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Evaluation of wheat genotypes using stress tolerance indices under irrigated and drought at late sown condition

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Late sowing and drought under late sown conditions of wheat are the major constraints on wheat production in South Asian countries. The yield of wheat is significantly reduced due to the lack of irrigation water and temperature-induced late sown in Nepal. To identify late sown drought tolerant genotypes of wheat a field experiment was conducted using twenty elite wheat genotypes at the Institute of Agriculture and Animal Science (IAAS), Paklihawa Campus, Nepal in an alpha lattice design with two replications using ten stress tolerance indices (STIs) (Tolerance Index (TOL), Mean Productivity (MP), Stress Susceptibility Index (SSI), Geometric Mean Productivity (GMP), Stress Tolerance Index (STI), Yield Stability Index (YSI), Modified Stress Tolerance Index 1 (MSTI 1), and Modified Stress Tolerance Index 2 (MSTI 2)). NL 1368 and Bhirkuti was found to have highest yield under late sown and drought under late sown condition. The grain yield was found to be reduced from 10.7% to 43.1 % under late sown drought conditions with a mean reduction of 23.67% in comparison with late sown condition showing a direct effect of drought under late sown condition on grain yield of wheat. Correlation analysis showed, yield at late sown condition and yield at drought under late sown condition were significantly positively correlated to MP, GMP, STI, MSTI1, and MSTI2. Principal component biplot analysis showed, Yp and Ys both were positively correlated with MP, GMP, MSTI1, and MSTI2. Hence, selection based on MP, GMP, MSTI1, and MSTI2 would give a high-yielding genotype under both conditions. The first two principal

components cumulatively explain 98.720% of total variation for stress tolerance indices and Bhirkuti, BL 4919, NL 1368, and NL 1376 were found to be high yielding potential genotypes across both environments. Thus, these can be used as a genetic material for yield improvement in wheat.

Keywords: *biplots, high yielding, improvement, principal component analysis, tolerance*

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the mostly cultivated cereal belonging to family Poaceae and provides 19% calorie requirement in the world (Sendhil et al., 2022) in the world. It is the major staple food by 2.5 billion people in the world (Poudel et al., 2021; Sendhil et al., 2022). Wheat is cultivated on 219.01 million hectares of land with the production of 760.92 million metric tons sharing a 10% value addition in agriculture in 2020 (Khan et al., 2020). Wheat has an average productivity of 3.54 tons/ha in the world, which is much higher as compared to Nepal's net productivity of 3.01 tons/ha (FAOSTAT, 2022). It provides more than 20% calorie requirement in West and Central Asia (Sendhil et al., 2022). In Nepal, wheat ranks third position in terms of production and serves as a stable food crop for 25% of the population providing 14% of the total calorie requirement in the diet (Bhandari et al., 2021; Djanaguiraman et al., 2020). Approximately 0.771 million hectares of land were allocated for wheat cultivation, yielding around 2.13 million metric tons in 2020/21 (MOALD, 2022). It shares 19% of the total cereal cultivating area of Nepal contributing 7.14% to the agriculture's gross domestic product (AGDP) in 2020 (Bhatta et al., 2020). The majority of wheat growing area in Nepal lies in tropical Terai under a rice-wheat cropping pattern where the average productivity is 2.99 tons per hectare. Abiotic stresses are the major limiting factor for agriculture production of cereals in the world (Poudel et al., 2019). The crops were routinely subjected to the simultaneous effect of both heat and drought stress due to the gradual change in rainfall patterns and rise in temperature (López-Hidalgo et al., 2023). About 52% crop growing area of Nepal is weather dependent for irrigation with an annual decline in precipitation of 16.09 mm (Paudel et al., 2020). Lack of irrigation reduces the annual productivity of wheat from 800 kg ha^{-1} to 12 t ha^{-1}(Dorostkar et al., 2015). About 25% of the wheat growing area of Nepal is under heat stress. Wheat suffers from heat stress when the temperature exceeds from 22 °C (Djanaguiraman et al., 2020). Climate change rising the temperature of earth at the rate of 0.06 °C annually. Rice-wheat cropping pattern of Nepal causes late sowing of wheat that induces heat stress during the reproductive stage of wheat (KC et al., 2021). Climate induced heat stress reduces the productivity of wheat from 240 kg ha^{-1} to 1380 kg ha^{-1} (Poudel et al., 2020). Prolonged exposure to high temperature reduces the yield by 6% for each degree rise in temperature (Abhinandan et al., 2018; Lesk et al., 2016; Liu et al., 2016). Wheat yield is further predicted to aggravate in the future due to lack of water for irrigation and late sowing of wheat (Abhinandan et al., 2018; Lesk et al., 2016; Liu et al., 2016). Heat stress and drought have been a major issue worldwide, therefore heat stress and drought has become a major subject of intense research. Since, the climate change induced heat-drought is inevitable, future wheat cultivation will be under the combined effect of heat stress and drought. Since the effect of heat stress and drought is different in comparison to their individual effects but the simultaneous effect of both heat stress and drought has not been studied yet. The world, currently facing issues such as climate change, population growth, and lower crop productivity will be the major concern of food security in the future (Carraro et al., 2015). By 2050, about 1.8 billion of people were projected to suffer from food deficit problem [24]. Ending hunger and malnutrition are the major goal of Sustainable Development Goals (SDGs) by United Nations and Agriculture Development Strategy (ADS). In 1961, about 1.36 billion hectares of land were cultivated for 3.5 billion people around the world but after half a century, the population became doubled (7 billion) but the area under cultivation increased only by 12-13% (FAOSTAT, 2022). Due to rapid rise in global population, the rate of conversion of agriculture land to residential areas is increasing day by day therefore the production of wheat is difficult to increase by increasing the wheat growing area. In the scenario of changing global climatic conditions, it can be predicted that the combine effect of heat stress and drought would be the major constraint for wheat production in future. The productivity of wheat should be increased by 50% by 2050 to meet the global food requirement. Heat-drought tolerant genotypes are a prerequisite step for wheat breeding to overall improvement in production and productivity of wheat. Therefore, the main objective of this research is to identify suitable stress tolerance indices and a climate resilient heat-drought tolerant wheat genotypes that could further be employed in various breeding programs to improve wheat productivity and food security of the world.

