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Effect of Heat Stress on Morphological, Physiological and Yield-Related Traits in Forty Maize (Zea mays L.) Inbred Lines Under Natural Late-Sown Conditions

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Abstract*— Heat stress during reproductive stages is a major constraint to maize productivity, particularly under late-sown spring regimes. In present investigation, forty maize inbred lines were evaluated for morphological, physiological and yield-related responses under normal (7 February) and late (12 March) sowing at two locations (CCS HAU RRS, Uchani, Karnal and KVK, Damla, Yamunanagar) across Spring 2021 and 2022. A randomized complete block design with two replications generated eight environments. Traits recorded included days to 50% anthesis and silking, anthesis–silking interval (ASI), leaf senescence score (1–9), tassel blast (%), leaf firing (%), silk receptivity (%), kernels per row, hundred grain weight, shelling percentage, canopy temperature and plot grain yield. Pooled ANOVA indicated highly significant effects of genotype (G), environment (E) and G×E for all traits. Late sowing accelerated phenology, increased ASI and heat-injury symptoms (senescence, tassel blast, leaf firing), reduced silk receptivity and caused severe yield reductions (0.049–0.288 kg plot^{-1} under late sowing vs. 0.584–0.862 kg plot^{-1} under normal sowing). Genotypes HKI 1011, HKI MBR139, HKI 1344 and HKI 1664 maintained lower ASI, reduced senescence, higher silk receptivity and relatively stable yields under stress, qualifying them as potential donors for heat-tolerance breeding.

***Keywords*— maize, heat stress, late sowing, anthesis–silking interval, grain yield, inbred lines, canopy temperature, G×E**

I. INTRODUCTION

Maize (Zea mays L.) is a globally important cereal noted for high yield potential and diverse uses. Its reproductive development is particularly sensitive to high temperatures, with documented reductions in pollen viability, silk receptivity and grain filling when daytime temperatures exceed 32–35°C. Several studies estimate that small increases in mean temperature can cause significant yield penalties in maize through combined effects on phenology and reproductive success (e.g., Lobell et al., 2011; Zaidi et al., 2019). In northern India, spring maize often faces terminal heat stress when sowing is delayed, exposing flowering and grain filling to high April–May temperatures and heat waves. Heat stress symptoms in maize include leaf firing, premature senescence, tassel blast, increased anthesis–silking interval (ASI) and reduced kernel set and grain weight.

Breeding for heat tolerance requires identification of stable genetic sources exhibiting reproductive resilience (short ASI, sustained silk receptivity), maintained assimilate supply (delayed senescence), and lower canopy temperatures. Prior studies have used field-imposed late-sowing regimes and controlled-environment assays to screen for tolerance, but multi-environment evaluation under natural stress is essential to capture realistic G×E interactions. This study aimed to (i) quantify the effect of late-sown heat stress on morphological, physiological and yield-related traits across forty inbred lines, (ii) identify tolerant genotypes with stable performance under stress, and (iii) discuss physiological bases for tolerance and implications for maize breeding under warming climates.

II. MATERIALS AND METHODS

Germplasm and experimental sites

Forty maize inbred lines maintained at CCS Haryana Agricultural University Regional Research Station, Uchani, Karnal were evaluated. Details of each inbred (pedigree, origin) are provided in Table 1.

