura-281 406, Uttar Pradesh, India.
[6]ICAR-Central Research Institute for Jute and Allied Fibres, Kolkata-700 121, West Bengal, India.

Corresponding Author: Ananya Baidya, Department of Plant Physiology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia-741 252, West Bengal, India. Email: theananya4@gmail.com ORCID: 0009-0001-0476-2892

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concerns, limited information exists on the combined effects of terminal heat and drought across phenophases. Therefore, the present study evaluated lentil genotypes under different sowing dates to quantify impacts on phenology, physiology, yield and nutritional quality (Choukri *et al.*, 2022).

MATERIALS AND METHODS

Experimental design and soil-climate conditions

Field experiments were conducted during the *Rabi* seasons of 2016-17 and 2017-18 to evaluate five lentil genotypes contrasting in heat and terminal drought tolerance, selected based on late-sown performance (Baidya *et al.*, 2021). The study was carried out at the District Seed Farm, BCKV, Kalyani, West Bengal (Fig 1), on well-drained Gangetic alluvial inceptisol with clay loam texture and medium fertility. A split-plot design with three replications was adopted, with three sowing dates 15th November, 30th November and 15th December to impose heat and drought stress. Standard crop management under rainfed conditions was followed. Soil moisture and water potential were measured periodically (Richards, 1948), while weather parameters and soil moisture dynamics are presented in Fig 2 and 3.

Phenological observations

Crop phenophases, including days to germination, branching, flowering, podding, physiological maturity and harvest maturity, were recorded through periodic field observations following Erskine *et al.* (1990).

Dry matter production and partitioning

Dry matter accumulation and partitioning were recorded at early seedling, pre-flowering and physiological maturity stages. Three plants per replication were uprooted and separated into roots, shoots, leaves and reproductive parts. Plant components were oven-dried at 80°C to constant weight for dry matter estimation.

Growth and physiological parameters

Absolute growth rate (AGR), relative growth rate (RGR) and crop growth rate (CGR) were calculated following standard formulas (Fisher, 1971; Watson, 1952). Biomass allocation was assessed using leaf, stem and root weight ratios

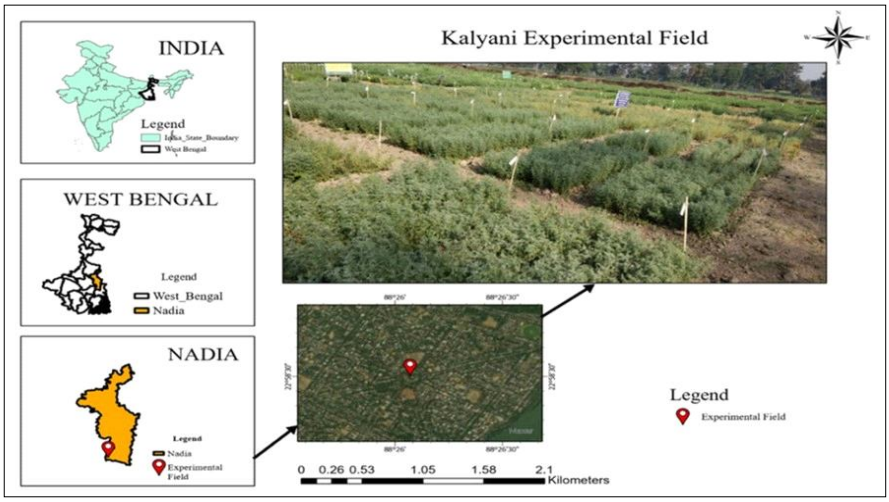


Fig 1: Experimental site of the field.

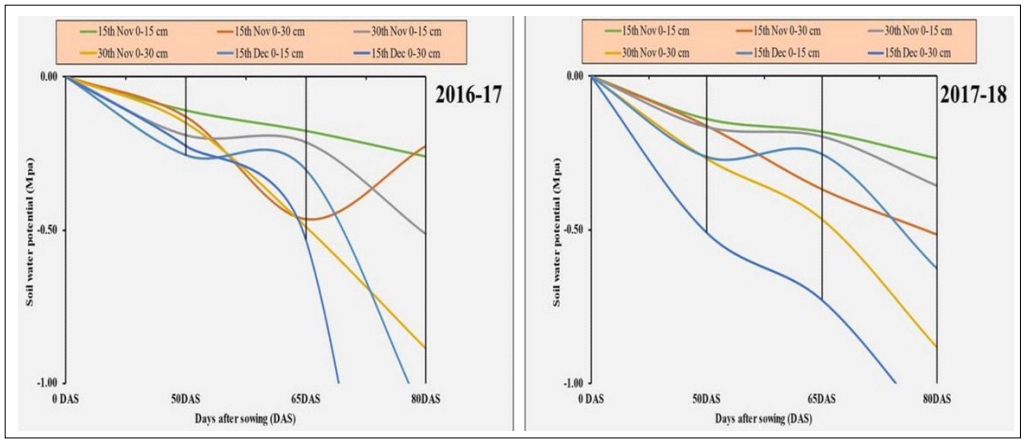


Fig 2: Soil water potential (MPa) during the crop growth period of the experiment (2016-17 and 2017-18).

(Kvet *et al.*, 1971). Relative leaf water content (RLWC) was estimated using the method of Perez *et al.* (2002) based on fresh, turgid and dry weights of leaf samples.

Biochemical traits

Stress-related biochemical parameters were analyzed in field-grown leaf samples collected at 50 and 80 DAS. Lipid peroxidation was estimated as malondialdehyde (MDA) content using the thiobarbituric acid reactive substances (TBARS) method (Heath and Packer, 1968). Free proline content was determined following Mohanty and Sridhar (1982). Leaf chlorophyll content was measured using a SPAD-502 chlorophyll meter at flowering and 50% podding stages.

Yield and yield attributes

At harvest, plant height, primary branches, pods per plant, seeds per pod, 100-seed weight, biological yield, seed yield and harvest index were recorded.

Stress response index

Stress response indices (SRI) were calculated for seed yield and key phenological traits using mean values from late and very late sowing relative to normal sowing.

Grain micronutrient analysis

Grain micronutrients (Fe, Zn, Cu, Mn) were analyzed by atomic absorption spectrophotometry after wet digestion of seed samples using diacid mixture, following Jackson (1973).

Pollen germination studies

Flowers collected at anther dehiscence were used for *in vitro* pollen germination assays at 18°C, 24°C and 30°C. Germination was recorded at 30 minute intervals up to 90 minutes, following Niles and Quesenberry (1992) and observed under a Zeiss Axiocam 305 microscope.

