

ASSESSMENT OF HEAT STRESS TOLERANCE USING YIELD-BASED INDICES IN BREAD WHEAT (*TRITICUM AESTIVUM* L.) GENOTYPES UNDER TIMELY AND LATE SOWN CONDITIONS UNDER DOON VALLEY OF UTTARAKHAND

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ABSTRACT

Terminal heat stress is one of the major abiotic constraints limiting wheat productivity under changing climatic conditions. The present investigation was conducted to evaluate 32 bread wheat (*Triticum aestivum* L.) genotypes under timely sown and late sown environments for identification of heat tolerant genotypes using yield based stress indices and heat map analysis. Significant variation was observed among the genotypes for grain yield and all heat tolerance indices, indicating substantial genetic variability for heat stress tolerance. Grain yield under timely sown conditions ranged from 4.91 to 8.80 g plant⁻¹ with a mean of 6.32 g plant⁻¹, whereas under late sown conditions it ranged from 4.49 to 6.10 g plant⁻¹ with a mean of 5.11 g plant⁻¹, resulting in an overall yield reduction of 19.15% under terminal heat stress. Different stress indices including Stress Tolerance Index (STI), Tolerance Index (TOL), Mean Productivity (MP), Geometric Mean Productivity (GMP), Harmonic Mean (HM), Yield Stability Index (YSI), Stress Susceptibility Percentage Index (SSPI), Relative Stress Index (RSI), Mean Relative Performance (MRP), and Percent Yield Reduction (PYR) were evaluated for identification of stable genotypes. Genotypes HI1634, MP3336, HD3086, GW463, and DBW303 exhibited superior performance under both stress and non-stress conditions and were identified as promising heat tolerant genotypes based on higher STI, GMP, MP, HM, and MRP values coupled with lower TOL and PYR values. Heat map analysis grouped the indices into productivity based and susceptibility based clusters. Productivity indices including STI, GMP, MP, HM, MRP, YI, Yp, and Ys exhibited strong positive association with grain yield under both environments, whereas susceptibility indices such as TOL, SSPI, RSI, and PYR showed negative association with yield stability. The strong correlation among STI, GMP, MP, and HM confirmed their suitability for simultaneous selection of high yielding and heat tolerant genotypes. The study concluded that combined utilization of stress indices along with heat map based correlation analysis is an effective approach for identification of heat tolerant wheat genotypes. The identified superior genotypes may serve as valuable donor parents in future breeding programmes aimed at developing climate resilient wheat cultivars suitable for late sown and terminal heat stress environments.

KEYWORDS: Heat stress, wheat, timely sown, late sown, stress indices, genotype stability, climate resilience

1. INTRODUCTION

Heat stress has emerged as one of the most severe abiotic constraints affecting global wheat production under changing climatic conditions. Continuous rise in global temperature, increased frequency of heat waves, erratic rainfall patterns, and terminal heat stress during reproductive stages have significantly reduced wheat productivity worldwide. Wheat (*Triticum aestivum* L.) is highly sensitive to elevated temperature, particularly during flowering, anthesis, and grain filling stages, where even short periods of high temperature can severely impair grain development and final yield. According to Lobell and Field (2007), global wheat yield declines by approximately 5–6% with every 1°C rise in temperature. Similarly, Asseng et al. (2015) reported that global wheat production may decline by nearly 6% for each degree increase in mean temperature under future climate scenarios. The optimum temperature for wheat growth ranges between 15–22°C, whereas temperatures exceeding 30–35°C during reproductive stages negatively affect photosynthesis, pollen viability, grain filling duration, starch synthesis, and assimilate translocation. Heat stress accelerates leaf senescence, reduces chlorophyll content, increases reactive oxygen species (ROS) accumulation, and ultimately decreases grain weight and grain yield. Studies conducted by Farooq et al. (2011) and Prasad and Djanaguiraman (2014) demonstrated that terminal heat stress significantly reduces grain filling duration and thousand grain weight in wheat. Furthermore, Farhad et al. (2023) highlighted that high temperature stress alters physiological and biochemical processes including chlorophyll stability, membrane integrity, and enzyme activity, ultimately affecting crop productivity.

In India, particularly in the Indo-Gangetic Plains and Himalayan foothill regions such as Uttarakhand, delayed sowing and increasing spring temperatures expose wheat crops to severe terminal heat stress during February and March. This condition shortens the grain filling period and causes substantial reduction in yield and grain quality.

Rising temperatures and irregular climatic conditions in the Dehradun valley have further intensified the need for identifying heat tolerant wheat genotypes capable of maintaining stable yield under stress environments.