Table 1 List of forty maize inbred lines

Detail of maize inbred lines					
Sr. No.	**Name of inbred line**	**Source**	**Sr. No.**	**Name of inbred line**	**Source**
1.	HKI 139	CML 139	21.	HKI 1344	Subtropical heterotic group B
2.	HKI 1025	BC 176	22.	HKI 1654-15	HKI 163×HKI 1128
3.	HKI 1041-2	BC 318	23.	HKI 1040-4	BC 318
4.	HKI 1011	BC 175	24.	HKI 327 T	CML 327
5.	HKI 1040-7	BC 318	25.	LM 16	(JS 2×J 3022)×(Tarun×Makka Safed)-yellow
6.	HKI 1654	HKI 163×LM 13	26.	HKI 163	CML 163
7.	HKI 295	Karnal 4	27.	HKI 1354-2	Sub tropical heterotic group A
8.	HKI 1041	BC 318	28.	HKI 1354-7	HKI 1352-2
9.	HKI 488 T	Cargil 501	29.	HKI 1378	HKI 1344 X1354-2
10.	HKI 1558-4	Hybrid selected from farmers' field	30.	LM 17	Partap 69
11.	HKI 1657	HKI 161×LM13	31.	HKI 161	CML 161
12.	HKI 1128	Hybrid selected from farmers' field	32.	Bio inbred 47	HKI 194-7×HKI 193-2
13.	HKI 488	Cargil 501	33.	HKI 164-7-2	CML 164
14.	DQL 2300	1278-4-2-1-1-1	34.	HKI 164-7-4	CML 164
15.	HKI 1126	Hybrid selected from farmers' field	35.	HKI 164-7-6	CML 164
16.	HKI 766 WG	HM1	36.	HKI 193-2	CML 193
17.	HKI 323	Pool 28, sub-tropocal	37.	HKI 1664	HKI1128×LM 13
18.	HKI 1105	Cargil 633	38.	HKI 193-1	CML 193
19.	HKI MBR139	Pozarica 86	39.	HKI L287	CML 287
20.	HKI 2067 Y	HKI 193-2×HKI 163	40.	HKI 288-2	CML 288

Field experiments and sowing regimes

Field trials were conducted at two locations (Uchani, Karnal and KVK Damla, Yamunanagar) in Spring 2021 and 2022, generating four location–year combinations. Two sowing dates were used: normal (7 February) and late (12 March), creating eight environments. Each environment was a randomized complete block design with two replications with plot size 3.6 m². Standard agronomic practices and plant protection measures were followed uniformly across sites and seasons. Irrigation was applied to avoid confounding drought stress; hence observed effects are attributable primarily to thermal regimes.

Environmental monitoring

Daily maximum, minimum and mean temperatures and relative humidity were recorded at each site. Canopy temperature was measured at midday during the peak reproductive stage using an infrared thermometer from non-senescing leaves, averaged across five representative plants per plot. Typical high temperatures during April–May ranged 34–40°C (Figure a,b,c and d).

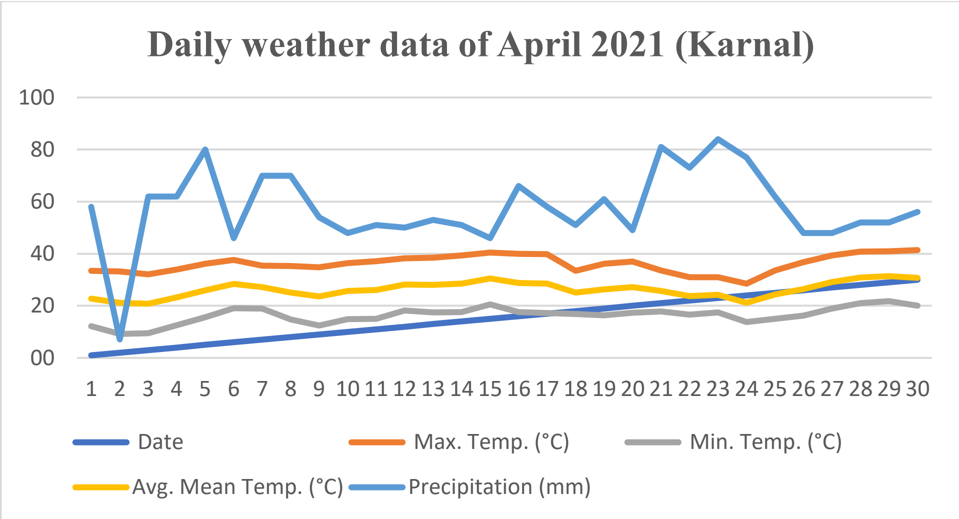

Figure (a) Daily temperature (mean, maximum and minimum) and precipitation during crop season of Spring 2021