Statistical analysis

Data were analyzed using ANOVA for split-plot design (Gomez and Gomez, 1984). Mean comparisons were performed using Statistix 10 software. Pearson correlation and principal component analysis were conducted to assess trait associations and variability. Data visualization and analysis were further performed using Python.

RESULTS AND DISCUSSION

Influence of sowing dates on phenological phases of lentil genotypes

Sowing date significantly affected the phenological development of lentil genotypes, highlighting the crop's sensitivity to planting time shown in interaction effect of sowing dates and genotypes in Fig 4. Under normal sowing (15th November), rapid germination and seedling emergence occurred within 5-6 days, whereas delayed and very late sowing prolonged early establishment probably due to lower soil and air temperatures (Venugopalan *et al.*, 2021). WBL-77 showed the maximum delay in emergence under late sowing, likely due to temperature-induced suppression of metabolic activity. Vegetative stages, including first and second branching, occurred earlier under normal sowing but were altered under delayed conditions. Reproductive phases were highly sensitive, with 15th December sowing inducing early flowering and podding owing to higher temperatures and shorter photoperiods. Delayed sowing shortened crop duration (103-106 days) compared with normal sowing (~111 days). Genotypic variation was evident, with L-13-123 flowering earliest, WBL-58 having a longer reproductive phase and PRECOZ showing extended maturity. Overlapping growth phases and accelerated development under stress were governed by temperature, moisture stress, growing degree days and photoperiod (Fig 5 and 6). Data presentation using tables could show these results better.

Effect of sowing dates on dry matter accumulation and partitioning

Dry matter accumulation and partitioning strongly influence crop yield and are affected by sowing time and environment (Table 1). Delayed sowing significantly reduced root dry weight at all stages and progressively decreased leaf and

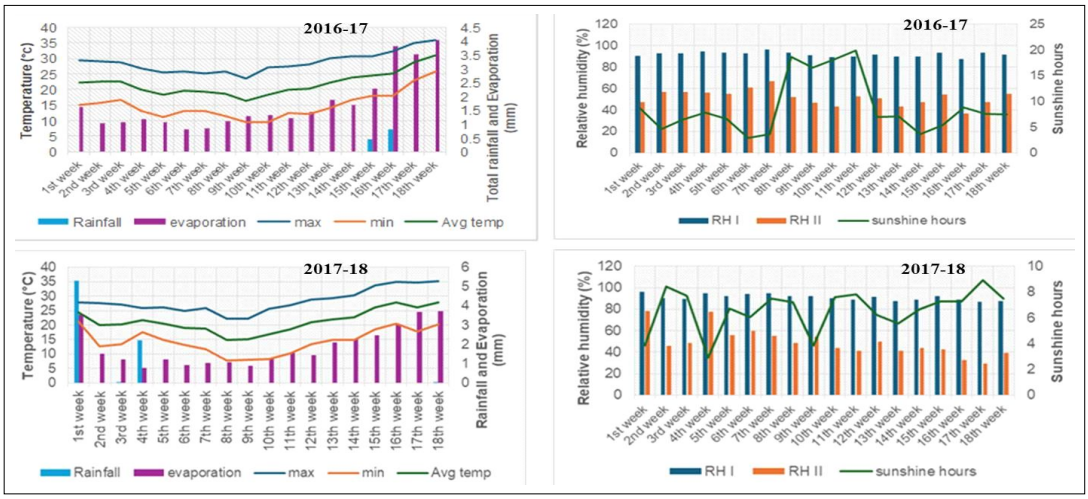


Fig 3: Different meteorological data during the crop growth period of the experiment (2016-17 and 2017-18).

reproductive biomass compared with normal sowing (15th November), mainly due to shortened growth duration, higher temperature, moisture stress and reduced photosynthesis (Akter and Islam, 2017). Genotypic variation was evident, with WBL-58 showing the highest root biomass, indicating better stress adaptation. Delayed sowing (15th December) reduced total biomass by nearly 56%, consistent with earlier reports in chickpea, rapeseed, wheat and lentil (Venugopalan *et al.*, 2021; Xu *et al.*, 2022; Bera *et al.*, 2024).

Effects of sowing dates on growth parameters

Growth indices including AGR, RGR, CGR, LWR, SWR and RWR were significantly affected by sowing dates and genotypes (Table 2). AGR and CGR increased with crop age, whereas RGR declined at later stages. Delayed sowing enhanced AGR and CGR but reduced RGR at 80 DAS, indicating stress-induced growth adjustments. Late and very late sowing markedly reduced most growth indices due to impaired photosynthate production and partitioning.

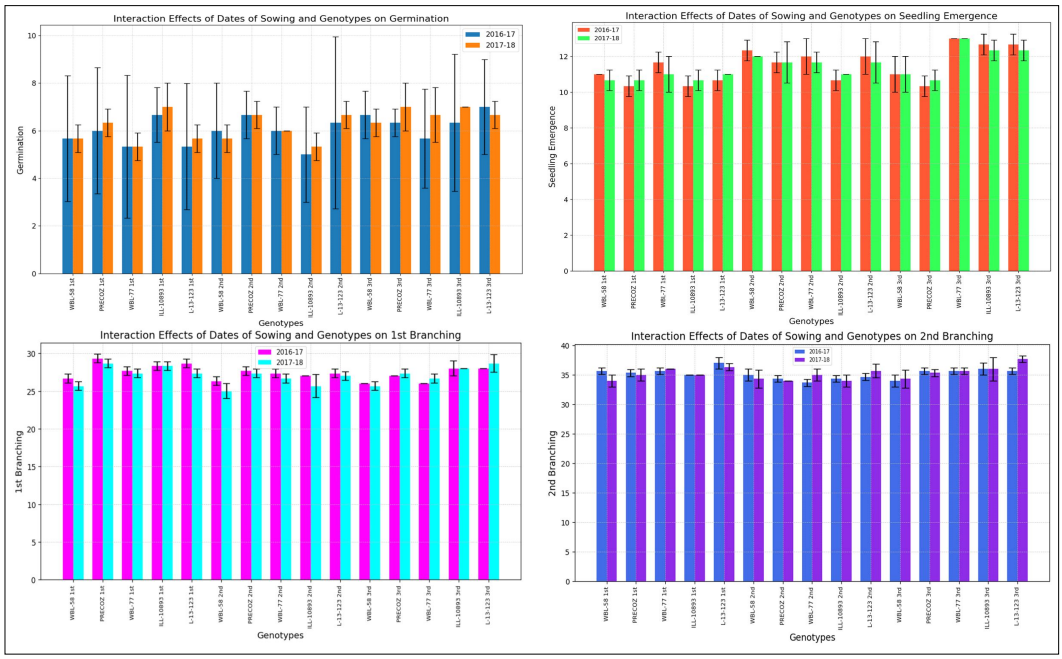


Fig 4: Interaction effects of sowing dates and genotypes on pre-flowering *pheno*-phases in lentil.