MATERIALS AND METHODS

An experiment was carried out at the Agronomy farm of the Institute of Agriculture and Animal Science (IAAS), Paklihawa campus, Bhairahawa, Rupandehi from December 2021 to April 2022 (Figure 1).

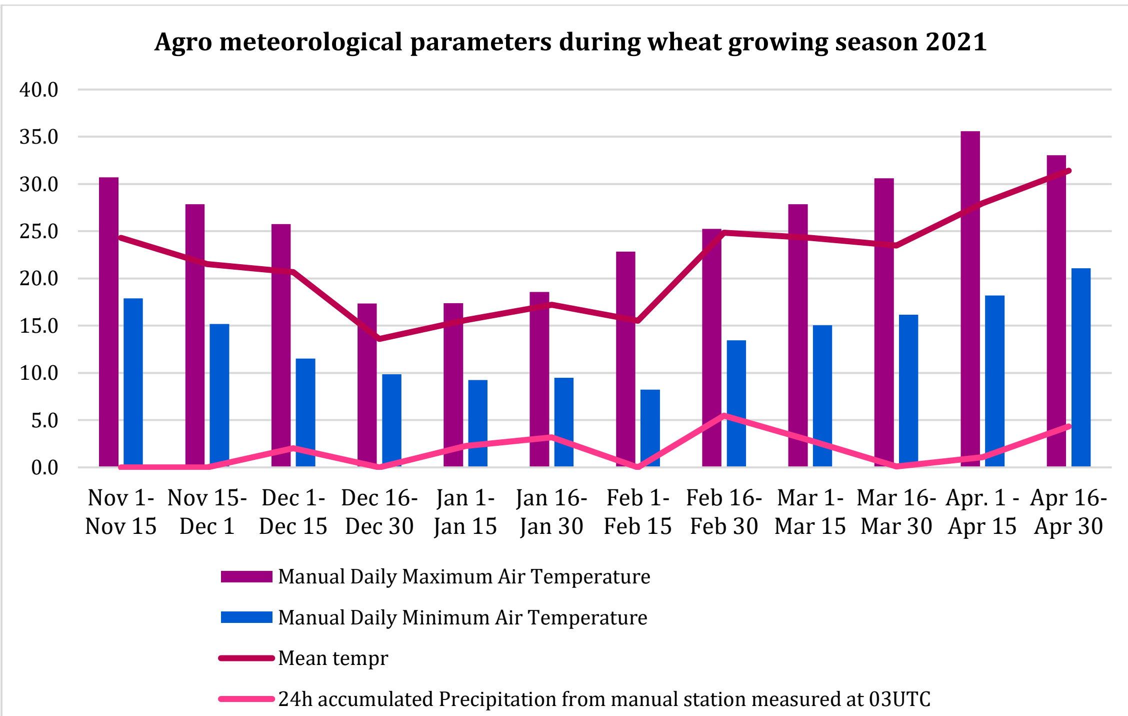

Figure 1. Agrometeorological parameters during the wheat growing season 2021

There were twenty elite wheat lines including fifteen Nepal Lines (NL), three Bhairahawa lines (BL), and two commercial check *viz.*; Bhrikuti and Gautam. These are the emerging lines of wheat provided by the National Wheat Research Program (NWRP), Bhairahawa. Genotypes were evaluated under late sown and drought under late sown condition in an alpha lattice design having five blocks and four plots replicated twice with the plot dimension of 4m x 2.5m (10 m^2).

