Current Applied Science and Technology e-ISSN: 2586-9396

Curr. Appl. Sci. Technol. 2025, Vol. 25 (No.1), e0259959

Research article

Performance and Stability of Elite Wheat Genotypes under Irrigated, Heat Stress and Heat Drought Environment

Radhakrishna Bhandari*, Harikala Paudel and Mukti Ram Poudel

Institute of Agriculture and Animal Science (IAAS), Tribhuvan University, Paklihawa Campus, Bhairahawa, Rupandehi, Nepal

Received: 11 Sepember 2023, Revised: 18 March 2024, Accepted: 4 July 2024, Published: 17 October 2024

Abstract

Heat stress and drought are a significant threat to wheat production globally. These abiotic stresses influence growth, physiology, and yield-attributing parameters of wheat. To evaluate the performance and stability of elite wheat genotypes, a field experiment was conducted in the western region of Nepal at Bhairahawa, Rupandehi comprising twenty elite wheat lines under irrigated, heat stress, and heat drought conditions using alpha lattice design with two replications. The combined ANOVA across environments and AMMI model ANOVA revealed that traits, days to booting (DTB), days to heading (DTH), days to anthesis (DTA), spike weight (SW), thousand-kernel weight (TKW), and grain yield (GY) were significantly influenced by the environment ($p \leq 0.05$). The yield of wheat was reduced by 20% and 39% under heat stress and heat drought environments as compared to irrigated environment. BL 4919, NL 1368, and Bhrikuti were the highest yielding genotypes under irrigated, heat stress, and heat drought environments with mean grain yields of 6254, 4261.5, and 3322.5 kg ha^{-1}, respectively. AMMI analysis revealed that BL 4919, NL 1417, and NL 1420 were the most adaptive genotypes under irrigated, heat-stress, and heat-drought environments. Whereas the Which Won Where (WWW) model revealed that BL 4919, NL 1368, and Bhrikuti were the most adaptive genotype under irrigated, heat stress, and heat drought environments. From Mean vs. Stability assessment, NL 1412 and NL 1369 were identified as high-yielding stable genotypes. Both the AMMI and WWW models identified NL 1386 as the most stable genotype with the lowest AMMI stability value (ASV) of 0.13. Hence, these selected genotypes should further be promoted in wheat improvement programs to further develop potential climate-resilient varieties.

Keywords: abiotic stress; climate resilient breeding; stable genotype; stress tolerant genotype; wheat improvement program

*Corresponding author: E-mail: radha.181401@pakc.tu.edu.np
https://doi.org/10.55003/cast.2024.259959

1. Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop in the world (Bhandari et al., 2024b; Shewry & Hey, 2015). It is the major staple crop of 35% of the global population and provides about 25% of the total calories and 22% total protein in the diet (Poudel et al., 2023). Wheat is a major part of the economy and is the third most important cereal crop in Nepal (AITC, 2021; MOF, 2022). Wheat cultivation takes up 19.13% of the total cereal cropping area (MoALD, 2023) and contributes about 6.98% to the agriculture GDP of Nepal (AITC, 2021). The productivity of wheat in Nepal (2.99 t ha^{-1}) is lower than in India (3.47 t ha^{-1}) and China (5.81 t ha^{-1}) (FAOSTAT, 2023). The majority of wheat in Nepal is cultivated in the western region of Nepal, contributing about 50% to national wheat production (Poudel et al., 2024). One of the major reasons behind the lower productivity of wheat is the lack of sufficient water for irrigation and terminal heat stress during the reproductive and grain-filling periods. The majority of the wheat-growing area in South Asia is weather-dependent (Gupta et al., 2022) and 52% of the total cultivated area of Nepal is rainfed. Wheat has 30-40% yield loss under rainfed conditions, 50-60% under drought, and 8-46% under heat-stress conditions (Bhandari & Poudel, 2024).

The optimum temperatures for growth, anthesis, and ripening of wheat are 16-22°C, 12-22°C, and 21-25°C, respectively (Khan et al., 2020). Temperatures above 25°C cause heat stress, which has raised concerns about the overall production of wheat. Climate change and global warming have become major threats to cereal production (Timalsina et al., 2023; Bhandari & Poudel, 2024). In Nepal, a mean annual rise of 0.0539°C with an annual reduction of 16.09 mm of precipitation per year was reported. The productivity of wheat reduces up to 6% for each degree rise in temperature. With the ongoing concerns about global warming, it is predicted that wheat yields in South Asia could decrease by 44-47% by 2050 (Shiferaw et al., 2013). In 2005, wheat productivity decreased by 32 kg/ha, but due to the impact of heat and drought, this decline has increased to 1534 kg/ha in 2020 (Chaudhary et al., 2023; Sharma et al., 2023).

Rice-wheat cropping dominates in most of the agricultural land of Nepal. Late sowing and cultivation of late maturing rice cultivars push the sowing of wheat into late December, which means that the reproductive stage of wheat coincides with the terminal heat wave of Feb-March. Nepal had only 42 wheat lines with a mean genetic yield potential of 4.47 t ha^{-1}which gets reduced by 33% to 2.99 t ha^{-1}under field conditions (Bhandari et al., 2024a) because about 34% and 25% of total wheat growing area in Nepal is under rainfed and heat stress, respectively. Of the wheat lines, only Bhrikuti, Gautam, and Badganda are accepted by farmers as heat-tolerant genotypes.

Agriculture development strategy (ADS) and the fifteenth five-year plan reported that 21% of the Nepalese population has no direct access to sufficient nutritious food (ADS, 2015). Nepal has 16.67% of the population in poverty (MOF, 2022), 6.1% in malnutrition, and 17% of the population under severe micronutrient deficiency. It ranks in 81st position on the global hunger index (von Grebmer et al., 2023). About 13.6% of the Nepalese population are food insecure, 5.5% are undernourished, 12% are wasted, 31.5% are stunted, and 2.8% of the children below 5 years of age are dying each year due to lack of nutritious food (ADS, 2015; Bhandari et al., 2023). ADS and sustainable development goals (SDGs) are aimed at achieving food security, ending hunger, and improving human nutrition (Sachs et al., 2022). The aims of ADS and SDGs can be achieved by increasing the production and productivity of wheat. Wheat production was reported to be 3-4 t ha^{-1}, 2-3 t ha^{-1}, and 1.79-2 t ha^{-1} under irrigated, heat stress, and heat drought environments, respectively. These need to be increased to fulfill the demand of the growing population

(Abhinandan et al., 2018). Being the number one crop, increment in wheat production and the productivity is a key to eradicate existing hunger and malnutrition. Lack of land and poor irrigation infrastructure make it impossible to achieve yield improvement via increasing land area and irrigation (ADB, 2013; Bhandari & Upadhyaya, 2021). An increment of only 14% (1.36 billion ha to 1.5 billion ha) in net cropping area provided food for a 200% increased population (3.5b to 7b) from 1961 to 2011 (FAOSTAT, 2023). Hence, the best option for the sustainable production of wheat is to breed for abiotic stress-tolerant genotypes.