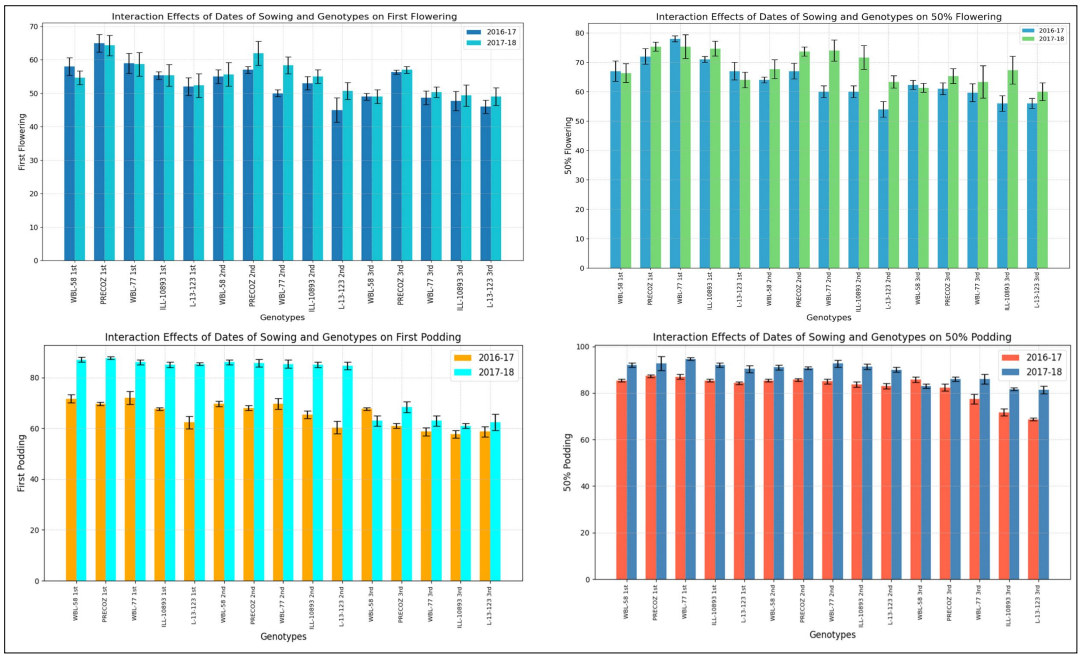


Fig 5: Interaction effects of sowing dates and genotypes on reproductive *pheno*-phases in lentil.

Table 1: Effect of sowing dates on dry matter content and its partitioning on different plant parts in lentil.

Date of sowing	Root DW (gm)						Shoot DW (gm)						Leaf DW (gm)						Reproductive DW (gm)	
	50 DAS		65 DAS		80 DAS		50 DAS		65 DAS		80 DAS		50 DAS		65 DAS		80 DAS		80 DAS	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
15th Nov	0.087± 0.020c	089± 0.0.014c	0.256± 0.006b	0.258± 0.015c	0.333± 0.009c	0.575± 0.039c	0.161± 0.006c	0.140± 0.014a	0.367v 0.010b	0.234± 0.008c	1.782± 0.050a	1.175± 0.050b	0.200± 0.012b	0.217± 0.014c	0.284± 0.005c	0.409± 0.009c	1.678± 0.084a	1.024± 0.010a	2.382± 0.088a	2.559± 0.037a
30th Nov	0.149± 0.020b	0.129± 0.014b	0.255± 0.006b	0.322± 0.015b	0.382± 0.009b	0.959± 0.039b	0.212± 0.006b	0.166± 0.014a	0.389± 0.010b	0.477± 0.008a	1.728± 0.050b	1.394± 0.050a	0.268± 0.012a	0.252± 0.014b	0.430± 0.005b	0.689± 0.009a	1.228± 0.084b	0.983± 0.010a	1.854± 0.088b	2.373± 0.037b
15th Dec	0.354± 0.020a	0.315± 0.014a	0.477± 0.006a	0.478± 0.015a	0.858± 0.009a	1.011± 0.039a	0.248± 0.006a	0.109± 0.014a	0.460± 0.010a	0.373± 0.008b	1.330± 0.050c	1.027± 0.050c	0.195± 0.012b	0.286± 0.014a	0.581± 0.005a	0.557± 0.009b	1.169± 0.084b	0.996± 0.010a	1.536± 0.088c	1.593± 0.037c

Table 2a: Effect of genotypes on growth parameters in lentil.

Genotypes	Absolute growth rate (AGR) gm.day^{-1}				Relative growth rate (RGR) gm^{-1}.day^{-1}				Crop growth rate (CGR) gm.m^{-2}.day^{-1}			
	50 DAS		80 DAS		50 DAS		80 DAS		50 DAS		80 DAS	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
WBL-58	0.042± 0.002a	0.043± 0.001a	0.265± 0.003a	0.173± 0.007a	0.539± 0.018a	0.538± 0.011ab	0.381± 0.008cd	0.337± 0.007a	0.038± 0.003bc	0.042± 0.002c	0.309± 0.005e	0.232± 0.009a
PRECOZ	0.028± 0.002c	0.033± 0.001c	0.240± 0.003d	0.172± 0.007ab	0.464± 0.018b	0.538± 0.011ab	0.349± 0.008d	0.308± 0.007c	0.057± 0.003a	0.057± 0.002a	0.319± 0.005d	0.230± 0.009ab
WBL-77	0.024± 0.002d	0.030± 0.001d	0.232± 0.003e	0.154± 0.007b	0.399± 0.018d	0.499± 0.011b	0.422± 0.008a	0.329± 0.007bc	0.031± 0.003c	0.041± 0.002cd	0.354± 0.005a	0.206± 0.009c
ILL-10893	0.030± 0.002b	0.041± 0.001b	0.256± 0.003b	0.137± 0.007c	0.430± 0.018c	0.539± 0.011a	0.387± 0.008c	0.281± 0.007d	0.039± 0.003b	0.053± 0.002b	0.342± 0.005b	0.183± 0.009d
L-13-123	0.023± 0.002d	0.030± 0.001d	0.251± 0.003c	0.160± 0.007ab	0.338± 0.018e	0.430± 0.011c	0.401± 0.008b	0.330± 0.007b	0.033± 0.003c	0.040± 0.002d	0.333± 0.005c	0.215± 0.009b

Genotype WBL-58 maintained comparatively higher AGR, CGR and RGR under 15th December sowing, contributing to better yield performance, consistent with Venugopalan *et al.* (2021). Delayed sowing increased RWR as a compensatory root response to moisture stress, while LWR and SWR declined, indicating reduced canopy development, corroborating genotypic trends reported by Akter *et al.* (2022).