The inter-block space was maintained at one meter, and the intra-block space was fifty centimeters. Inter-replication space was maintained at one meter. Wheat genotypes were sown on 25th December for both late sown and drought under late sown conditions provided with six critical doses at (crown root initiation (CRI), tillering, heading, flowering, milking, and soft dough stage) while no irrigation was provided with same sowing date for the drought under late sown condition. One-meter square area of the crop was harvested with a serrated sickle at harvestable maturity and yield data were collected for both conditions.

Microsoft Excel- 2016 was used for data entry and processing. Combined analysis of variance across genotypes and condition was performed through IBM SPSS statistics V.26. The computation of stress tolerance indices (STI) was done using Microsoft Excel- 2016. Correlation among Yp, Ys, and stress tolerance indices was performed using IBM SPSS statistics V.26. Past4.06b was used to perform principle component analysis among the stress tolerance indices. Evaluation of genotype was done using stress tolerance indices (STI) (Table 1).

Table 1. Stress tolerance indices (STIs)

S.No.	Stress Tolerance Indices	Formula	References
1.	Tolerance Index (TOL)	$(Yp - Ys)$	(Ramirez-Vallejo & Kelly, 1998)
2.	Mean Productivity (MP)	$\left(\frac{Yp + Ys}{2}\right)$	(Bouslama & Schapaugh, 1984)
3.	Geometrical Mean productivity (GMP)	$(\sqrt{Yp * Ys})$	(Fernandez, 1992)
4.	Yield stability Index (YSI)	$\left(\frac{Ys}{Yp}\right)$	(Fischer & Maurer, 1978)
5.	Stress Tolerance Index (STI)	$\left(\frac{Yp * Ys}{Ypi^2}\right)$	(Fernandez, 1992)
6.	Modified Stress Tolerance Index 1 (MSTI 1)	$\left[\left(\frac{Yp^2}{Ypi^2}\right) * STI\right]$	(Farshadfar & Sutka, 2002)
7.	Modified Stress Tolerance Index 2 (MSTI 2)	$\left[\left(\frac{Ys^2}{Ysi^2}\right) * STI\right]$	(Farshadfar & Sutka, 2002)
8.	Stress Susceptibility Index (SSI)	$\left[\left(1 - \frac{Ys}{Yp}\right) / \left(1 - \frac{Ysi}{Ypi}\right)\right]$	(Fischer & Maurer, 1978)

Yp= Yield of each genotype under late sown condition; Ys= Yield of each genotype at drought under late sown condition; Ypi= Mean yield under late sown condition; Ysi= Mean yield at drought under late sown condition

RESULTS AND DISCUSSION

Yield performance

The grain yield was reduced by 23.67% under a drought under late sown condition as compared to late sown condition (Table 2). Reports from (Mahrookashani et al., 2017) showed late sown drought condition was more lethal to wheat in comparison to a late sown condition where yield was reduced up to 32.14 % - 77.33%. The yield loss ranged from 10.7% - 43.4% at drought under late sown condition compared to late sown condition (Table 2). The result led to the selection of drought under late sown tolerant genotypes of wheat.

High temperature and water stress after flowering were highly sensitive that causes a hazardous effect on reproductive organs that leads to ovule abortion (Aiqing et al., 2017), pollen sterility (Chaturvedi et al., 2021), increases reactive nitrogen species (RNS) and reactive oxygen species (ROS) (Suriyasak et al., 2017), intensifies lipid peroxidation, decreases net chlorophyll content (Aiqing et al., 2017).