To minimize the adverse effects of heat stress, identification of heat tolerant genotypes through reliable stress indices has become an important approach in wheat breeding programmes. Yield based heat tolerance indices provide a quantitative measure of genotype performance under stress and non-stress conditions and help breeders identify stable and high yielding genotypes. Among the most widely used indices are Stress Tolerance Index (STI), Mean Productivity (MP), Geometric Mean Productivity (GMP), Harmonic Mean (HM), Yield Stability Index (YSI), Tolerance Index (TOL), and Stress Susceptibility Percentage Index (SSPI). The foundational work of **Fernandez (1992)** established STI and GMP as highly effective selection criteria for identifying genotypes with superior performance under both stress and optimum environments. Similarly, **Rosielle and Hamblin (1981)** suggested that lower TOL values indicate better stress tolerance and yield stability.

Several researchers have demonstrated that combined use of STI, GMP, MP, and HM effectively identifies wheat genotypes possessing high yield potential and stress adaptability. Heat map analysis has further strengthened the interpretation of stress indices by visually representing correlation patterns among indices and yield traits. Heat maps group indices into productivity based and susceptibility based categories, thereby helping breeders identify the most reliable parameters for genotype selection. Studies by **Mohammadi and Amri (2008)** and **Talebi et al. (2009)** reported that STI, GMP, and MP exhibit strong positive correlation with grain yield under stress conditions, whereas TOL and SSPI are more closely associated with susceptibility and yield reduction. Similar clustering patterns in heat map analysis have been widely reported in wheat stress physiology and breeding studies.

In the present investigation, heat stress indices along with heat map based correlation analysis were utilized to evaluate 32 bread wheat genotypes under timely and late sown environments. The study aimed to identify superior wheat germplasm possessing stable yield performance, physiological adaptability, and heat stress tolerance for their potential utilization in future wheat improvement programmes targeting climate resilient agriculture.

2. MATERIALS AND METHODS

The field experiment was conducted at Jigyasa University, Dehradun, during Rabi 2024-25. The experimental material comprised thirty-two wheat genotypes evaluated under two sowing conditions, namely timely sown in November 2024 and late sown in December 2024 to impose terminal heat stress.

The experiment was laid out in a randomized block design with three replications. Standard agronomic practices were followed to raise a healthy crop. Grain yield per plant was recorded under both environments, designated as Y_p (normal condition) and Y_s (heat stress condition).

The following calculations were used to compute heat tolerance indices:

- Stress tolerance (TOL) = Y_p – Y_s — **Rosielle and Hamblin (1981)**
- Stress tolerance index (STI) = (Y_p × Y_s)/X_p² — **Fernandez (1992)**
- Stress susceptibility percentage index (SSPI) = (Y_p – Y_s/2X_p) × 100 — **Moosavi et al. (2008)**
- Yield index (YI) = Y_s/X_s — **Gavuzzi et al. (1997)**
- Yield stability index (YSI) = Y_s/Y_p — **Bousslama and Schapaugh (1984)**
- Relative stress index (RSI) = (Y_p/Y_s)/(X_s/X_p) — **Fischer and Maurer (1978)**
- Mean productivity (MP) = (Y_p + Y_s)/2 — **Rosielle and Hamblin (1981)**
- Geometric mean productivity (GMP) = √(Y_s × Y_p) — **Fernandez (1992)**
- Harmonic mean (HM) = 2(Y_p × Y_s)/(Y_p + Y_s) — **Bidinger et al. (1987)**
- Mean relative performance (MRP) = (Y_s/X_s) + (Y_p/X_p) — **Ramirez and Kelly (1998)**
- Percent yield reduction (PYR) = [(Y_p – Y_s)/Y_p] × 100 — **Farshadfar et al. (2012)**

Yield index (YI) and yield stability index (YSI) were computed as ratios of yield under stress conditions to mean yield and normal yield, respectively. Mean relative performance (MRP) and stress susceptibility percentage index (SSPI) were calculated following standard procedures. Percent yield reduction (PYR) was estimated as [(Y_p – Y_s)/Y_p] × 100. **Redhu et al. (2024)**

3. RESULTS AND DISCUSSION

3.1 Effect of Heat Stress on Grain Yield

Grain yield under timely sown conditions ranged from 4.91 t/ha to 8.80 t/ha with a mean of 6.32 t/ha, whereas under late sown conditions it ranged from 4.49 t/ha to 6.10 t/ha with a mean of 5.11 t/ha (figure :1). The overall reduction of 19.15% indicated a substantial adverse effect of terminal heat stress on wheat productivity. Similar reductions in grain yield under elevated temperature conditions have been reported by **Farooq et al. (2011)**, and **Redhu et al. (2024)**.