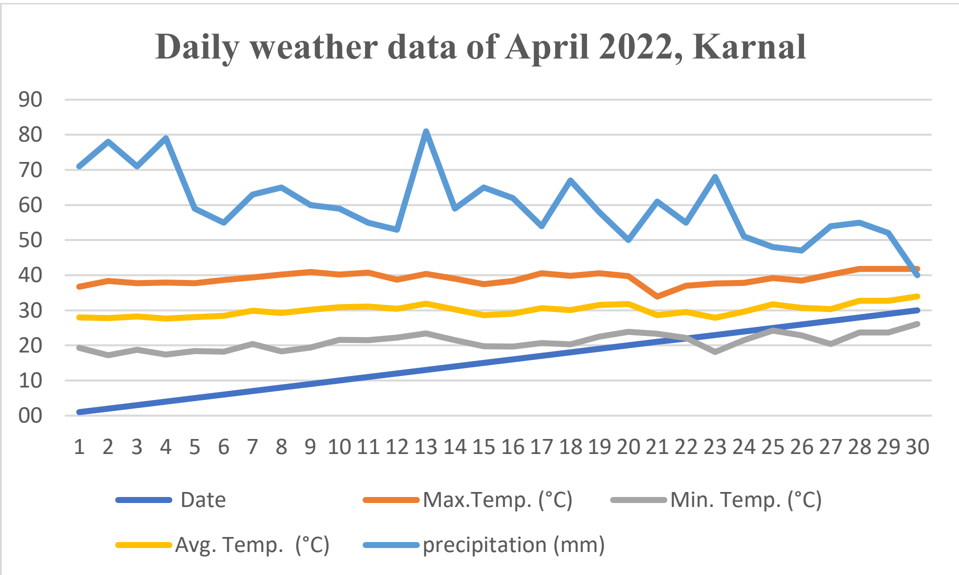

Figure (b) Daily temperature (mean, maximum and minimum) and precipitation during crop season of Spring 2022

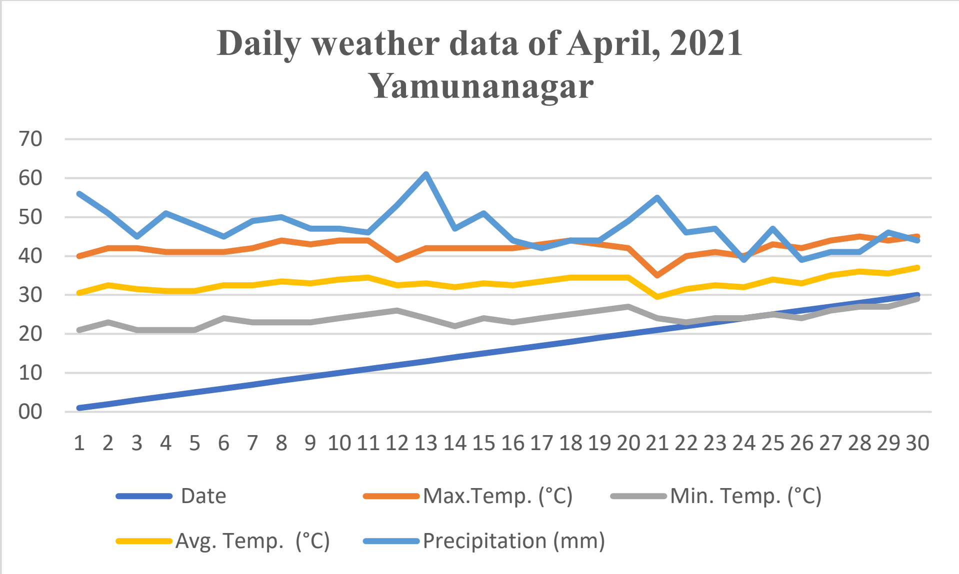

Figure (c) Daily temperature (mean, maximum and minimum) and precipitation during crop season of Spring 2021