Effects of sowing dates on stress indicators

SPAD value

SPAD values were significantly higher under optimal sowing (15 November) and declined under late and very late sowing. WBL-58 maintained the highest SPAD values at both 50 and 90 DAS under stress (Fig 7), indicating better chlorophyll retention and photosynthetic capacity. Reduced SPAD values in late-sown crops reflect chlorophyll degradation and nitrogen limitation under heat and drought stress (Atta *et al.*, 2023).

Relative leaf water content (RLWC)

RLWC declined progressively with delayed sowing, with the lowest values recorded under 15th December sowing. Higher RLWC at 50 DAS compared to 90 DAS indicated progressive dehydration under stress (Fig 7). Reduced RLWC under late sowing reflects diminished cell turgor and impaired growth (Nandi *et al.*, 2023).

Lipid peroxidation

Late-sown crops exhibited significantly higher malondialdehyde (MDA) content, indicating increased oxidative damage (Fig 7). WBL-58 showed comparatively

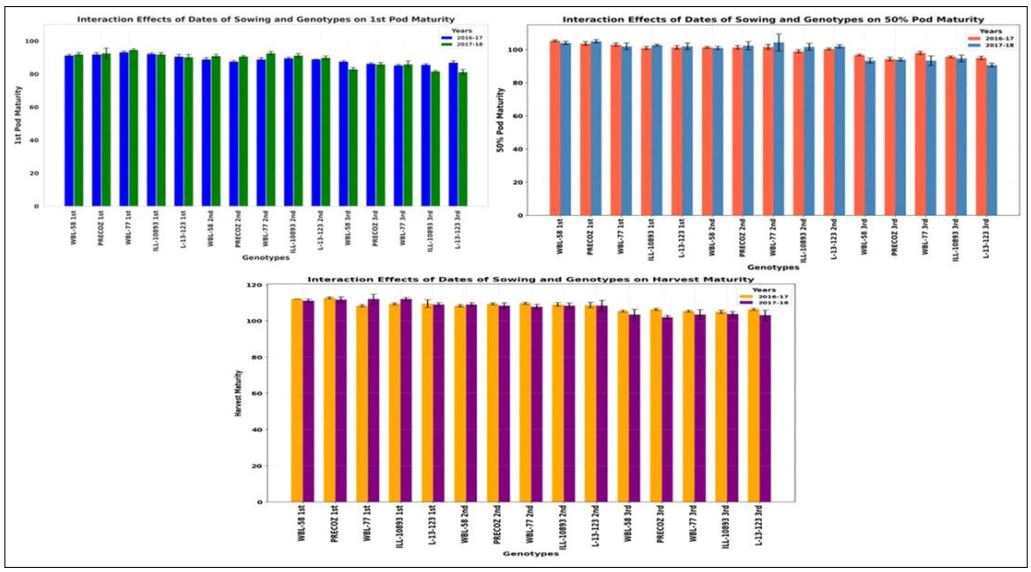


Fig 6: Interaction effects of sowing dates and genotypes on maturity phases in lentil.

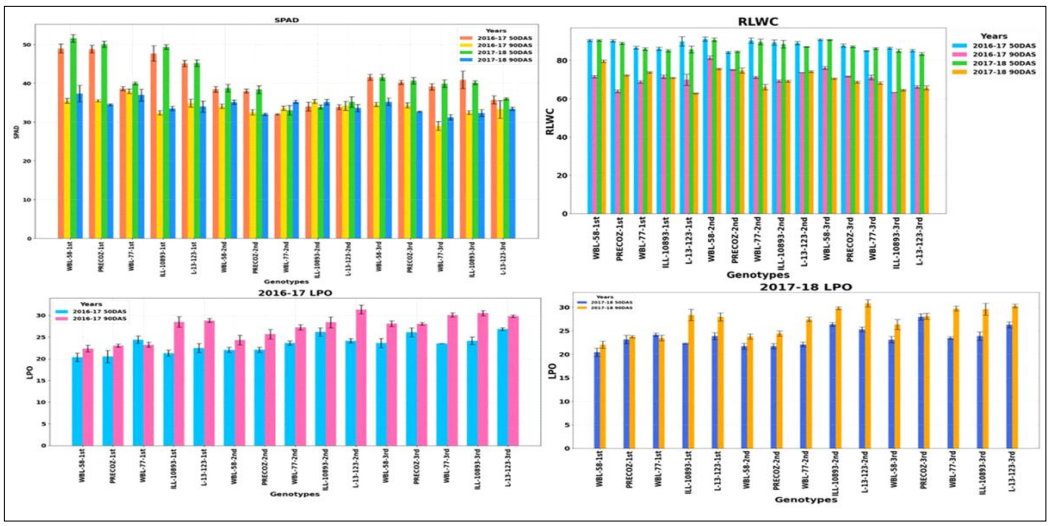


Fig 7: Comparative study of SPAD, RLWC and LPO value on different growth stages and different dates of sowing in different years.

higher MDA levels but maintained yield, suggesting efficient antioxidative defence mechanisms (Zeroual *et al.*, 2022).

Proline accumulation

Proline content increased significantly under late and very late sowing, particularly at 90 DAS (Fig 8). Genotypes WBL-58 and L-13-123 accumulated higher proline under stress, highlighting its role as an osmo-protectant and stress-adaptive metabolite (Brini and Saibi, 2023).

Effects of sowing dates on yield and yield attributes

Sowing date significantly influenced yield and yield-attributing traits in lentil, with highly significant effects of sowing dates, genotypes and their interactions. Optimal sowing on 15th November resulted in superior performance for major agronomic traits, including flowering time, pods per plant, seed weight, biological yield, seed yield and harvest index. In contrast, delayed sowing, particularly on 15th December, caused marked reductions in these traits and overall seed yield. Delayed sowing particularly on 15th December caused substantial reductions due to shortened growth duration, flower and pod abortion and impaired seed filling (Sen *et al.*, 2016). Considerable genotypic variability was observed, with L-13-123 consistently recording the lowest performance, indicating poor adaptation to delayed conditions (Table 3). The stress responsive index (SRI) further confirmed significant declines in yield traits under delayed sowing (Fig 9).