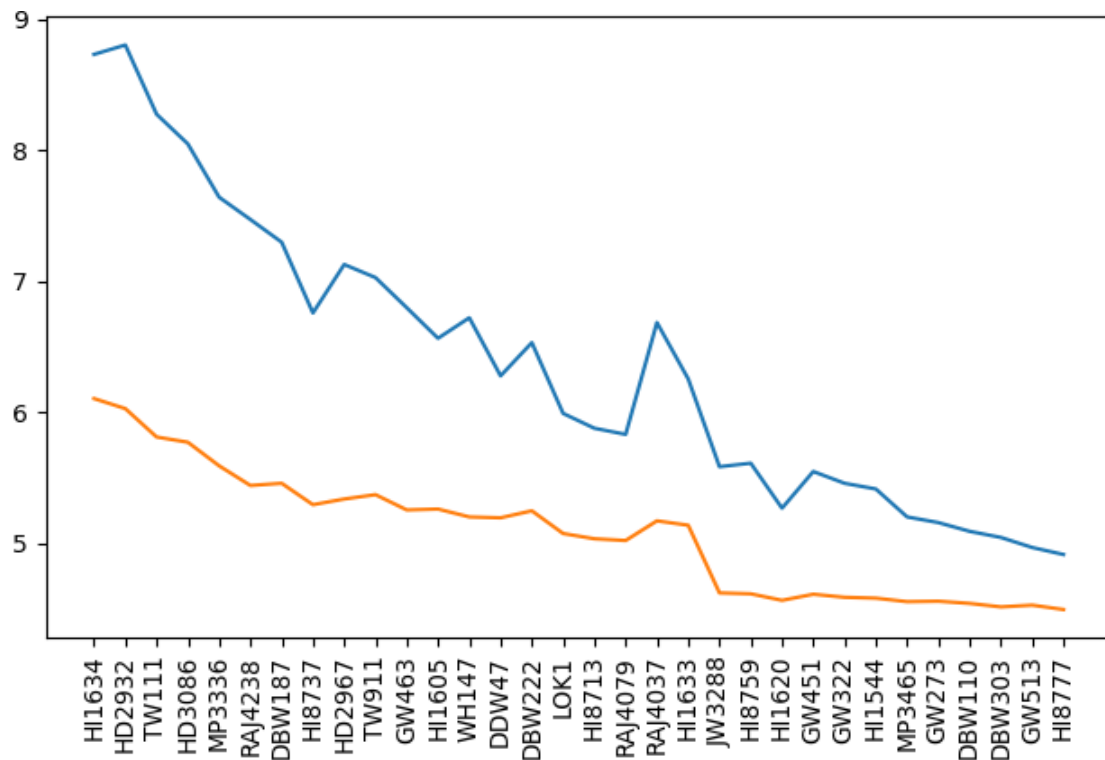


Figure 1: Yield under normal and heat stress conditions

3.2 Evaluation of Stress Indices

Heat Tolerance Indices under Timely and Late Sown Conditions

The performance of 32 wheat genotypes under timely sown (Yp) and late sown (Ys) conditions was evaluated using different heat tolerance indices including TOL, STI, SSPI, YI, YSI, RSI, MP, GMP, HM, MRP and PYR. (Table:1) Considerable variability was observed among the genotypes for all the indices, indicating differential response of genotypes to terminal heat stress.

Yield under Timely Sown Condition (Yp)

The yield under timely sown condition (Yp) ranged from 4.91 to 8.73. The highest Yp was recorded in HI1634 (8.73), followed by HD2932 (8.80), TW111 (8.27) and HD3086 (8.05), indicating their superior yield potential under optimum conditions. The lowest Yp was observed in HI8777 (4.91), followed by GW513 (4.97) and DBW303 (5.04). Genotypes with higher Yp values generally maintained better performance under stress conditions and contributed positively towards heat tolerance indices.

Yield under Late Sown Condition (Ys)

The yield under late sown condition (Ys) varied from 4.49 to 6.10. The maximum Ys was recorded in HI1634 (6.10), followed by HD2932 (6.03), TW111 (5.81) and HD3086 (5.77), indicating better adaptation under heat stress conditions. The minimum Ys was observed in HI8777 (4.49), followed by GW513 (4.53) and DBW303 (4.51). Higher Ys values reflected the ability of genotypes to withstand terminal heat stress and maintain productivity.

Tolerance Index (TOL)

Tolerance index (TOL), which measures reduction in yield under stress conditions, ranged from 0.42 to 2.75. The highest TOL value was observed in HD2932 (2.77), followed by HI1634 (2.63), TW111 (2.46) and HD3086 (2.28), indicating greater yield reduction under stress despite their high yield potential. The lowest TOL was recorded in HI8777 (0.42), followed by GW513 (0.44), DBW303 (0.53) and DBW110 (0.55), indicating lower yield reduction under heat stress.

Stress Tolerance Index (STI)

The stress tolerance index (STI) ranged from 0.54 to 1.31. The highest STI value was recorded in HI1634 (1.31), followed by HD2932 (1.30), TW111 (1.18) and HD3086 (1.14), indicating superior performance under both optimum and stress conditions. The lowest STI was observed in HI8777 (0.54), followed by GW513 (0.55), DBW303 (0.56) and DBW110 (0.57). Genotypes with higher STI values are considered more desirable for heat stress tolerance breeding programmes.