The objective of the study was to quantify the impact of heat stress and heat drought environment on the yield and yield-related parameters of bread wheat. The research was focused on the identification of climate-resilient heat stress and heat drought tolerant wheat genotypes using AMMI and GGE biplot analysis to help the varietal improvement program of Nepal. Since population growth is putting pressure on the demand for food, maintaining a balance between food demand and supply has become a major concern. In particular, the breeding of climate-resilient wheat varieties has become very significant in the current scenario.

2. Materials and Methods

The on-field experiment was carried out at the Agronomy farm of the Institute of Agriculture and Animal Science (IAAS), Paklihawa Campus, Rupandehi in 2021. The experimental site lies in the western Terai region of Nepal at the geographic location of 27°29'02"N and 83°27ˈ17" E and at an altitude of 104 m above sea level (masl). The weather parameters (maximum, minimum, and average temperature) with average precipitation from the time of sowing to harvesting are presented in Figure 1. Twenty elite wheat lines including fifteen Nepal lines (NL), three Bhairahawa lines (BL), and two commercial check varieties documented in Seed Quality Control Centre (SQCC) (SQCC, 2021) viz; Bhrikuti and Gautam are shown in Table 1.

The experiment was carried out in an alpha lattice design, replicated twice with five blocks for all irrigated, heat stress, and heat drought environment. Each genotype was sown on a net plot size of 10 m^2 having the dimensions of 4 m x 2.5 m. The interblock and inter replication space were maintained at one m. The irrigated environment was created by sowing the genotypes in the third week of November (25th November) and the heat stress environment was created by sowing the genotypes one month later (25th December) so that the flowering and reproductive stage of the wheat coincided with the hot wave blown over February-March in the western region of Nepal. The heat drought environment was created by sowing the genotypes on 25th December without providing any artificial irrigation. Six critical doses of irrigation were applied at crown root initiation (CRI), tillering, jointing, booting, heading, and soft dough stages for both irrigated and heat stress environments.

Each experimental plot consisted of 10 rows of wheat in east-west direction, and the ten random samples were taken from middle 8 rows leaving the borderlines. The phenological data of days to booting (DTB), days to heading (DTH), and days to anthesis (DTA) were taken when 50% of the population achieved their respective stage. Inter-phenological duration such as booting to heading duration (BtoH), booting to anthesis duration (BtoA), and heading to anthesis duration (HtoA) were also collected. Spike length (SL) was measured from the base of the spike to the top of the uppermost floret. The number of spikes per meter square, spikelets per spike (SPS), and grains per spike (GPS) were measured by counting them manually whereas ten spike weights (TSW) and

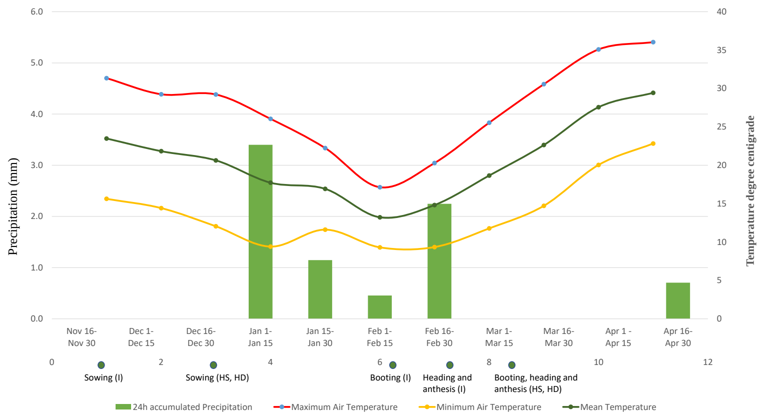

Figure 1. Agrometeorological parameters of the experimental duration

Table 1. Plant materials used in the experiment

S. N.	Genotypes*	Source	Released Year	S. N.	Genotypes*	Source	Released Year
1	Bhrikuti	CIMMYT, Mexico	1994	**11**	NL 1376	CIMMYT, Mexico	not released yet
2	BL 4407	Nepal	not released yet	**12**	NL 1381	CIMMYT, Mexico	not released yet
3	BL 4669	Nepal	not released yet	**13**	NL1384	CIMMYT, Mexico	not released yet
4	BL 4919	Nepal	not released yet	**14**	NL 1386	CIMMYT, Mexico	not released yet
5	Gautam	Nepal	2004	**15**	NL 1387	CIMMYT, Mexico	not released yet
6	NL 1179	CIMMYT, Mexico	not released yet	**16**	NL 1404	CIMMYT, Mexico	not released yet
7	NL 1346	CIMMYT, Mexico	not released yet	**17**	NL 1412	CIMMYT, Mexico	not released yet
8	NL1350	CIMMYT, Mexico	not released yet	**18**	NL 1413	CIMMYT, Mexico	not released yet
9	NL 1368	CIMMYT, Mexico	not released yet	**19**	NL 1417	CIMMYT, Mexico	not released yet
10	NL 1369	CIMMYT, Mexico	2018	**20**	NL 1420	CIMMYT, Mexico	not released yet

*The parentage of the genotype is confidential and is maintained at the National Wheat Research Program (NWRP), Bhairahawa.

thousand kernel weights (TKW) were determined by weighing 10 spikes and 1000 grains on a weighing balance. The grain yield was determined by harvesting two quadrants of 1 m^2 plots, averaging, and conversion to tons per hectare. When the crop reached harvestable maturity, wheat was harvested manually with serrate edges sickles. The yield of wheat was determined by harvesting two quadrants of 1 m^2 plots, averaging, and conversion to tons per hectare.