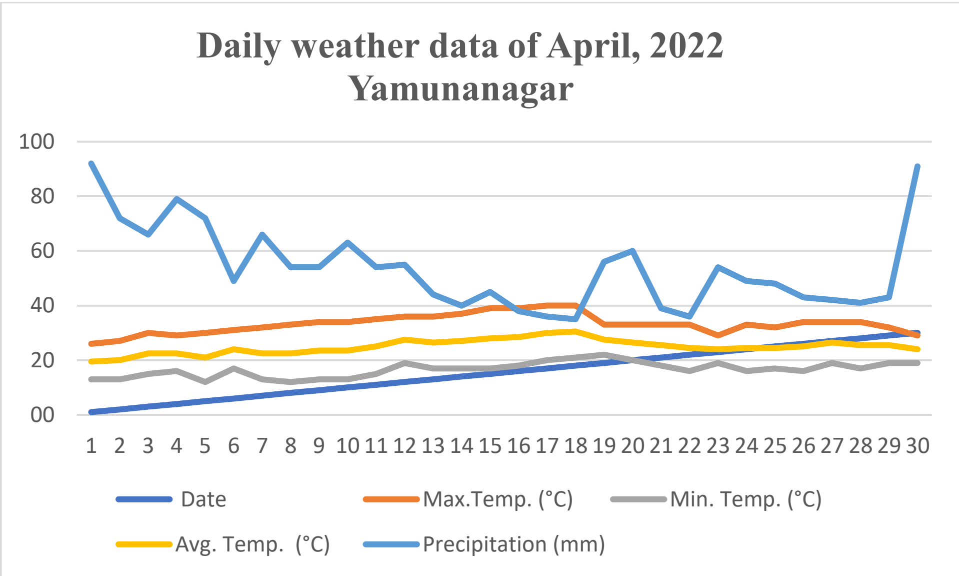

Figure (d) Daily temperature (mean, maximum and minimum) and precipitation during crop season of Spring 2022

Trait measurement

Observations were recorded on five competitive plants per plot for anthesis and silking dates to compute days to 50% anthesis/silking and ASI. Silk receptivity (%) was measured within 2–3 days of silking by scoring successful kernel set following controlled pollination. Leaf senescence was scored on a 1–9 visual scale (1 = healthy, 9 = fully senesced). Tassel blast and leaf firing were scored as percent incidence per plot. Kernels per row were counted from five cobs per plot; hundred kernel weight and shelling percentage were measured from plot-harvest samples; grain yield per plot was recorded at physiological maturity and adjusted to kg plot^{-1}.

Statistical analysis

Combined (pooled) analysis of variance across environments was performed. Genotype means across environments and under each sowing regime were estimated using least-square means and compared. Stability and adaptability under stress were assessed via G×E interaction patterns and traits associated with tolerance (ASI, silk receptivity, canopy temperature).

III. RESULTS

Late sowing shifted reproductive stages into a warmer period; mean maximum temperatures during anthesis–

silking increased by ~3–6°C relative to normal sowing, with peak daily maxima reaching 34–40°C in April–May across sites. Consequently, days to 50% anthesis and silking were significantly reduced under late sowing (phenological acceleration), reflecting thermal time effects.

Pooled ANOVA

Combined ANOVA across eight environments depicted in table 2 revealed highly significant ($p < 0.01$) effects of genotype, environment and G×E interaction for all measured traits (Table 2). For most traits, the environment mean squares were considerably higher than those of genotypes and G×E interactions, suggesting that environmental factors exerted the greatest influence on phenotypic performance. This was particularly evident for phenology-related traits such as days to 50% anthesis (DA), days to 50% silking(DS), and as well as for grain yield per plant (GYP). Such high environmental influence implies that location and seasonal conditions play a major role in trait expression and must be considered when selecting genotypes for stability and adaptability, while genotype and G×E contributed substantially to variance in reproductive synchrony (ASI), silk receptivity and senescence.

Table 2: Pooled Mean sum of squares of inbred lines for various traits

Source	Degree of Freedom	DA	DS	ASI	TB	LF	LS	NKR
Trials	912	18.60	2.78	15.20	18.34	164.44***	1.18	13.67
Genotypes	39	198.06 ***	4.96***	238.23***	119.41***	285.24***	3.55***	63.29***
Environments	7	1074.64 ***	257.07***	290.77***	141.78***	8393.30***	70.78***	242.68*
G*E interaction	273	1.63**	0.84***	2.83***	19.58***	64.06***	0.68***	11.71***
Pooled error	312	2.09	0.26	1.59	1.14	3.57	0.23	4.19