Stress Susceptibility Percentage Index (SSPI)

The SSPI values ranged from 3.30 to 21.77. The highest SSPI was recorded in HD2932 (21.77), followed by HI1634 (20.61), TW111 (19.33) and HD3086 (17.86), indicating comparatively higher susceptibility to stress. The lowest SSPI values were observed in HI8777 (3.30), GW513 (3.45), DBW303 (4.16) and DBW110 (4.31), reflecting lower susceptibility to heat stress.

Yield Index (YI)

Yield index (YI) varied from 0.88 to 1.20. The maximum YI was observed in HI1634 (1.20), followed by HD2932 (1.19), TW111 (1.14) and HD3086 (1.14). The minimum YI was recorded in HI8777 (0.88), followed by GW513 (0.89), DBW303 (0.89) and DBW110 (0.89). Higher YI values indicated better yield performance under stress relative to the overall mean.

Yield Stability Index (YSI)

The yield stability index (YSI) ranged from 0.68 to 0.91. The highest YSI was recorded in HI8777 (0.91), followed by GW513 (0.91), DBW303 (0.89) and GW273 (0.88), indicating greater stability under stress conditions. The lowest YSI values were observed in HD2932 (0.68), HI1634 (0.70), TW111 (0.70) and HD3086 (0.72), suggesting comparatively lower yield stability despite high productivity.

Relative Stress Index (RSI)

The RSI values ranged from 0.87 to 1.16. The highest RSI was recorded in HD2932 (1.16), followed by TW111 (1.13), HI1634 (1.14) and HD3086 (1.11), indicating better relative performance under stress. The minimum RSI was observed in HI8777 (0.87), followed by GW513 (0.87), DBW303 (0.89) and DBW110 (0.89).

Mean Productivity (MP)

Mean productivity (MP) ranged from 4.70 to 7.42. The highest MP was recorded in HI1634 (7.42), followed by HD2932 (7.41), TW111 (7.04) and HD3086 (6.91). The lowest MP was observed in HI8777 (4.70), followed by GW513 (4.75), DBW303 (4.78) and DBW110 (4.82). Higher MP values indicate better average performance across both environments.

Geometric Mean Productivity (GMP)

The geometric mean productivity (GMP) varied from 4.70 to 7.30. The highest GMP was recorded in HI1634 (7.30), followed by HD2932 (7.28), TW111 (6.93) and HD3086 (6.81). The lowest GMP was observed in HI8777 (4.70), followed by GW513 (4.74), DBW303 (4.77) and DBW110 (4.81). Higher GMP values indicate stable performance under both stress and non-stress conditions.

Harmonic Mean (HM)

Harmonic mean (HM) ranged from 4.69 to 7.18. The highest HM was observed in HI1634 (7.18), followed by HD2932 (7.15), TW111 (6.83) and HD3086 (6.72). The lowest HM was recorded in HI8777 (4.69), followed by GW513 (4.74), DBW303 (4.76) and DBW110 (4.80). Genotypes with higher HM values are considered more stable under variable environments.

Mean Relative Performance (MRP)

The MRP value ranged from 1.66 to 2.57. The highest MRP was recorded in HI1634 (2.57), followed by HD2932 (2.57), TW111 (2.44) and HD3086 (2.40). The minimum MRP was observed in HI8777 (1.66), followed by GW513 (1.67), DBW303 (1.68) and DBW110 (1.69).

Percent Yield Reduction (PYR)

Percent yield reduction (PYR) ranged from 8.55 to 31.53%. The maximum PYR was observed in HD2932 (31.53%), followed by HI1634 (30.09%), TW111 (29.77%) and HD3086 (28.29%), indicating greater reduction in yield under heat stress. The minimum PYR was recorded in HI8777 (8.55%), followed by GW513 (8.86%), DBW303 (10.51%) and DBW110 (10.81%), suggesting better tolerance to terminal heat stress. Similar findings were observed by **Lamba et al. (2023)** and **Yadav et al. (2023)**, who reported STI as one of the most reliable indices for identifying heat tolerant wheat genotypes.

Genotypes	Yp	Ys	TOL	STI	SSPI	YI	YSI	RSI	MP	GMP	HM	MRP	PYR
HI1634	8.73	6.10	2.62	1.31	20.60	1.20	0.699	1.14	7.416	7.299	7.184	2.571	30.087
HD2932	8.80	6.02	2.77	1.30	21.77	1.18	0.684	1.16	7.414	7.283	7.154	2.567	31.528
TW111	8.27	5.81	2.46	1.18	19.32	1.14	0.702	1.13	7.041	6.933	6.826	2.442	29.774
HD3086	8.04	5.77	2.27	1.14	17.86	1.13	0.717	1.11	6.908	6.813	6.720	2.398	28.293
MP3336	7.64	5.59	2.05	1.05	16.08	1.10	0.73	1.08	6.615	6.535	6.456	2.299	26.832
RAJ4238	7.47	5.44	2.03	1.00	15.92	1.07	0.728	1.09	6.455	6.374	6.295	2.243	27.175
DBW187	7.29	5.45	1.84	0.98	14.43	1.07	0.747	1.06	6.376	6.309	6.243	2.219	25.216
HI8737	6.75	5.29	1.46	0.88	11.48	1.04	0.78	1.01	6.025	5.980	5.936	2.102	21.657
HD2967	7.12	5.33	1.79	0.93	14.04	1.05	0.748	1.06	6.231	6.167	6.103	2.168	25.116
TW911	7.02	5.37	1.65	0.92	12.99	1.05	0.764	1.04	6.198	6.142	6.087	2.159	23.576
GW463	6.79	5.25	1.54	0.87	12.10	1.03	0.77	1.031	6.025	5.975	5.926	2.100	22.707
HI1605	6.56	5.26	1.30	0.85	10.22	1.03	0.80	0.994	5.911	5.875	5.839	2.065	19.857
WH147	6.72	5.2	1.52	0.86	11.92	1.02	0.773	1.029	5.96	5.911	5.863	2.078	22.619
DDW47	6.27	5.19	1.08	0.80	8.49	1.02	0.827	0.963	5.735	5.709	5.683	2.007	17.259
DBW222	6.53	5.24	1.28	0.84	10.06	1.03	0.803	0.991	5.888	5.853	5.818	2.057	19.652