The AMMI (Additive Main effects and Multiplicative Interaction) and GGE (Genotype plus Genotype by Environment Interaction) models were used as statistical methods for analyzing multi-environment trials (METs). Specifically, they were used to study the interaction between genotypes and environments, analyzing the variation into two orthogonal components: the additive main effects of the genotypes and the multiplicative interaction effects between the genotypes and the environments. The AMMI model can be expressed as (Purchase et al., 2000):

$$Yij = \mu + gi + ej + \sum \lambda k\ tk + \varepsilon ij$$

where Yij is the observed value of the i^{th} genotype in the j^{th} environment, μ is the overall mean, gi is the i^{th} genotype effect, ej is the j^{th} environment effect, λk is the singular value of the kth principal component, tki is the score of the i^{th} genotype on the kth principal component, sik is the kth principal component loading of the j^{th} environment, and εij is the residual error.

The GGE model, on the other hand, is a graphical model that allows for the visualization and interpretation of genotypes by environment interactions. The GGE model assumes that the genotype and environment effects can be separated and that the interaction effect can be expressed as a linear combination of the two main effects. The GGE model can be expressed as:

$$Yij = \mu + gi + ej + (gj - \mu)wi + \varepsilon ij$$

where Yij is the observed value of the i^{th} genotype in the j^{th} environment, μ is the overall mean, gi is the i^{th} genotype effect, ej is the j^{th} environment effect, gj is the grand mean of the j^{th} environment, wi is the weight of the j^{th} environment, and εij is the residual error.

The GGE biplot provides a two-dimensional representation of the genotype and environment effects, allowing for the identification of stable and adaptive genotypes across multiple environments. The GGE biplot can be generated by plotting the genotypes and environments in a two-dimensional space, where the distance between genotypes represents their similarity and the angle between genotypes and environments represents their interaction. The GGE biplot can be used to identify stable and adaptive genotypes by examining their performance across different environments and their relationship with the ideal genotype.

In the present study, the AMMI and GGE models were used to identify stable and adaptive wheat genotypes in the western region of Nepal, by analyzing data from a multi environmental trial involving several genotypes grown across irrigated, heat stress, and heat drought environments. The stability and adaptability of each genotype were evaluated based on their mean performance, stability parameters, and biplot analysis.

The data entry and processing were done on Microsoft EXCEL- 2021. The combined analysis of variance (ANOVA) was performed using IBM SPSS statistics V.26. The AMMI model ANOVA and AMMI and GGE biplot analysis were performed in GEAR-4.0 software provided by CIMMYT, Mexico.

3. Results and Discussion

The combined analysis of Variance (ANOVA) revealed that there was a significant reduction in the performance of quantitative traits under both stress environments for DTB, DTH, DTA, NSW, TGW, and GY ($p \leq 0.05$). In comparison to irrigated environment, DTB, DTH, DTA, NSW, TGW, and GY were reduced by 13, 16, 17, 8, 13, and 20%, respectively, under heat-stressed environment. Under heat drought environment, the performance was reduced by 13% for DTB, 16% for DTH, 17% for DTA, 10% for NSW, 15% for TGW, and 39% for GY (Table 2).

The mean grain yield of wheat was reduced by 20 and 39% under heat stress and heat drought environments, respectively, compared to yield in the irrigated environment. The addition of drought heat-stress further aggravated yield by 24%. The result revealed that heat drought was the most destructive environment for the production of wheat (Figure 2).

The lower productivity of wheat under heat stress environment is due to its effect on plant growth, physiology, photosynthesis (Kamrani et al., 2017), membrane stability, CHO partitioning (Djanaguiraman et al., 2020), saturated lipid reserve (Nyaupane et al., 2024), floral fertility, pollen viability, and stigmatic receptivity (Djanaguiraman et al., 2018). The meiosis stage of wheat is susceptible to a temperature below 4°C (Oyewole, 2016) and above 25°C (Lesk et al., 2016) which reduces the percentage of fertile floret under heat-stress environment. Post-anthesis heat stress causes early leaf senescence and reduces the grain-filling period due to hot wave (Bhandari et al., 2024b). It also affects the yield-attributing characteristics of wheat such as thousand-kernel weight, spikes per meter square, and days to booting and heading which are the most important direct contributing traits of wheat (Bhandari et al., 2024a). With predicted global warming and climate change, mitigation and adaptation practices should be promoted as early as possible and as effectively as possible to prevent future consequences (Narayanan et al., 2016; IPCC, 2021; Paudel et al., 2021).

The grain yield of wheat ranged from 3164.4 kg ha^{-1} (NL 1420) to 6254 kg ha^{-1} (BL 4919) under irrigated environment whereas 2184.5 kg ha^{-1} (NL 1387) to 4261.5 kg ha^{-1} (NL 1368) were observed under heat stress environment. Under the heat drought environment, the wheat yield ranged from 1883.4 kg ha^{-1} (NL 1179) to 3322.8 kg ha^{-1} (Bhrikuti). BL 4919 (4375.5 kg ha^{-1}) and NL 1420 (2901.1 kg ha^{-1}) were the highest and lowest-yielding genotypes under the combined environment, respectively. The yield loss under heat stress environment ranged from 1.1% (NL 1420) to 47.4 % (NL 1387) while under the heat drought environment, the yield loss ranged from 13.20 (Bhrikuti) to 51.94% (BL 4669) (Table 3). The wheat genotypes had an average yield reduction of 20 and 39% under the heat stress and heat drought environment, respectively, when compared to the irrigated environment.

The ANOVA of the AMMI model revealed that there was a significant difference in the yield of genotypes across the irrigated, heat stress, and heat drought environments ($p \leq 0.01$) (Table 4). Environment, genotype, and G x E interaction explained 67.83%, 16.65%, and 15.50% of yield variation, showing that environment had a direct effect on the wheat yield (Table 4). The higher environmental-related variation is an important factor for a yield improvement program. The first two principal components in the AMMI model ANOVA explained 100% of the total variation in grain yield (Table 4).