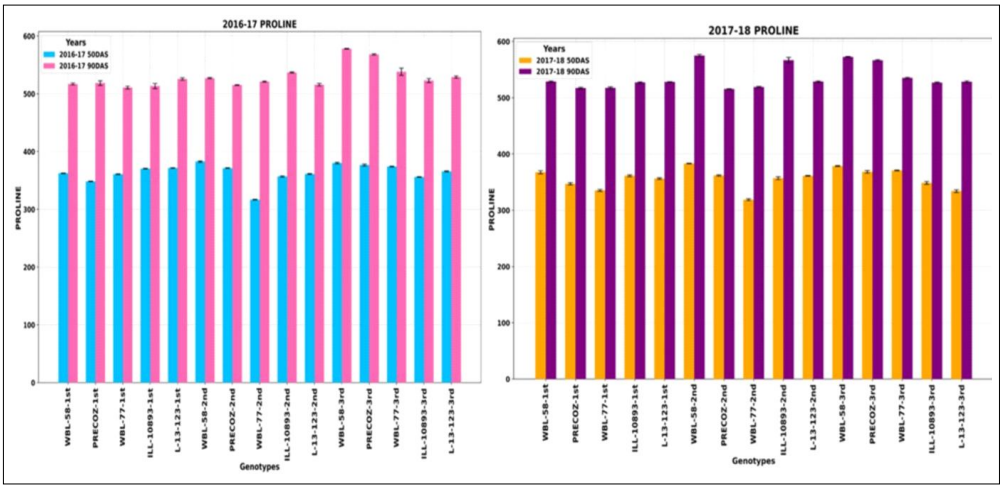


Fig 8: Comparative study of proline content on different growth stages and different dates of sowing in different years.

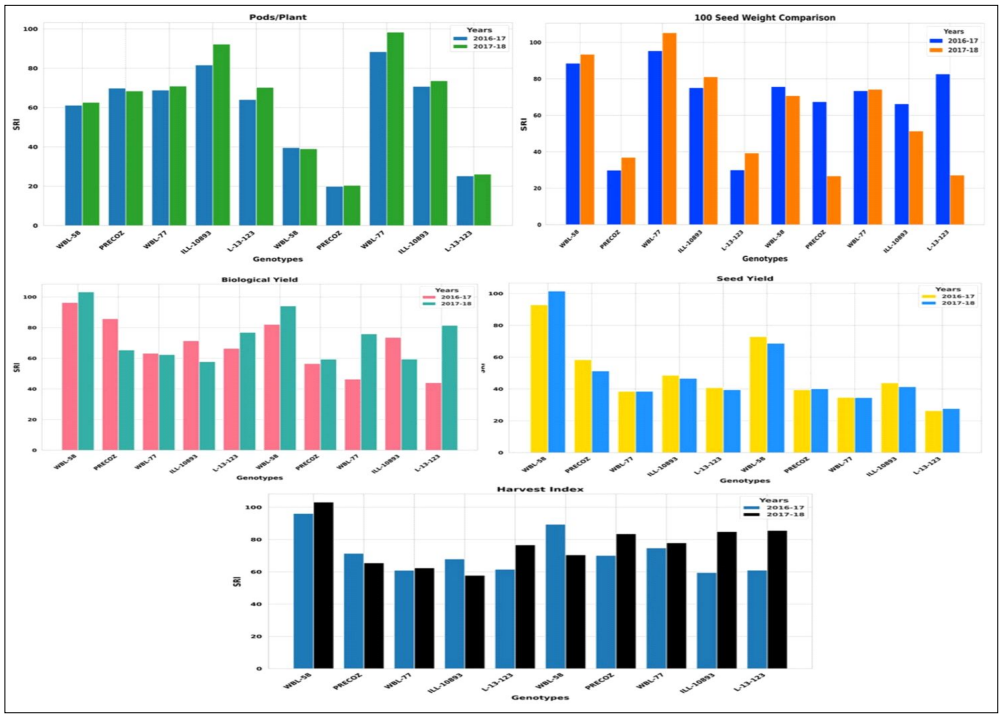


Fig 9 (a, b, c, d, e): Stress-responsive index (SRI) of key yield attributing traits under delayed sowing conditions.

Table 2b: Effect of genotypes on growth parameters in lentil.

Genotypes	Leaf wt ratio				Stem wt ratio				Root wt ratio			
	50 DAS		80 DAS		50 DAS		80 DAS		50 DAS		80 DAS	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
WBL-58	0.417±	0.380±	0.184±	0.204±	0.329±	0.395±	0.270±	0.317±	0.373±	0.324±	0.183±	0.117±
	0.020c	0.017b	0.004d	0.016d	0.019a	0.018a	0.015a	0.015a	0.021a	0.015a	0.006a	0.005a
PRECOZ	0.507±	0.383±	0.187±	0.286±	0.209±	0.300±	0.245±	0.307±	0.283±	0.317±	0.136±	0.076±
	0.020a	0.017ab	0.004c	0.016a	0.019e	0.018b	0.015b	0.015ab	0.021c	0.015bc	0.006e	0.005d
WBL-77	0.464±	0.399±	0.217±	0.271±	0.306±	0.391±	0.219±	0.306±	0.230±	0.210±	0.176±	0.094±
	0.020b	0.017a	0.004b	0.016b	0.019b	0.018a	0.015c	0.015ab	0.021e	0.015d	0.006b	0.005cd
ILL-10893	0.370±	0.364±	0.221±	0.242±	0.257±	0.311±	0.207±	0.312±	0.255±	0.318±	0.159±	0.097±
	0.020d	0.017c	0.004a	0.016cd	0.019c	0.018b	0.015d	0.015ab	0.021d	0.015b	0.006c	0.005c
L-13-123	0.464±	0.329±	0.179±	0.253±	0.219±	0.305±	0.201±	0.261±	0.317±	0.277±	0.145±	0.103±
	0.020b	0.017d	0.004e	0.016c	0.019d	0.018c	0.015d	0.015b	0.021b	0.015c	0.006d	0.005b

Table 3: Effect of genotypes on yield and yield attributing traits of lentil.