LOK1	5.99	5.07	0.91	0.74	7.19	0.99	0.8469	0.941	5.531	5.512	5.493	1.938	15.303
HI8713	5.87	5.03	0.84	0.72	6.61	0.99	0.8564	0.930	5.455	5.438	5.422	1.913	14.350
RAJ4079	5.83	5.02	0.81	0.72	6.35	0.98	0.8610	0.925	5.425	5.409	5.394	1.903	13.893
RAJ4037	6.68	5.17	1.51	0.85	11.87	1.01	0.773	1.03	5.926	5.878	5.830	2.066	22.643
HI1633	6.25	5.13	1.11	0.79	8.76	1.01	0.8214	0.970	5.695	5.667	5.640	1.992	17.857
JW3288	5.58	4.62	0.96	0.63	7.55	0.90	0.8274	0.963	5.10	5.078	5.056	1.785	17.253
HI8759	5.61	4.61	0.99	0.63	7.81	0.90	0.8223	0.969	5.111	5.087	5.063	1.788	17.765
HI1620	5.26	4.56	0.70	0.59	5.51	0.89	0.866	0.919	4.915	4.902	4.889	1.724	13.354
GW451	5.54	4.61	0.93	0.62	7.34	0.90	0.83	0.958	5.078	5.056	5.035	1.777	16.887
GW322	5.45	4.58	0.87	0.61	6.82	0.90	0.84	0.948	5.021	5.002	4.983	1.759	15.943
HI1544	5.41	4.58	0.83	0.61	6.53	0.90	0.84	0.942	4.996	4.979	4.961	1.751	15.394
MP3465	5.2	4.55	0.64	0.58	5.07	0.89	0.87	0.910	4.876	4.865	4.855	1.712	12.435
GW273	5.15	4.55	0.6	0.57	4.70	0.89	0.88	0.901	4.856	4.847	4.838	1.706	11.635
DBW110	5.09	4.54	0.55	0.56	4.31	0.89	0.89	0.893	4.815	4.807	4.799	1.692	10.805
DBW303	5.04	4.51	0.53	0.56	4.15	0.88	0.89	0.890	4.778	4.770	4.763	1.679	10.508
GW513	4.96	4.52	0.44	0.55	3.45	0.89	0.91	0.874	4.746	4.741	4.736	1.670	8.859
HI8777	4.91	4.49	0.42	0.54	3.29	0.88	0.91	0.871517	4.703333	4.698	4.693	1.655	8.548

Table 1: Descriptive statistics for yield and heat tolerance indices across all studied genotypes

3.3 Heat Map Analysis

The heat map analysis clearly differentiated the heat stress indices into two major groups based on their correlation pattern. The first group consisted of productivity and tolerance based indices including STI, GMP, MP, HM, MRP, YI, Yp, and Ys, which showed strong positive association among themselves and with grain yield under both environments. The second group comprised susceptibility related indices such as TOL, SSPI, RSI, and PYR, which were positively associated with each other but negatively associated with stress tolerance and yield stability. This clustering pattern indicated that productivity based indices are more reliable for identification of superior heat tolerant wheat genotypes.

Among the evaluated genotypes, HI1634 and HD2932 recorded the highest Stress Tolerance Index (STI) values (1.31 and 1.30, respectively), indicating superior adaptability under both stress and non-stress environments. These genotypes also exhibited higher values for Geometric Mean Productivity (GMP), Mean Productivity (MP), Harmonic Mean (HM), and Mean Relative Performance (MRP), reflecting better yield stability under heat stress conditions. Similar observations were reported by **Fernandez (1992)**, **Gavuzzi et al. (1997)**, and **Mohammadi and Amri (2008)**, who identified STI, GMP, and MP as highly effective indices for selecting stress tolerant and stable wheat genotypes.