Source	Degree of Freedom	S%	HGW	SR	GYP	CT
Trials	912	198.44	10.15	211.97	64.56	1.69***
Genotypes	39	288.00***	26.64***	377.53***	29.83***	4.27***
Environments	7	20925.22***	730.36***	16371.98***	7592.94***	96.02***
G*E interaction	273	38.48***	4.65***	104.91***	7.41***	0.99***
Pooled error	312	6.68	1.69	20.69	1.58	

** Significant at (P< 0.01) percent,* significant at (P<0.05) percent level of probability, respectively and *** TB and LF data was not availableunder normal sown conditions

Phenological responses

Performance of various inbred lines for contrasting traits are presented in table 3. Under normal sowing, days to 50% anthesis ranged 66.25–80.75 days; under late sowing this range reduced to 59.63–74.38 days. ASI increased markedly under late sowing, from 1.00–3.00 days (normal) to 3.63–6.75 days (late), with the largest increases in HKI 1558-4 and HKI 288-2 (indicative of severe reproductive asynchrony). Genotypes HKI 139 and HKI 1664 maintained lower ASI under stress, suggesting better reproductive synchrony and potential tolerance. Leaf senescence scores increased under late sowing (up to 5.25 in HKI 1378), indicating accelerated chlorophyll loss and reduced leaf functional duration. Tassel blast and leaf firing were negligible under normal sowing but prevalent under late sowing ranged between 10-25 % and 10-20% respectively; maximum tassel blast occurred in HKI 323 (20.88%), HKI 1128 (15.54%) and HKI 288-2 (14.84%). Canopy temperatures measured at peak reproductive stage were higher for susceptible genotypes; tolerant genotypes displayed relatively lower canopy temperatures, suggesting better transpirational cooling or stomatal regulation. Silk receptivity declined sharply under late sowing (normal: 34.93–63.23%; late: 9.09–34.07%). Genotypes HKI 163, HKI MBR139 and Bio inbred 47 retained comparatively higher silk receptivity under stress. Kernels per row and kernel set were significantly reduced under heat stress, corresponding to increased ASI and reduced silk viability. Heat stress caused substantial reductions in hundred kernel weight, shelling percentage and grain yield. Under normal sowing, grain yield ranged 0.584–0.862 kg per plot; under late sowing it dropped to 0.049–0.288 kg per plot. Genotypes HKI MBR139, HKI 1011 and HKI 1025 recorded the highest yields under stress, with HKI MBR139 showing the best combination of silk receptivity, kernel set and reduced ASI.

Table 3: Pooled mean of traits of forty maize inbred across normal sown and late sown environment

		GYP (kg)		% Yield Reduction	DA (days)		DS (days)		ASI	
Sr. No.	**Genotype**	**Normal**	**Late**		**Normal**	**Late**	**Normal**	**Late**	**Normal**	**Late**
1	**HKI 139**	0.728	0.240	67.09	66.50	60.13	67.88	63.75	1.25	3.63
2	**HKI1025**	0.644	0.255	60.46	66.25	59.63	68.50	64.50	1.25	4.88
3	**HKI 1041-2**	0.646	0.229	64.48	67.38	60.50	68.38	64.88	1.00	4.38
4	**HKI 1011**	0.712	0.287	59.64	67.63	61.38	69.50	65.38	1.75	4.00
5	**HKI 1040-7**	0.713	0.164	77.00	73.13	66.38	74.25	71.38	1.25	5.00
6	**HKI 1654**	0.584	0.215	63.22	73.75	64.88	74.75	70.75	1.00	5.88
7	**HKI 295**	0.681	0.174	74.47	73.25	66.25	74.75	71.13	1.50	4.88
8	**HKI 1041**	0.783	0.225	71.22	73.50	66.38	75.00	71.13	1.50	4.75
9	**HKI 488 T**	0.815	0.142	82.56	72.88	66.50	73.88	72.63	1.00	6.13
10	**HKI 1558-4**	0.825	0.141	82.86	73.13	67.13	74.13	73.88	1.00	6.75
11	**HKI 1657**	0.689	0.238	65.49	73.38	66.63	75.13	71.50	2.00	4.88
12	**HKI 1128**	0.724	0.049	93.18	73.00	67.13	74.75	73.25	1.75	6.13
13	**HKI 488**	0.813	0.209	74.28	73.88	66.88	74.88	71.00	1.00	4.13
14	**DQL 2300**	0.814	0.239	70.67	74.13	66.63	75.75	71.38	1.75	4.75
15	**HKI1126**	0.692	0.078	88.68	73.88	68.50	75.88	75.25	2.00	6.75
16	**HKI 766 WG**	0.704	0.251	64.31	73.75	67.00	75.75	72.13	2.00	5.13
17	**HKI 323**	0.738	0.074	90.01	74.50	69.13	76.00	74.63	1.63	5.50
18	**HKI 1105**	0.760	0.205	73.08	75.25	67.88	76.25	72.00	1.00	4.13
19	**HKI MBR139**	0.699	0.288	58.81	73.75	67.00	75.13	71.13	1.38	4.13
20	**HKI 2067 Y**	0.786	0.214	72.82	74.50	67.50	76.50	72.63	2.00	5.13
21	**HKI 1344**	0.862	0.186	78.40	74.88	68.25	75.88	73.38	1.25	5.13
22	**1654-15-ER 1-1-1 WINK11**	0.717	0.233	67.55	74.00	67.63	76.00	71.75	2.00	4.13
23	**HKI 1040-4**	0.717	0.239	66.75	75.00	68.25	76.75	73.13	1.88	4.88
24	**HKI 327 T**	0.722	0.052	92.80	74.63	68.00	76.13	74.63	1.50	6.63
25	**LM 16**	0.801	0.200	74.99	77.63	69.88	79.63	75.63	2.00	5.75
26	**HKI 163**	0.852	0.249	70.72	77.63	70.25	78.63	74.50	1.00	4.25