Genotypes	Pl. ht.(cm)		No of primary branches		Days to 1st flower		Days to 50% flower		Pods/pl		Seeds/ pod		100 seed wt (gm)		Biological yield/pl (gm)		Seed yield /pl(gm)		Harvest index (%)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
WBL-58	28.74±	28.49±	3.55±	3.00±	59.44±	59.22±	66.67±	66.00±	24.30±	29.12±	2.00±	2.11±	2.57±	2.51±	3.52±	3.36±	1.50±	1.51±	42.77±	36.92±
	0.63d	0.81d	0.26a	0.20b	0.61b	0.63a	0.81ab	0.54a	0.64a	0.43a	0.13a	0.19a	0.11a	0.07a	0.09d	0.13d	0.026a	0.035d	0.707a	1.34a
PRECOZ	38.07±	36.60±	2.78v	2.67±	54.00±	53.67±	64.44±	64.22±	19.91±	18.19±	2.11±	2.11±	2.15±	2.14±	4.07±	4.19±	1.19±	1.29±	8.44±	30.08±
	0.63b	0.81bc	0.26a	0.20c	0.61a	0.63b	0.81a	0.54b	0.64b	0.43b	0.13a	0.19a	0.11ab	0.07b	0.09c	0.13c	0.026c	0.035cd	20.707d	1.34b
WBL-77	37.56±	37.02±	3.55±	3.44±	52.56±	53.11±	65.89±	66.00±	14.89±	17.68±	2.00±	1.89±	2.0±	2.13±	4.38±	4.53±	1.34±	1.45±	32.50±	30.59±
	0.63b	0.81b	0.26a	0.20a	0.61b	0.63bc	0.81a	0.54a	0.64c	0.43c	0.13a	0.19b	0.119b	0.07c	0.09ab	0.13b	0.026b	0.035b	0.707b	1.34b
ILL-10893	40.81±	38.55±	2.56±	3.33±	52.00±	52.89±	62.33±	61.67±	19.64±	12.51±	2.00±	2.00±	1.74±	1.72±	4.45±	4.19±	1.34±	1.30±	29.27±	30.01±
	0.63a	0.81a	0.26a	0.20ab	0.61b	0.63c	0.81bc	0.54c	0.64b	0.43d	0.13a	0.19ab	0.11b	0.07e	0.09b	0.13c	0.026b	0.035c	0.707c	1.34b
L-13-123	33.72±	32.95±	2.56±	2.44±	47.670.	48.00±	59.00±	57.33±	18.58±	18.11±	1.78±	1.33±	1.70±	2.02±	4.58±	5.28±	1.24±	1.23±	27.10±	28.26±
	0.63c	0.81c	0.26a	0.20d	61±c	0.63d	0.81c	0.54d	0.64b	0.43bc	0.13a	0.19c	0.11b	0.07d	0.09a	0.13a	0.026c	0.03a	0.707e	1.34c

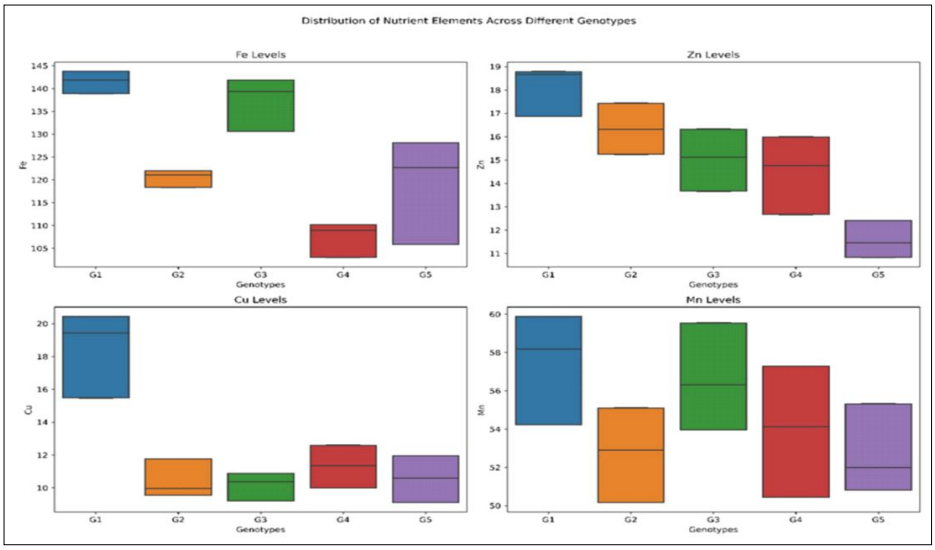


Fig 10: Genotyping difference of seed micronutrient content. Add a key to show what is G1…G5.

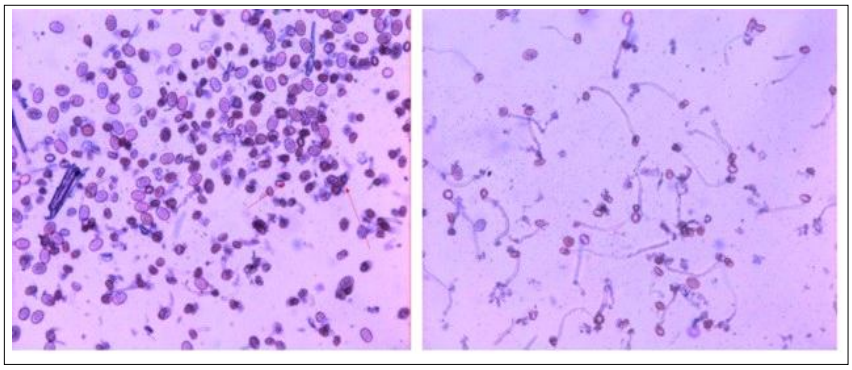


Fig 11*: In-vitro* pollen germination of L-13-123 and WBL-58 at 30°C temperature.

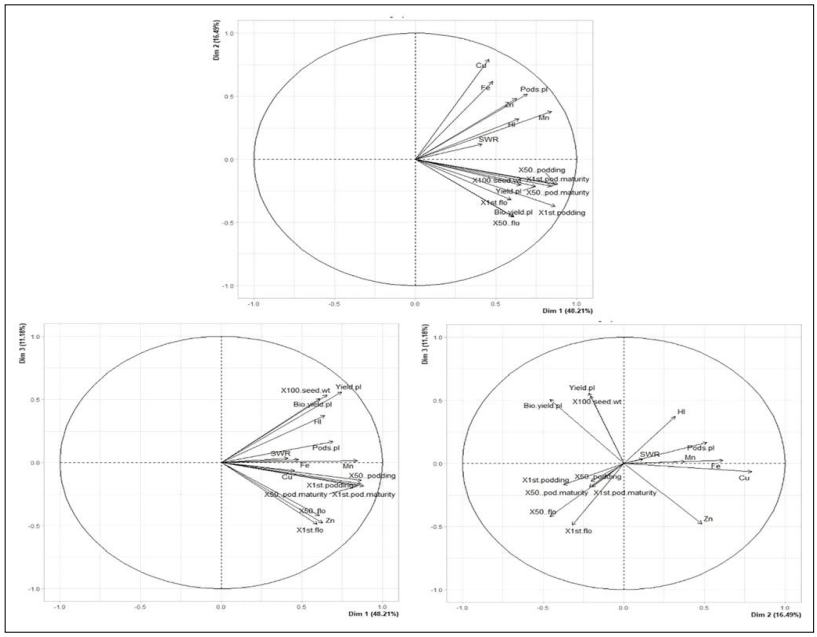


Fig 12: Biplot of principal component analysis.