Table 2. Influence of irrigated, heat stress, and heat drought environments on quantitative traits of wheat genotypes

ENV	DTB	DTH	DTA	BtoH	HtoA	BtoA	SL (cm)	NSPMS	NSPS	NGPS	TSW (gm)	TKW (gm)	GY (Kg ha^{-1})
Irrigated	78±4.4^{a}	86±3.6^{a}	91±3.18^{a}	8±1.91^{a}	5±1.82.4^{a}	13±2.44^{a}	10.3±0.8^{a}	358.2±1.4^{a}	18.1±1.40^{a}	46.6±5.4^{a}	23.0±3.3^{a}	39.8±5.8^{a}	4262.8±858.3^{a}
Heat stress	68±2.21^{b}	72±1.5^{b}	75±1.33^{b}	4±1.48^{b}	3±0.9^{b}	7±1.46^{b}	10.3±1.18^{a}	342.9±51.11^{a}	17.6±0.97^{a}	44.6±5.74^{a}	21.1±3.86^{b}	34.7±4.23^{b}	3398.7±548.18^{b}
Heat drought	68±2.04^{b}	72±1.33^{b}	75±0.70^{b}	4±1.29^{b}	3±0.99^{b}	7±1.74^{b}	10.1±0.72^{a}	335.1±42.00^{a}	17.6±0.94^{a}	44.5±5.12^{a}	20.8±2.89^{b}	33.8±2.54^{b}	2593.9±548.18^{c}
Grand Mean	71±5.7	77±6.9	80±7.7	5.33±2.3	3.67±1.6	9±3.2	10.3±0.9	345.4±51.2	17.8±1.1	45.2±5.5	21.6±3.5	36.1±5.1	3418.5±958.4
CV	8.0	9.1	9.6	44.2	42.5	35.9	9.0	14.8	6.4	12.1	16.1	14.1	28.0
F-Value	***	***	***	***	***	***	ns	ns	ns	ns	**	***	***
% Reduction (I Vs. HS)	13	16	17	50	40	46	0	4	3	4	8	13	20
% Reduction (I Vs. HD)	13	16	17	50	40	46	2	6	3	4	10	15	39

Days to booting (DTB), days to heading (DTH), days to anthesis (DTA), spike length (SL), net spike per meter square (NSPMS), net spikelet per spike (NSPS), net grains per spike (NGPS), net spike weight (NSW), thousand kernel weight (TKW), grain yield Kg ha^{-1} (GY)

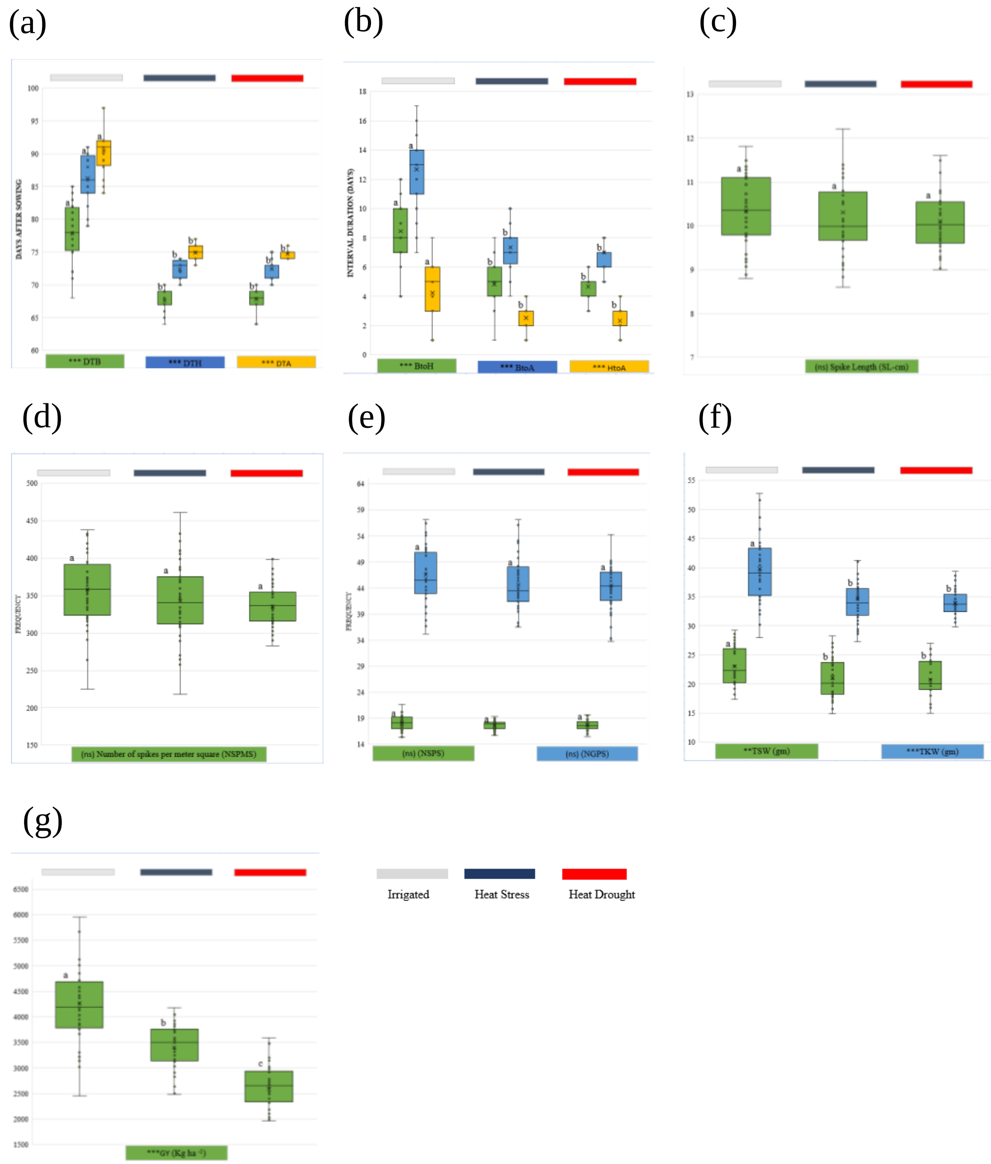

Figure 2. Performance of wheat genotypes across irrigated, heat stress and heat drought environments. (a) days to booting (DTB), days to heading (DTH), days to anthesis (DTA); (b) booting to heading duration (BtoH), booting to anthesis duration (BtoA), heading to anthesis duration (HtoA); (c) spike length (SL); (d) number of spikes per meter square (NSPMS); (e) number of spikelets per spike (NSPS), number of grains per spike (NGPS); (f) ten spike weight (TSW), thousand kernel weight (TKW); (g) grain yield (GY)

Table 3. Yield performance, percentage yield reduction, coefficient of variation, AMMI stability value (ASV), and ranked AMMI stability value (RASV) of twenty genotypes