27	**HKI 1354-2**	0.846	0.107	87.32	77.88	70.13	79.00	75.25	1.00	5.13
28	**HKI 1354-7**	0.819	0.177	78.42	78.13	71.50	80.38	76.88	2.25	5.38
29	**HKI 1378**	0.831	0.137	83.48	78.50	71.38	80.00	77.38	1.50	6.00
30	**LM 17**	0.831	0.187	77.54	78.50	71.50	81.13	77.25	2.63	5.75
31	**HKI 161**	0.828	0.227	72.54	77.88	70.88	79.63	76.00	1.75	5.13
32	**Bio inbred 47 ER3-1 Wink 11**	0.714	0.204	71.46	78.50	71.75	81.50	76.63	3.00	4.88
33	**HKI 164-7-2**	0.822	0.203	75.36	77.38	70.25	79.50	75.25	2.25	5.00
34	**HKI 164-7-4**	0.791	0.180	77.21	77.63	70.63	80.13	74.75	2.63	4.13
35	**HKI 164-7-6**	0.793	0.184	76.81	78.00	70.75	80.25	75.38	2.25	4.63
36	**HKI 193-2**	0.786	0.189	75.97	77.88	70.63	80.88	75.63	3.00	5.00
37	**HKI 1664**	0.825	0.237	71.29	78.00	72.75	80.50	76.63	2.50	3.88
38	**HKI 193-1**	0.766	0.204	73.32	78.25	71.63	80.50	76.75	2.38	5.13
39	**HKI L287**	0.721	0.090	87.48	79.38	74.38	82.13	80.75	2.88	6.38
40	**HKI 288-2**	0.782	0.058	92.59	80.75	73.88	83.75	80.63	3.00	6.75