The strong positive correlation among STI, GMP, MP, HM, and MRP observed in the heat map indicates that these indices effectively identify genotypes capable of maintaining higher productivity under both favorable and stress conditions. Genotypes possessing higher values for these indices exhibited lower yield reduction and superior stress adaptability. Similar findings were reported by **Talebi et al. (2009)** and **Mohammadi et al. (2010)**, who demonstrated that GMP and STI are strongly associated with yield performance under heat stress conditions.

Conversely, Tolerance Index (TOL), Stress Susceptibility Percentage Index (SSPI), Relative Stress Index (RSI), and Percent Yield Reduction (PYR) were associated with greater yield reduction under stress and therefore proved more useful for identifying susceptible genotypes. Genotypes with higher TOL and PYR values exhibited poor yield stability and greater sensitivity to terminal heat stress. Similar conclusions were reported by **Rosielle and Hamblin (1981)**, who suggested that lower TOL values are indicative of better stress tolerance. The heat map further revealed that STI, GMP, HM, and MP exhibited strong positive correlation with both Yp and Ys, confirming their suitability as ideal selection criteria for simultaneous improvement of yield potential and stress tolerance. The clustering of these indices near grain yield traits suggests that selection based on these parameters would effectively improve wheat productivity under late sown heat stress environments.

The superior performance of genotypes HI1634, HD2932, MP3336, and GW463 may be attributed to their ability to maintain physiological efficiency, chlorophyll stability, grain filling duration, and assimilate partitioning under elevated temperature conditions. Similar physiological mechanisms associated with heat tolerance in wheat were reported by **Reynolds et al. (2001)** and **Farhad et al. (2023)**. Overall, the combined use of STI, GMP, MP, and HM was found to be the most effective approach for identifying stable and heat tolerant wheat genotypes under terminal heat stress conditions. The heat map analysis further strengthened the reliability of these indices by demonstrating their close association with grain yield under both normal and stress environments. The study

therefore confirmed that heat stress indices coupled with correlation based heat map analysis can serve as efficient tools for screening wheat germplasm and developing climate resilient wheat cultivars.