Genotypes	2021 GY (kg ha $^{-1}$)				Percentage Reduction as compared to Irrigated Environment		Stability Parameters		
	I	HS	HD	Combined	Under HS	Under HD	CV	ASV	RASV
Bhrikuti	3828.3	3723.0	**3322.8**	3624.7	2.8	**13.2**	**6.0**	1.6	19
BL 4407	3957.1	3021.5	2551.0	3176.5	23.6	35.5	18.4	0.3	2
BL 4669	4612.8	3521.0	2216.7	3450.2	23.7	**51.9**	28.4	0.9	12
BL 4919	**6254.0**	3788.5	3084.1	**4375.5**	39.4	50.7	**31.1**	**2.6**	**20**
Gautam	3704.8	3129.5	2203.9	3012.7	15.5	40.5	20.5	0.4	6
NL 1179	3848.8	3204.5	**1883.4**	2978.9	16.7	51.1	27.5	0.4	4
NL 1346	5046.8	3476.5	2858.9	3794.1	31.1	43.4	24.3	1.0	15
NL1350	4181.4	3567.0	2825.2	3524.5	14.7	32.4	15.7	0.5	8
NL 1368	4395.3	**4261.5**	2410.9	3689.2	3.0	45.2	24.6	0.8	11
NL 1369	4393.8	3434.0	2337.8	3388.5	21.8	46.8	24.8	0.4	7
NL 1376	4097.5	3464.5	3092.6	3551.5	15.4	24.5	11.7	0.8	10
NL 1381	4427.4	3308.5	2293.9	3343.3	25.3	48.2	26.1	0.6	9
NL1384	3611.5	3322.5	2552.2	3162.1	8.0	29.3	14.1	1.0	13
NL 1386	4202.5	3414.0	2621.4	3412.6	18.8	37.6	18.9	**0.1**	**1**
NL 1387	4155.5	**2184.5**	2513.8	2951.3	**47.4**	39.5	29.2	1.2	17
NL 1404	4866.0	3408.5	2584.4	3619.6	30.0	46.9	26.1	1.0	14
NL 1412	4634.9	3594.5	2751.3	3660.2	22.4	40.6	21.1	0.3	3
NL 1413	4069.5	3266	2739.7	3358.4	19.7	32.7	16.3	0.4	5
NL 1417	3805.2	3717	2662.3	3394.8	2.3	30.0	15.3	1.1	16
NL 1420	**3164.4**	3130	2373.0	**2901.1**	**1.1**	25.0	12.9	1.4	18
Mean	**4262.8**	**3398.7**	**2593.9**	**3418.5**	**20.3**	**39.2**	**19.9**		
STD	630.8	387.9	334.9	337.7	38.5	46.9	38.2		
CV	14.8	11.4	12.9	9.9	22.9	12.8	14.0		
F-value	ns	ns	ns	ns					

Table 4. AMMI model ANOVA

Traits	% Variation Explained			Sum of Square					
	Environment (df=2)	Genotype (df=19)	G x E (df=38)	Environment (df=2)	Genotype (df=19)	G x E (df=38)	PC1 (df=20)	PC2 (df=18)	Residual (df=60)
DTB	73.11***	20.71***	6.17***	2754.7	780.4	232.7	213.2***	19.5	94.0
DTH	88.75***	8.03***	3.22***	5124.5	463.5	185.8	175.4***	10.5	26.0
DTA	93.39***	4.36***	2.25***	6542.3	305.1	157.7	151.3***	6.4	19.5
BtoH	65.74**	16.72	17.53**	365.5	93.0	97.5	80.1**	17.4	108.0
HtoA	36.57***	33.31***	30.11**	87.2	79.4	71.8	54.5**	17.3	50.5
BtoA	71.01***	18.12***	10.87*	809.1	206.5	123.9	99.4**	24.5	103.5
SL	1.45*	68.22***	30.33***	1.3	60.1	26.7	15.3***	11.4***	11.1
NSPMS	4.63*	65.26***	30.11	11082.7	156225.5	72094.4	49454.7*	22639.7	73205.3
NSPS	4.34**	62.65***	33.01***	5.7	81.9	43.2	31.5***	11.6*	23.1
NGPS	3.69*	68.00***	28.32*	105.7	1949.0	811.6	481.3*	330.3	699.8
TSW	11.17***	53.15***	35.67	121.0*	575.5	386.3	259.2*	127.1	365.0
TKW	32.36***	27.75***	39.89***	826.7	708.9	1019.0	692.4***	326.6*	537.6
GY	67.84***	16.66	15.50	55728302.8	13683453.0	12735216.4	9045766.0	3689450.4	27159856.3

Note: Genotype environment interaction (G x E), principal component of AMMI (PC), degree of freedom (df)

The AMMI model ANOVA showed that the majority of the variation in the studied traits was governed by environment, followed by genotype and genotype x environment interaction. Most of the variation of the phenological (DTB, DTH, DTA), interphenological duration (BtoH, HtoA, BtoA) and grain yield (GY) was governed by environment factors while the majority of the variation of spike related parameters (SL, NSPMS, NSPS, NGPS, TSW) was governed by genotypic factors followed by interaction factors. The AMMI biplot had the main factor as PC1 in the abscissa and grain yield as the ordinate. The genotypes and the environments that lie in the same vertical line have the same yield and the vector of genotypes that lie in the same horizontal axis share the same interaction patterns.

The genotypes lying near the origin were identified as stable genotypes. The adaptive genotypes were identified by the vector of genotypes with larger PC1 scores. The genotypes in the clusters were identified as similar across all tested environments. NL 1386 and NL 1413 were the stable genotypes under irrigated, heat stress, and heat drought environments with the lowest AMMI Stability Values (ASV) of 0.13 and 0.37, respectively (Figure 3). Whereas BL 4919, NL 1417, and NL 1420 were found to be specifically adapted to irrigated, heat stress, and heat drought environments, respectively. NL 1381, NL 1350, and BL 4669 behaved similarly across all tested environments (Figure 3). Environment was found to be the most important variable for GY and the performance and stability of genotypes. The results clear the path for the selection of the adaptive genotypes across a multi-environmental trial (Mohammadi et al., 2018; Ngailo et al., 2016).