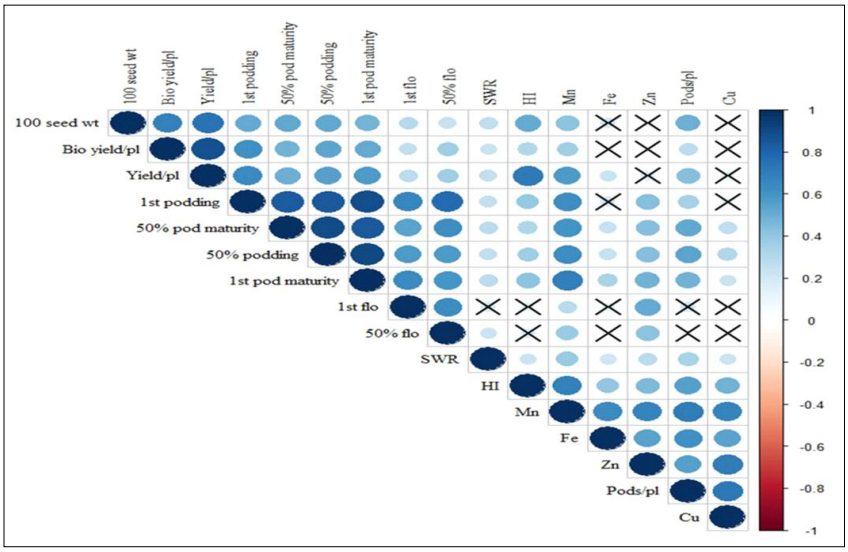


Fig 13: Correlation analysis of physiological, seed quality parameters and yield attribute.

Effect of sowing dates on seed micronutrients

There were no significant interactions between genotypes and sowing dates for seed micronutrient contents. However, the genotypic effect was significant with regards to Fe, Zn, Cu and Mn. But sowing date on its own was not significant effect. WBL-58 showed greater variability and relatively higher micronutrient levels compared to other genotypes (Fig 10). Relatively higher micronutrient accumulation due to genotypic effect is linked to impaired uptake, reduced transpiration and metabolic disruption during seed development (Ahmed *et al.*, 2024). Environmental stresses such as high temperature and drought exerted comparatively minimal effects on this WBL-58 genotype.

Effect of high temperature on pollen germination

In vitro pollen germination declined significantly with increasing temperature. At 30°C, pollen germination was severely inhibited, particularly in L-13-123, while WBL-58 retained partial germination and better pollen tube integrity (Fig 11). High temperature during flowering adversely affected pollen viability, leading to reduced seed set and yield (Sita *et al.*, 2018).

Principal component analysis

PCA revealed that the first three components explained 75.9% of total variation. PCA1 (48.2%) was dominated by flowering traits, PCA2 (16.5%) by pods per plant and copper content and PCA3 (11.2%) by seed weight and yield. Yield was positively associated with flowering traits, biological yield and iron content (Fig 12-13), indicating their critical role in determining performance under stress.

CONCLUSION

The study confirms that delayed sowing in lentil intensifies terminal heat and drought stress, markedly altering phenology, physiological traits, reproductive processes and yield and quality attributes. Shortened crop duration, impaired water relations, oxidative stress and reduced pollen viability collectively limited pod set, seed filling and micronutrient accumulation, leading to substantial yield losses. Significant genotypic variation was observed, with WBL-58 exhibiting superior physiological resilience, reproductive stability and dry matter partitioning under late sowing, while L-13-123 proved highly sensitive. These results emphasize the critical role of sowing time and stress-tolerant genotypes for sustaining lentil productivity under climate-vulnerable, late-sown conditions.

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Authors contribution

Ananya Baidya and Subhasis Mondal designed the study. Ananya Baidya conducted the field experiment and data acquisition and conducted lab analysis. Ananya Baidya, Subhasis Mondal, Rajeev Kumar, Ranjit Singh Gujjar, Santanu Banerjee, Kousik Atta and Nurnabi Meharul Alam conducted statistical analysis and prepared the graphs and figures. Ananya Baidya, Subhasis Mondal, Rajeev Kumar and Ranjit Singh Gujjar drafted and edited the manuscript. All authors contributed to the article and approved the submitted version.

Disclaimers

The views and opinions expressed in this article are solely those of the authors and do not necessarily reflect the official policy or position of the affiliated institutions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

REFERENCES

Ahmed, N., Zhang, B., Chachar, Z., Li, J., Xiao, G., Wang, Q. and Tu, P. (2024). Micronutrients and their effects on horticultural crop quality, productivity and sustainability. *Scientia Horticulturae*. **323:** 112512. https://doi.org/10.1016/j.scienta.2023.112512.

Akter, M., Paul, N.C., Sarkar, S.K., Mahapatra, C.K., Sarkar, M.A.R. and Paul, S.K. (2022). Growth analysis of short duration transplanted aus rice (cv. Parija) under three agronomic practices. *Archives of Agriculture and Environmental Science.* **7(1):** 51-60.

Akter, N. and Rafiqul Islam, M. (2017). Heat stress effects and management in wheat: A review. *Agronomy for sustainable development*. **37:** 1-17. https://doi.org/10.1007/s13593-017-0443-9.

Atta, K., Pal, A., Karmakar, S., Dutta, D., Jana, K. and Pal, A.K. (2023). Assessment of physiological and biochemical traits of ricebean [*Vigna umbellata* (Thunb.) Ohwi and Ohashi] seedling in response to equimolar concentration of copper and lead stress. *Legume Research.* **46(8):** 1001-1005. doi: 10.18805/LR-4820.

Baidya, A., Pal, A.K., Ali, M. A. and Nath, R. (2021). High-temperature stress and the fate of pollen germination and yield in lentil (*Lens culinaris* Medikus*). Indian Journal of Agricultural Research.* **55(2):** 144-150. doi: 10.18805/IJARe.A-5440.