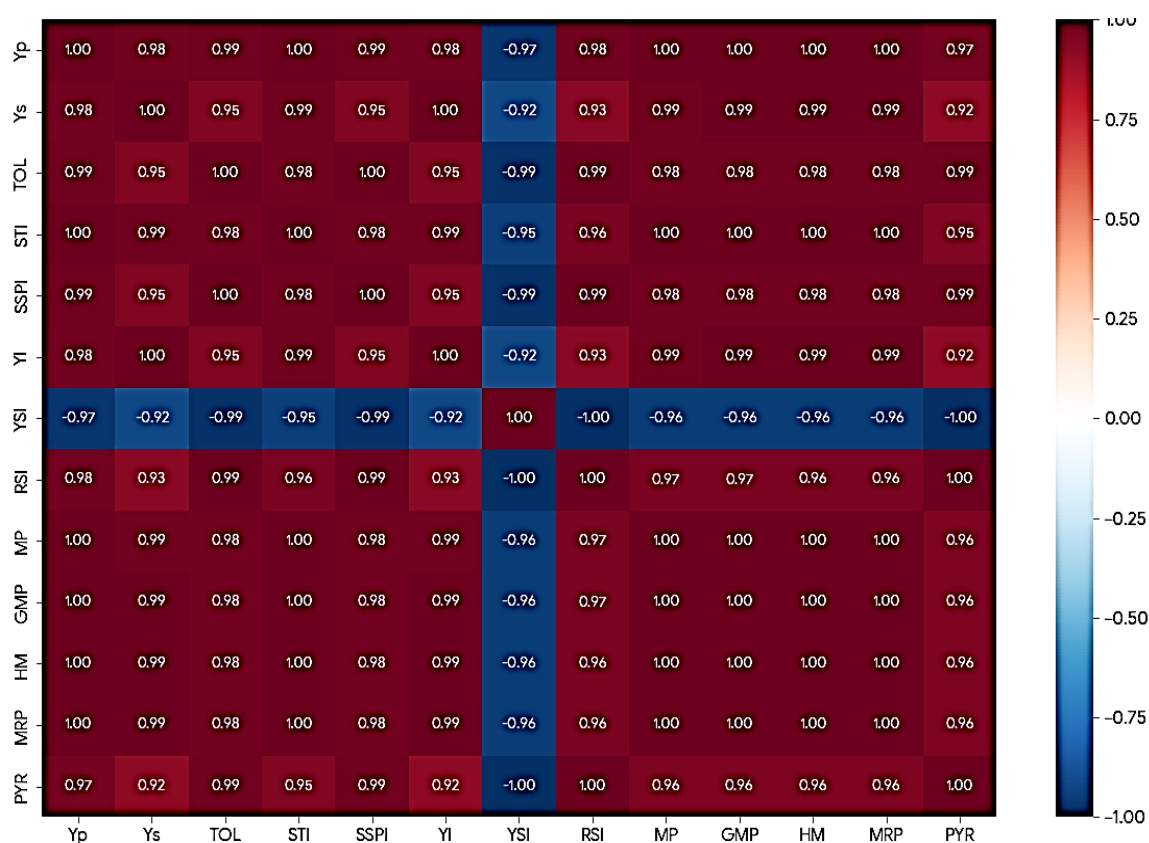


Figure 2 : correlation map of 13 wheat heat stress indices

3.4 Relationship Among Indices

A positive association was observed between STI and yield under stress conditions, indicating that genotypes with higher STI values tend to perform better under heat stress (Figure 2). Strong correlations among STI, GMP, MP and HM have also been reported by several recent studies including Redhu et al. (2024), Yadav et al. (2023). These findings validate the usefulness of combined stress indices for screening heat tolerant wheat germplasm.

3.5 Identification of Heat-Tolerant Genotypes

Based on combined evaluation of indices, genotypes HI1634, MP3336, and HD3086 were identified as heat tolerant due to their superior performance across multiple indices (figure 3). Genotypes MP3465, DBW303, and HI8777 showed minimal yield reduction and were categorized as tolerant. In contrast, HD2932 and TW111 exhibited higher susceptibility, indicating their unsuitability for late sown conditions.

These findings are in agreement with recent studies emphasizing the importance of combining multiple indices for accurate genotype selection. The evaluation of 32 wheat genotypes under heat stress revealed significant quality variations, with Quality Index (QI) scores ranging from approximately -1.1 to 1.5 (Figure 4). Genotypes MP3336, GW463, HI1544, JW3288, and HI8759 emerged as the top five most resilient varieties, demonstrating superior grain quality maintenance under thermal stress. Conversely, genotypes like RAJ4238 and HI1634 proved highly sensitive, exhibiting severe quality degradation. For future breeding selection, the top five resilient genotypes are recommended as premium parental lines in hybridization programs to transfer heat-tolerance traits into high-yielding cultivars. Similar trends were reported by Lamba et al. (2023) in Scientific Reports, where combined utilization of stress indices improved accuracy of genotype classification under heat stress environments.

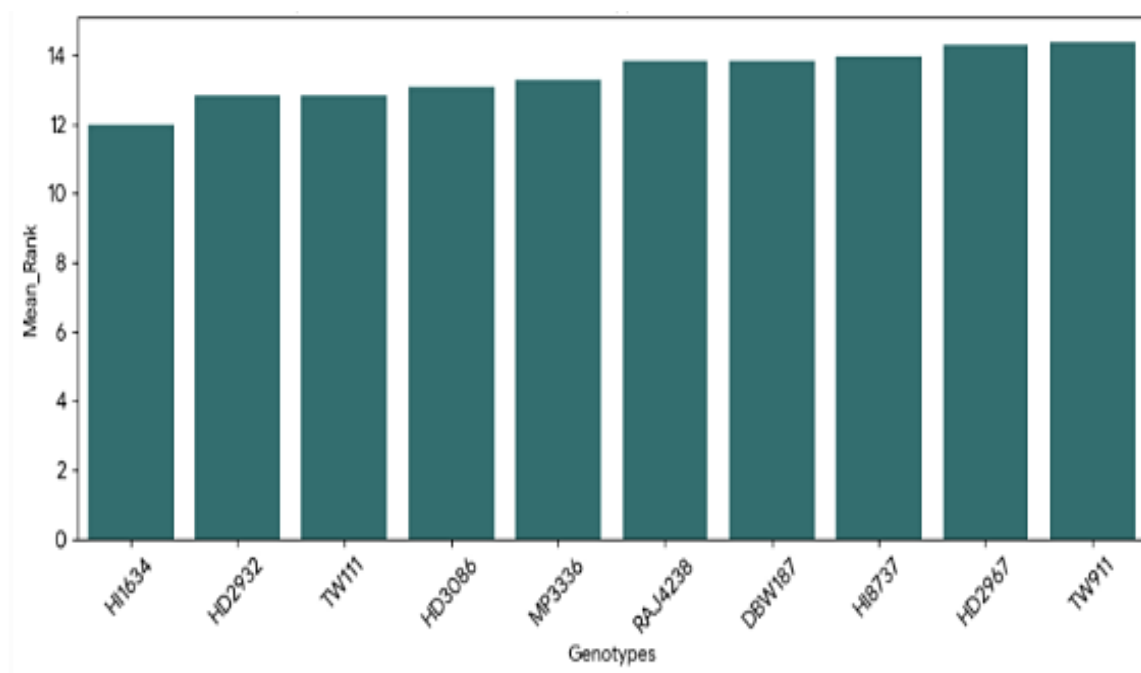


Figure 3: Performance ranking of top 10 genotypes based on Mean Rank.