Stable genotypes in a multi-environmental trial can be identified from the WWW model (Bhandari et al., 2024b). The WWW model visualizes the performance and stability

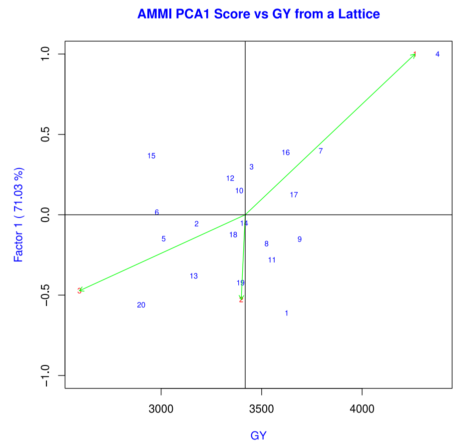

Figure 3. AMMI PCA1 vs GY from a lattice biplot for GY of twenty elite wheat genotypes across irrigated (I), heat stress (HS), and heat drought (HD) environments

of genotypes on a graph (Figure 4). It uses a polygon-view model and average environmental coordinates (AEC) and connects genotypes farthest from the biplot origin with straight lines that denote which genotypes are superior (Neisse et al., 2018; Thungo et al., 2019, Sood et al., 2020). The stability of genotypes is determined based on the length of projection drawn in the form of dotted vertical lines from the AEC axis.

The genotypes which lie near the origin in the polygon are stable (Bhandari & Poudel, 2024; Mohammadi et al., 2018). In our study, NL 1386 and NL 1412 were stable genotypes across irrigated, heat-stress, and heat-drought environments whereas, BL 4919, NL 1368, and Bhrikuti were found to be specifically adapted to the irrigated, heat stress, and heat drought environments. The genotypes lying far from a specific environment were poorly adapted genotypes whereas genotypes in clusters behaved similarly across all tested environments (Figure 4).

High-yielding stable genotypes can be identified from mean vs. stability. Genotypes lying on the positive side of the horizontal axis from the origin are above-average yielding genotypes whereas the genotypes lying to the left of the origin are below-average yielders (Thungo et al., 2019). The stability is determined based on the length of the arrowhead projection in the biplot. The genotypes with smaller arrowheads were highly stable and vice versa is true (Akter et al., 2015).

NL 1368, NL 1179, NL 1412, NL 1369, NL 1381, NL 1346, NL 1179, NL 1404, BL 4669, and NL 4919 were above-average yielding genotypes, and NL 1412, NL 1369, and NL 1381 were above average yielding stable genotypes. Similarly, Bhrikuti, NL 1420, NL 1384, NL 1417, NL 1376, NL 1350, NL 1413, Gautam, BL 4407, and NL 1386 were below-average yielding genotypes and NL 1386, NL 1350, and Gautam were below average yielding stable genotypes (Figure 4). The ranking biplot identifies and ranks ideal genotypes for cultivation (Anuradha et al., 2022; Neisse et al., 2018). The ranking is done by drawing two coordinate axes - a line joining the arrowhead and origin and the first axis and the line perpendicular to it at the origin (Anuradha et al., 2022; R. Bhandari, Paudel, et al., 2024). The ideal genotype across all environments is selected based on the arrowhead at the innermost concentric circles. Genotypes lying toward the center of the concentric circles are ideal for cultivation. Bhrikuti was identified as the ideal genotype across irrigated, heat stress, and heat drought environment. The ranking of the genotypes was;

NL 1420 (20) > NL 1384 (13) > Bhrikuti (1) >NL 1417 (19) > NL 1376 (11) > NL 1350 (8) > Gautam (5) > NL 1413(18) > BL 4407 (2) > NL 1386 (14) > NL 1412 (17) > NL 1179 (6) > NL 1369 (10) > NL 1381 (12) > NL 1368 (9) > NL 1404 (16) > BL 4669 (3) > NL 1346 (7) > NL 1387 (15) > BL 4919 (4) (Figure 4).

Discriminative vs. representative shows the discriminating power of the experimental sites. Discriminating means the ability of an environment to separate high-yielding and low-yielding genotypes. An experimental site with a longer vector from the origin will have a higher standard deviation within the environment and will have a higher ability to discriminate genotypes. An environment with a smaller vector from the origin is considered an environment unable to discriminate the performance of genotypes (Bhandari et al., 2024; Bhandari & Poudel, 2024). An environment with a smaller cosine of the angle between environment vectors drawn from the origin to the average environmental axis (AEA) is described as a higher representative of the environment. The cosine of the angle between environments gives the interrelationship of the environments.

The vector of irrigated environment was the best discriminators of the performance of the genotypes whereas HS and HD environments were almost equal in their discrimination of yield (Figure 5). Furthermore, the heat stress environment had the highest angle between the HS vector genotype and AEC and was hence the least representative environment across all tested environments (Figure 5).

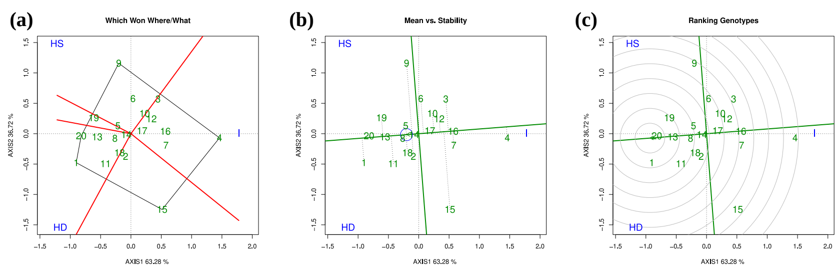

Figure 4. Genotype x environment interaction models showing which won where pattern (a), mean vs stability pattern (b), and ranking genotype pattern (c), for the grain yield of twenty different wheat genotypes across irrigated (I), heat stress (HS), and heat drought (HD) environments

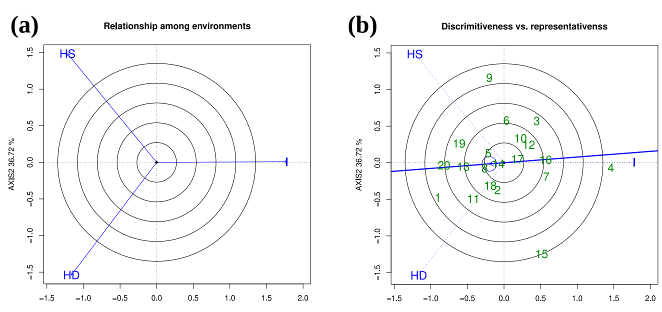

Figure 5. Relationships among tested wheat growing environments (a) and discriminativeness vs representativeness of twenty elite wheat genotypes across irrigated (I), heat stress (HS), and heat drought (HD) environments

4. Conclusions

Climate change has been one a major yield limiting factors of wheat farming. Irregular rainfall patterns and the rise in atmospheric temperature as a result of climate change have been a great threat to food and nutritional security of the world. The AMMI model ANOVA revealed the significant impact of heat stress and heat drought environment on yield and yield attributing parameters of wheat. It was of value to evaluate the performance and stability of wheat genotypes for climate resilient breeding programs. According to the AMMI and WWW model, NL 1386 was the most stable genotypes while BL 4919, NL 1417 and NL 1468 were found to be the most adaptable genotypes under irrigated, heat stress, and heat drought environments, respectively. Hence, these genotypes should be developed in climate resilient crop programs.