		LS (score)		**NKR**		**SR (%)**		**S%**		**hgw**	
Sr. No.	**Genotype**	**Normal**	**Late**	**Normal**	**Late**	**Normal**	**Late**	**Normal**	**Late**	**Normal**	**Late**
1	**HKI 139**	3.25	3.50	19.42	19.33	52.96	28.10	51.81	27.74	19.74	14.39
2	**HKI1025**	2.63	3.38	19.50	17.71	38.20	31.55	51.54	29.74	18.59	12.09
3	**HKI 1041-2**	3.25	3.75	19.80	17.10	47.24	31.48	52.24	27.81	19.80	13.15
4	**HKI 1011**	2.50	3.75	19.95	17.02	45.05	28.33	49.90	31.23	18.04	15.07
5	**HKI 1040-7**	2.63	4.50	18.61	17.60	46.44	21.49	50.98	20.34	19.35	15.02
6	**HKI 1654**	3.00	3.50	22.97	16.10	46.38	30.70	45.91	27.58	18.05	15.06
7	**HKI 295**	2.13	3.50	21.46	18.70	49.89	20.87	51.56	23.64	20.09	15.25
8	**HKI 1041**	2.38	3.25	23.72	18.65	54.32	28.71	54.91	26.71	20.02	15.55
9	**HKI 488 T**	2.13	4.75	25.21	14.75	55.94	24.36	54.56	19.27	20.35	12.47
10	**HKI 1558-4**	1.88	4.75	19.49	14.85	53.80	21.82	54.21	18.63	19.90	13.51
11	**HKI 1657**	2.13	3.50	22.93	18.60	44.97	31.30	49.93	28.73	21.30	15.43
12	**HKI 1128**	2.25	5.00	23.36	14.50	43.97	11.43	52.38	8.82	22.65	14.74
13	**HKI 488**	2.25	3.25	21.69	15.00	52.57	30.19	59.28	25.14	23.11	17.43
14	**DQL 2300**	1.25	3.00	24.25	24.30	52.69	19.42	59.54	28.33	23.68	17.20
15	**HKI1126**	2.38	4.75	19.60	16.10	48.06	11.31	50.06	11.17	21.48	14.23

16	**HKI 766 WG**	2.13	3.50	15.47	17.50	47.72	32.71	50.59	29.88	18.45	17.33
17	**HKI 323**	2.25	4.75	18.85	14.40	46.22	17.00	51.56	11.03	21.28	13.12
18	**HKI 1105**	2.00	3.00	22.70	17.00	52.66	24.47	59.67	26.91	22.53	17.15
19	**HKI MBR139**	2.00	2.75	19.91	19.10	49.62	32.29	59.81	30.05	18.85	16.06
20	**HKI 2067 Y**	1.88	3.25	21.21	15.93	53.60	25.45	51.06	25.01	18.55	17.64
21	**HKI 1344**	1.38	3.25	23.12	23.75	57.17	19.56	62.86	21.92	22.85	19.02
22	**1654-15-ER 1-1-1 WINK11**	2.13	3.00	17.10	17.30	48.58	28.21	60.06	30.86	21.85	17.47
23	**HKI 1040-4**	2.75	3.00	16.40	22.10	53.81	22.90	54.16	27.65	19.66	17.55
24	**HKI 327 T**	1.38	4.25	22.50	15.10	34.93	9.09	51.01	8.52	23.03	11.11
25	**LM 16**	1.25	3.50	25.20	18.40	44.57	23.69	52.31	24.68	22.05	15.57
26	**HKI 163**	1.25	2.75	19.29	15.50	54.75	33.80	59.56	28.62	21.78	15.73
27	**HKI 1354-2**	1.63	3.00	26.81	21.30	57.82	12.72	56.86	14.22	23.35	16.41
28	**HKI 1354-7**	1.50	2.50	18.27	21.30	54.26	20.24	47.71	23.88	21.55	17.48
29	**HKI 1378**	1.88	5.25	19.76	14.80	59.69	23.97	54.69	19.31	23.39	14.49
30	**LM 17**	1.50	3.50	20.69	23.30	54.44	18.32	55.56	24.66	25.03	16.64
31	**HKI 161**	1.50	3.00	18.48	14.45	60.17	32.05	63.06	28.48	19.13	17.88
32	**Bio inbred 47 ER3-1 Wink 11**	2.13	3.25	21.93	16.30	47.16	34.07	53.56	26.82	20.11	15.49
33	**HKI 164-7-2**	1.75	3.00	21.13	17.30	51.83	26.54	48.60	24.78	21.95	15.86
34	**HKI 164-7-4**	1.50	3.25	18.77	14.35	51.64	29.46	59.66	23.10	24.88	15.73
35	**HKI 164-7-6**	2.13	3.25	19.78	13.55	51.98	30.57	48.69	22.97	18.15	16.66
36	**HKI 193-2**	2.00	3.25	21.32	19.05	47.51	22.33	48.56	25.07	22.45	15.28
37	**HKI 1664**	1.38	4.50	17.63	22.20	63.23	24.49	49.06	27.71	18.55	19.30
38	**HKI 193-1**	1.25	3.63	17.62	18.00	50.74	30.61	49.16	26.81	19.65	15.85
39	**HKI L287**	1.88	4.50	18.01	16.35	43.43	13.45	49.32	13.45	21.23	13.65
40	**HKI 288-2**	1.25	4.88	21.02	15.75	49.91	10.75	53.06	9.54	21.19	14.76