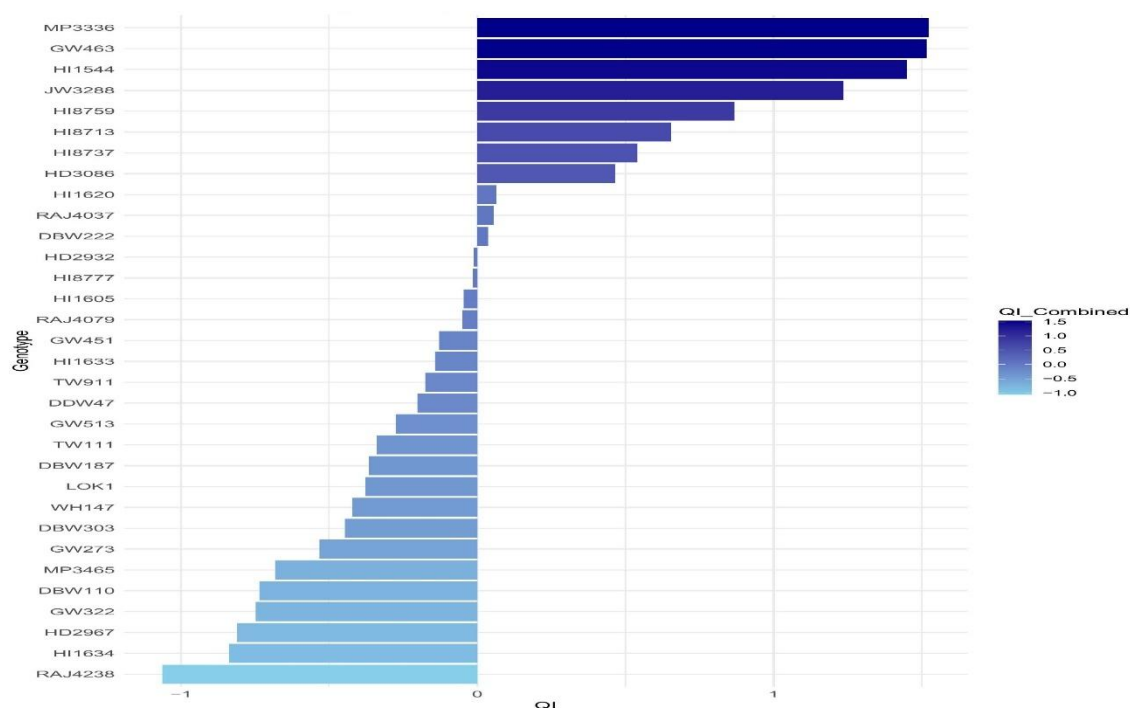


Figure 4 : Combined Quality Index of 32 genotypes

4. CONCLUSION

The present study demonstrated that terminal heat stress significantly affected wheat productivity, resulting in an overall grain yield reduction of 19.15% under late sown conditions compared to timely sown conditions. Considerable variability was observed among the 32 wheat genotypes for grain yield and heat tolerance indices, indicating the existence of substantial genetic diversity for heat stress tolerance. The descriptive statistics further confirmed wide variation among indices such as TOL, STI, SSPI, YSI, GMP, MP, HM, and PYR, suggesting differential response of genotypes to elevated temperature stress.

Among the evaluated genotypes, HI1634, MP3336, HD3086, GW463, and DBW303 exhibited superior performance under both stress and non-stress environments and were identified as promising heat tolerant genotypes. These genotypes maintained higher grain yield, greater yield stability, and lower yield reduction under terminal heat stress conditions. In contrast, susceptible genotypes exhibited higher TOL, SSPI, and PYR values along with poor yield stability under stress environments.

The stress indices STI, GMP, MP, HM, and MRP showed strong positive association with grain yield under both environments and proved highly effective for identifying stable and high yielding genotypes. Conversely, TOL, SSPI, RSI, and PYR were associated with greater susceptibility and yield reduction. The heat map analysis clearly grouped productivity based and susceptibility based indices into separate clusters, thereby validating the reliability of these indices for genotype classification under heat stress conditions.

The close association among STI, GMP, MP, HM, Yp, and Ys observed in the heat map indicated that these indices can effectively identify genotypes capable of maintaining productivity under both favorable and stress conditions. Therefore, combined utilization of these indices provides a more reliable approach for selection of heat tolerant wheat genotypes than use of individual indices alone.

The superior performance of tolerant genotypes may be attributed to their ability to maintain physiological efficiency, chlorophyll stability, assimilate partitioning, and grain filling duration under elevated temperature conditions. The findings of the present investigation confirm that heat stress indices integrated with correlation-based heat map analysis are efficient tools for screening wheat germplasm for terminal heat stress tolerance.

Overall, genotypes HI1634, MP3336, HD3086, GW463, and DBW303 can be considered promising donor parents for future wheat breeding programmes aimed at developing climate resilient and heat tolerant wheat cultivars suitable for late sown and high temperature environments.

DECLARATIONS

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Consent for publication: Not applicable.

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Plant guidelines: The plant materials used in this study were collected from cultivated sources following the institutional and national guidelines. No special permission or license was required for the collection of cultivated plant materials.

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