5. Acknowledgements

The authors thank the National Wheat Research Program (NWRP, Bhairahawa) for providing the genetic material. The authors also acknowledge the assistance of the Institute of Agriculture and Animal Science (IAAS), Paklihawa Campus for providing the field for the research.

6. Conflicts of Interest

The authors declare that they have no conflicts of interest.

ORCID

Radhakrishna Bhandari https://orcid.org/0000-0001-5624-6307

Harikala Paudel https://orcid.org/0009-0000-9808-1416

Mukti Ram Poudel https://orcid.org/0000-0002-3114-0407

References

Abhinandan, K., Skori, L., Stanic, M., Hickerson, N. M. N., Jamshed, M., & Samuel, M. A. (2018). Abiotic stress signaling in wheat – An inclusive overview of hormonal interactions during abiotic stress responses in wheat. *Frontiers in Plant Science*, 9, 1-25. https://doi.org/10.3389/fpls.2018.00734

ADB. (2013). *Sector assessment (summary): irrigation Nepal: Community irrigation project sector*. https://www.adb.org/sites/default/files/linked-documents/38417-02-nep-ssa.pdf

ADS. (2015). *Agriculture development strategy (ADS) 2015 to 2035*. https://faolex.fao.org/docs/pdf/nep171433.pdf

AITC. (2021). *Krishi_diary 2078*. Nepal.

Akter, A., Hasan, M. J., Kulsum, U., Rahman, M., Khatun, M., & Islam, M. (2015). GGE biplot analysis for yield stability in multi-environment trials of promising hybrid rice (Oryza sativa L.). *Bangladesh Rice Journal*, 19(1), 1-8. https://doi.org/10.3329/brj.v19i1.25213

Anuradha, N., Patro, T. S. S. K., Singamsetti, A., Rani, Y. S., Triveni, U., Kumari, A. N., Govanakoppa, N., Pathy, T. L., & Tonapi, V. A. (2022). Comparative study of AMMI- and BLUP-based simultaneous selection for grain yield and stability of finger millet [Eleusine coracana (L.) Gaertn.] genotypes. *Frontiers in Plant Science*, 12, Article 786839. https://doi.org/10.3389/FPLS.2021.786839

Bhandari, R. K., Nyaupane, S., & Poudel, M. R. (2023). Expression and association of quantitative traits of wheat (*Triticum aestivum* L .) genotypes under different wheat growing environments. *Cogent Food & Agriculture*, 9(2), 1-21. https://doi.org/10.1080/23311932.2023.2288394

Bhandari, R., & Poudel, M. R. (2024). Genotype × environment interaction and selection parameters for high yielding wheat genotypes under irrigated and heat stress environment. *Journal of Sustainable Agriculture and Environment*, 3(1), Article e12098. https://doi.org/10.1002/sae2.12098

Bhandari, R., Nyaupane, S., & Poudel, M. R. (2024a). Trait based selection of elite wheat genotypes under irrigated, heat stress, and heat drought conditions. *Fundamental and Applied Agriculture*, 9(2), 91-103. https://doi.org/10.5455/FAA.165653

Bhandari, R., Paudel, H., Nyaupane, S., & Poudel, M. R. (2024b). Climate resilient breeding for high yields and stable wheat (*Triticum aestivum* L .) lines under irrigated and abiotic stress environments. *Plant Stress*, 11, Article 100352. https://doi.org/10.1016/j.stress.2024.100352

Chaudhary, E., Sharma, S., Gautam, P., Ghimire, S., Sapkota, S., Bhattarai, K., Roka, P., Poudel, R., Timalsina, B., Neupane, K., Ganesh, G. C., Aryal, A., Poudel, M. R., & Bhandari, R. (2023). AMMI GGE biplot analysis of wheat genotypes under heat stress and heat drought environment. *Archives of Agriculture and Environmental Science*, 8(4), 484-489. https://doi.org/10.26832/24566632.2023.080404

Djanaguiraman, M., Boyle, D. L., Welti, R., Jagadish, S. V. K., & Prasad, P. V. V. (2018). Decreased photosynthetic rate under high temperature in wheat is due to lipid desaturation, oxidation, acylation, and damage of organelles. *BMC Plant Biology*, 18(1), Article 55. https://doi.org/10.1186/s12870-018-1263-z

Djanaguiraman, M., Narayanan, S., Erdayani, E., & Prasad, P. V. V. (2020). Effects of high temperature stress during anthesis and grain filling periods on photosynthesis, lipids and grain yield in wheat. *BMC Plant Biology*, 20(1), Article 268. https://doi.org/10.1186/S12870-020-02479-0

FAOSTAT. (2023). *FAOSTAT*. Fao.Org. http://www.fao.org/faostat/en/#data/QC

Gupta, S., Yadav, B., Timalsina, B., Ganesh, G. C., Bhuj, N., Roka, P., & Bhandari, R. (2022). Physiological , morphological & biochemical response of wheat (*Triticum aestivum*) against heat & drought stress and the tolerance mechanism - a review. *Reviews in Food and Agriculture (RFNA)*, *3*(1), 43-47. https://doi.org/10.26480/rfna.01.2022.43.47

IPCC. (2021). *IPCC sixth assessment report. Working group I: Climate change 2021: The physical science basis*. https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/

Kamrani, M., Hoseini, Y., & Ebadollahi, A. (2017). Evaluation for heat stress tolerance in durum wheat genotypes using stress tolerance indices. 64(1), 38-45. https://doi.org/10.1080/03650340.2017.1326104

Khan, A., Ahmad, M., Ahmed, M., & Hussain, M. I. (2020). Rising atmospheric temperature impact on wheat and thermotolerance strategies. *Plants*, 10(1), Article 43. https://doi.org/10.3390/plants10010043

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, 529(7584), 84-87. https://doi.org/10.1038/nature16467

MoALD. (2023). *Statistical information on Nepalese agriculture 2078/79 (2021/22)*. https://moald.gov.np/wp-content/uploads/2023/08/Statistical-Information-on-Nepalese-Agriculture-2078-79-2021-22.pdf

MOF. (2022). *Economic Survey 2020/21.* Government of Nepal Ministry of Finance.