Bera, A., Nath, R., Banerjee, P., Ghosh, A. and Reja, M.H. (2024). Evaluation of lentil genotypes in different sowing windows in the new alluvial zone of West Bengal. *Legume Research.* **47(6):** 911-916. doi: 10.18805/LR-5086.

Brini, F. and Saibi, W. (2023). Role of proline in regulating physiological and molecular aspects of plants under abiotic stress. In the role of growth regulators and phytohormones in overcoming environmental stress. *Academic Press*. (pp. 317-326).

Choukri, H., El Haddad, N., Aloui, K., Hejjaoui, K., El-Baouchi, A., Smouni, A. and Kumar, S. (2022). Effect of high temperature stress during the reproductive stage on grain yield and nutritional quality of lentil (*Lens culinaris* Medikus). *Frontiers in Nutrition.* **9:** 857469.

Erskine, W., Muehlbauer, F.J. and Short, R.W. (1990). Stages of development in lentil. *Experimental Agriculture.* **26(3):** 297-302.

FAOSTAT (2022). Food and agriculture organization of the United Nations, Statistical database, Rome. (Accessed July 01, 2023).

Fisher, J.C. and Pry, R.H. (1971). A Simple Substitution Model of Technological Change. *Technological Forecasting and Social Change.* **3:** 75-88.

Gomez, K.A. and Gomez, A.A. (1984). Statistical Procedures for Agricultural Research. John Wiley and Sons.

Heath, R.L. and Packer, L. (1968). Photoperoxidation in isolated chloroplasts: I. Kinetics and stoichiometry of fatty acid peroxidation. *Archives of Biochemistry and Biophysics.* **125(1):** 189-198.

Jackson, W.A., Flesher, D. and Hageman, R.H. (1973). Nitrate uptake by dark-grown corn seedlings: Some characteristics of apparent induction. *Plant Physiology.* **51(1):** 120-127.

Kvet, J. (1971). Methods of growth analysis. *Plant Photosynthetic Production Manual of Methods.* pp. 343-391.

Liu, K., Zhang, C., Guan, B., Yang, R., Liu, K., Wang, Z., Li, X., Xue, K., Yin, L. and Wang, X. (2021). The effect of different sowing dates on dry matter and nitrogen dynamics for winter wheat: An experimental simulation study. *Peer* **9:** 11700. https://doi.org/10.7717/peerj.11700.

Malik, D.P., Devi, M. and Reddy, A.A. (2022). Global status of lentil production with special reference to India. *The Indian Journal of Agricultural Sciences.* **92(4):** 46-50.

Mohanty, S.K. and Sridhar, R. (1982). Physiology of rice tungro virus disease: Proline accumulation due to infection. *Physiologia Plantarum.* **56(1):** 89-93.

Nandi, R.A.M.P.R.O.S.A.D., Mukherjee, S., Bandyopadhyay, P. K., Saha, M., Singh, K.C., Ghatak, P. and Chakraborti, P. (2023). Assessment and mitigation of soil water stress of rainfed lentil (*Lens culinaries* Medik) through sowing time, tillage and potassic fertilization disparities. *Agricultural Water Management.* **277:** 108120.

Niles, W.L. and Quesenberry, K.H. (1992). Pollen germination of rhizome peanut cv. Florigraze. *Peanut Science.* **19:** 105-107.

Perez, N., GarcÍÍa-Espinosa, R., LóÓpez-Castañeda, C., Acosta-Gallegos, J.A. and Simpson, J. (2002). Water relations, histopathology and growth of common bean (*Phaseolus vulgaris* L.) during pathogenesis of *Macrophomina phaseolina* under drought stress. *Physiol. Mol. Plant Pathol.* **60:** 185-195.

Prasad, S., Agrawal, K.K. and Kumar, R. (2019). Productivity, profitability, quality and nutrient uptake of heat tolerant wheat (*Triticum aestivum*) cultivars as influenced by staggered sowing and nutrition levels. *Indian Journal of Agricultural Sciences.* **89(4):** 670-677.

Rather, A.A., Natrajan, S., Lone, A.S., Tiwari, R.K., Lal, M.K. and Kumar, R. (2022). Exogenous application of salicylic acid improves growth and yield of black gram *Vigna mungo* L. by improving antioxidant defense mechanism under saline conditions. *Russian Journal of Plant Physiology.* **69(7):** 151.

Richards, L.A. (1948). Porous plate apparatus for measuring moisture retention and transmission by soil. *Soil Science.* **66(2):** 105-110.

Sehgal, A., Sita, K., Kumar, J., Kumar, S., Singh, S., Siddique, K.H.M. and Nayyar, H. (2017). Effects of drought, heat and their interaction on the growth, yield and photosynthetic function of lentil (*Lens culinaris* Medikus) genotypes varying in heat and drought sensitivity. *Front. Plant Sci.* **8:** https://doi.org/10.3389/fpls.2017.01776.

Sen, S., Ghosh, M., Mazumdar, D., Saha, B. and Dolui, S. (2016). Effect of sowing date and variety on phenology and yield of lentil during *rabi* season. *Journal of Crop and Weed.* **12(1):** 135-138.

Sita, K., Sehgal, A., Bhandari, K., Kumar, J., Kumar, S., Singh, S. and Nayyar, H. (2018). Impact of heat stress during seed filling on seed quality and seed yield in lentil (*Lens culinaris Medikus*) genotypes. *Journal of the Science of Food and Agriculture.* **98(13):** 5134-5141. https://doi.org/10.1002/jsfa.9054.

Venugopalan, V.K., Nath, R., Sengupta, K., Nalia, A., Banerjee, S., Chandran, M.A.S. and Hossain, A. (2021). The response of lentil (*Lens culinaris Medik*.) to soil moisture and heat stress under different dates of sowing and foliar application of micronutrients. *Frontiers in Plant Science.* **12:** 679-469.

Watson, D.J. (1952). The physiological basis of variation in yield. *Advances in Agronomy*. **4:** 101-145.

Xu, Q.Q., Sami, A., Zhang, H., Jin, X.Z., Zheng, W.Y., Zhu, Z.Y. and Zhu, Z.H. (2022). Combined influence of low temperature and drought on different varieties of rapeseed (*Brassica napus* L.). *South African Journal of Botany.* **147:** 400-414. https://doi.org/10.1016/j.sajb.2022.02.003.

Zeroual, A., Baidani, A. and Idrissi, O. (2022). Drought stress in lentil (*Lens culinaris,* medik) and approaches for its management. *Horticulturae.* **9(1):** 1. https://doi.org/10.3390/horticulturae9010001.