Late sown Conditions	**Normal sown Conditions**	**Traits**
		**Silk receptivity inbred line LM 16 decreases under Late sown conditions**

Late sown Conditions	**Normal sown Conditions**	**Traits**
		**Poor appearance of HKI 1025 cob under late sown conditions**
		**Comparatively better performing for grain yeild per plot under late sown conditions HKI MBR 139**

Late sown conditions	Normal sown conditions	Traits
		**q) Comparatively better performing for grain yeild per plot under late sown conditions HKI 163**
r) Leaf Senescence Trait (Score 3)	**s) Leaf firing in HKI 288-2**	**t) Tassel Blast in 327 T**
		

Identification of tolerant genotypes

Integrating mean performance, stability across environments and trait profiles, genotypes HKI 1011, HKI MBR139, HKI 1344 and HKI 1664 were identified as relatively heat tolerant: they combined lower ASI, higher silk receptivity, reduced senescence and better yield stability under late sowing. These inbreds represent promising donors for breeding heat-resilient hybrids and populations.

IV. DISCUSSION

The present study confirms that late sowing imposes terminal heat stress that accelerates phenology but disrupts reproductive processes in maize, thereby reducing grain yield. The marked increase in ASI under heat stress aligns with earlier reports linking reproductive asynchrony to poor kernel set and yield loss (Chiuta and Mutenga, 2025 and Yadav *et al.,* 2016). High temperature decreases the time for tasseling and pollen shedding, increases anthesis silking interval and parchedness of silk all of which reduces the pollen viability, pollen quantity and successful seed setting (Pranay *et al*., 2022 amd Jodage *et al.,* 2018). Further heat stresses maize plants are unable to convert photosynthates into starch in pollens. Thus, decreases the pollen numbers, their viability and starch synthesis contributes to the distorted fertilisation process and ultimately to the yield loss (Wang *et al.,* 2019). Reduced silk receptivity and pollen viability under high temperatures are primary physiological causes of kernel abortion (Noor *et al*., 2019 and Krishna *et al*., 2021); genotypes maintaining silk receptivity under stress (e.g., HKI MBR139) thereby maintain better kernel set and yield. Leaf senescence and canopy temperature differences suggest that tolerant genotypes preserve canopy function longer and/or maintain better transpirational cooling, contributing to sustained photosynthate supply for grain filling. Lower canopy temperature in tolerant lines may reflect higher stomatal conductance or deeper rooting enabling water uptake—traits often associated with heat tolerance but requiring direct physiological confirmation (Tollenaar and Lee, 2002 and Prasad *et al.,* 2011). Genetic variability and significant G×E interactions indicate that selection for heat tolerance must be performed across multiple stress environments. The tolerant inbreds identified here can be used in crossing programs.

V. CONCLUSIONS AND FUTURE PERSPECTIVES

Late-sown heat stress significantly impaired reproductive synchrony, silk receptivity and grain filling, causing heavy yield losses. However, substantial genetic variation exists among the evaluated inbreds. HKI 1011, HKI MBR139, HKI 1344 and HKI 1664 combined favorable reproductive and physiological traits under stress and are recommended as donor parents for developing heat-tolerant hybrids. Breeding programs should integrate multi-environment field screening with physiological and molecular characterization to select mechanisms conferring tolerance.

Present investigation can be further extend to controlled-environment experiments to validate field-identified tolerant lines and dissect physiological mechanisms (pollen viability, silk desiccation, stomatal behavior). Measuring the additional physiological traits (chlorophyll fluorescence, SPAD, membrane thermostability, root traits) and water relations to link phenotype to mechanism. QTL mapping or GWAS can be implemented across the inbred panel to identify genetic loci associated with ASI, silk receptivity and canopy temperature.

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