Mohammadi, R., Armion, M., Zadhasan, E., Ahmadi, M. M., & Amri, A. (2018). The use of AMMI model for interpreting genotype × environment interaction in durum wheat. *Experimental Agriculture*, 54(5), 670-683. https://doi.org/10.1017/S0014479717000308

Narayanan, S., Prasad, P. V. V., & Welti, R. (2016). Wheat leaf lipids during heat stress: II.

Lipids experiencing coordinated metabolism are detected by analysis of lipid co-occurrence. *Plant Cell Environment*, 39(3), 608-617. https://doi.org/10.1111/pce.12648

Neisse, A. C., Kirch, J. L., & Hongyu, K. (2018). AMMI and GGE biplot for genotype × environment interaction: a medoid–based hierarchical cluster analysis approach for high–dimensional data . *Biometrical Letters*, 55(2), 97-121. https://doi.org/10.2478/bile-2018-0008

Ngailo, S., Shimelis, H., Sibiya, J., Amelework, B., & Mtunda, K. (2016). Genetic diversity assessment of Tanzanian sweetpotato genotypes using simple sequence repeat markers. *South African Journal of Botany*, 102, 40-45. https://doi.org/10.1016/j.sajb.2015.08.001

Nyaupane, S., Poudel, M. R., Panthi, B., Dhakal, A., Paudel, H., & Bhandari, R. (2024). Drought stress effect, tolerance, and management in wheat–a review. *Cogent Food and Agriculture*, 10(1), Article 2296094. https://doi.org/10.1080/23311932.2023.2296094

Oyewole, C. (2016). The Wheat Crop. *Science*, 93(2423), 12-13. https://doi.org/10.1126/science.93.2423.12.t

Paudel, B., Wang, Z., Zhang, Y., Rai, M. K., & Paul, P. K. (2021). Climate change and its impacts on farmer's livelihood in different physiographic regions of the trans-boundary koshi river basin, central himalayas. *International Journal of Environmental Research and Public Health*, 18(13). https://doi.org/10.3390/ijerph18137142

Poudel, M. R., Neupane, M. P., Panthi, B., Bhandari, R., Nyaupane, S., Dhakal, A., & Paudel, H. (2023). Identification of drought tolerant wheat (*Triticum aestivum*) genotypes using stress tolerance indices in the western terai region of Nepal. *Research on Crops*, 24(4), 652-659. https://doi.org/10.31830/2348-7542.2023.ROC-1012

Poudel, M. R., Poudel, H. K., & Bhandari, R. (2024). Impact of terminal heat stress on performance of Nepalese wheat (*Triticum aestivum* L.) genotypes. *Research on Crops*, 25(1), 1-11. https://doi.org/10.31830/2348-7542.2024.ROC-1052

Purchase, J. L., Hatting, H., & van Deventer, C. S. (2000). Genotype × environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: II. Stability analysis of yield performance. *South African Journal of Plant and Soil*, 17(3), 101-107. https://doi.org/10.1080/02571862.2000.10634878

Sachs, J., Kroll, C., Lafortune, G., Fuller, G., & Woelm, F. (2022). *Sustainable development report 2022*. Cambridge University Press. https://doi.org/10.1017/9781009210058

Sharma, S., Chaudhary, E., Gautam, P., Poudel, R., Sapkota, S., Ghimire, S., Timalsina, B., Roka, P., Bhattarai, K., Pariyar, M., Neupane, K., Aryal, A., G. C, G., Poudel, M. R., & Bhandari, R. (2023). Identification of heat stress tolerant wheat genotype using stress tolerance indices. *Journal of Soil, Plant and Environment*, 2(2), 16-27. https://doi.org/10.56946/jspae.v2i2.185

Shewry, P. R., & Hey, S. J. (2015). The contribution of wheat to human diet and health. *Food and Energy Security*, 4(3), 178-202. https://doi.org/10.1002/FES3.64

Shiferaw, B., Smale, M., Braun, H. J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Security*, 5(3), 291-317. https://doi.org/10.1007/S12571-013-0263-Y

Sood, S., Bhardwaj, V., Kumar, V., & Gupta, V. K. (2020). BLUP and stability analysis of multi-environment trials of potato varieties in sub-tropical Indian conditions. *Heliyon*, 6(11), Article e05525. https://doi.org/10.1016/j.heliyon.2020.E05525

SQCC. (2021). *SQCC notified and denotified varieties*. https://www.sqcc.gov.np/pages/publications

Thungo, Z., Shimelis, H., Odindo, A. O., & Mashilo, J. (2019). Genotype-by-environment interaction of elite heat and drought tolerant bread wheat (*Triticum aestivum* L.) genotypes under non-stressed and drought-stressed conditions. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, 69(8), 725-733.

https://doi.org/10.1080/09064710.2019.1646797

Timalsina, B., Ghimire, S., Roka, P., Poudel, R., Sapkota, S., Aryal, A., Ganesh, G. C., Neupane, K., Gautam, P., Pariyar, M. K., Sharma, S., Chaudhary, E., Poudel, M. R., & Bhandari, R. (2023). AMMI and GGE biplot analysis of yield performance of wheat genotypes under irrigated, heat stress and heat drought environments. *Journal of Agriculture and Applied Biology*, 4(2), 191-201. https://doi.org/10.11594/jaab.04.02.09

Upadhyaya, N., & Bhandari, K. (2022). Assessment of different genotypes of wheat under late sowing condition. *Heliyon*, 8(1), Article e08726. https://doi.org/10.1016/j.heliyon.2022.e08726

von Grebmer, K., Bernstein, J., Wiemers, M., Reiner, L., Bachmeier, M., Hanano, A., Cheilleachair, R. N., Foley, C., Sheehan, T., Gitter, S., Laroque, G., & Fritschel, H. (2023). *2023 Global hunger Index: The power of youth in shaping food systems*. https://www.globalhungerindex.org/pdf/en/2023.pdf