The reduction in the activity of ADP- Glc pyro phosphorylase, granule-bound starch synthase, starch synthases, sucrose synthase, and starch branching enzymes under a drought under late sown condition reduce net starch accumulation (Lu et al., 2019). Starch contributes about 70-80% of the seed weight. Reduction in the activity of key enzymes along with increased leaf senescence reduces net photo-assimilates to the grain, and the ultimate effect on the grain yield was seen in (Poudel et al., 2020). Stress tolerance indices were calculated based on yield under late sown and drought under late sown condition. STIs had been used to identify stress-tolerant genotypes of wheat (Puri et al., 2020; Sharma et al., 2013; Singh et al., 2011). TOL, MP, GMP, YSI, STI, MSTI1, MSTI2, and SSI were used to evaluate the stress tolerance of tested genotypes (Bennani et al., 2017; Poudel et al., 2021; Shahryari et al., 2011).

Table 2. Yp, Ys, percentage reduction and STIs of wheat genotypes

SNo.	Genotypes	Yp	Ys	TOL	MP	GMP	YSI	STI	MSTI1	MSTI2	SSI	% yield reduction in HD
1	Bhrikuti	3723	3322.8	400.2	3522.9	3517.21	0.893	1.07	1.29	1.76	0.45	10.7
2	BL 4407	3021.5	2551	470.5	2786.25	2776.3	0.844	0.67	0.53	0.65	0.66	15.6
3	BL 4669	3521	2216.7	1304.3	2868.85	2793.74	0.63	0.68	0.73	0.49	1.56	37.0
4	BL 4919	3788.5	3084.1	704.4	3436.3	3418.2	0.814	1.01	1.26	1.43	0.79	18.6
5	Gautam	3129.5	2203.9	925.6	2666.7	2626.23	0.704	0.6	0.51	0.43	1.25	29.6
6	NL 1179	3204.5	1883.4	1321.1	2543.95	2456.7	0.588	0.52	0.46	0.28	1.74	41.2
7	NL 1346	3476.5	2858.9	617.6	3167.7	3152.61	0.822	0.86	0.9	1.05	0.75	17.8
8	NL 1350	3567	2825.2	741.8	3196.1	3174.51	0.792	0.87	0.96	1.03	0.88	20.8
9	NL 1368	4261.5	2410.9	1850.6	3336.2	3205.32	0.566	0.89	1.4	0.77	1.83	43.4
10	NL 1369	3434	2337.8	1096.2	2885.9	2833.37	0.681	0.7	0.71	0.56	1.35	31.9
11	NL 1376	3464.5	3092.6	371.9	3278.55	3273.27	0.893	0.93	0.96	1.32	0.45	10.7
12	NL 1381	3308.5	2293.9	1014.6	2801.2	2754.88	0.693	0.66	0.62	0.51	1.3	30.7
13	NL 1384	3322.5	2552.2	770.3	2937.35	2911.99	0.768	0.73	0.7	0.71	0.98	23.2
14	NL 1386	3414	2621.4	792.6	3017.7	2991.56	0.768	0.77	0.78	0.79	0.98	23.2
15	NL 1387	2184.5	2513.8	-329.3	2349.15	2343.37	1.151	0.48	0.2	0.45	-0.64	-15.1
16	NL 1404	3408.5	2584.4	824.1	2996.45	2967.98	0.758	0.76	0.77	0.76	1.02	24.2
17	NL 1412	3594.5	2751.3	843.2	3172.9	3144.77	0.765	0.86	0.96	0.96	0.99	23.5
18	NL 1413	3266	2739.7	526.3	3002.85	2991.3	0.839	0.77	0.72	0.86	0.68	16.1
19	NL 1417	3717	2662.3	1054.7	3189.65	3145.75	0.716	0.86	1.02	0.9	1.2	28.4
20	NL 1420	3166	2373	793	2769.5	2740.97	0.75	0.65	0.56	0.54	1.06	25.0
	Mean	**3398.65**	**2593.97**	**804.69**	**2996.31**	**2961**	**0.77**	**0.77**	**0.8**	**0.81**	**0.96**	**23.67**

HD= Drought under late sown condition

MP, GMP, and STI value was found maximum for Bhirkuti, and Bhirkuti was the most productive genotype under a drought under late sown condition (Table 2). MP, GMP, and STI were used to identify the most productive and stress-tolerant genotypes (Kamrani et al., 2018). NL 1368 (1850.6) and NL 1179 (1321.1) had the higher value of TOL in sequence indicating low yield at drought under late sown condition and were drought under late sown proned genotypes. The lowest value of TOL was found for NL 1387 (-329.3) and Bhirkuti (400.2). The lower the value of TOL, the higher would be the yield under a drought under late sown condition that helps in the selection of stress resistant and high yielding genotypes at drought under late sown condition (Poudel et al., 2021). The SSI value was found maximum for NL 1368 (1.83) followed by NL 1179 (1.74). The SSI value of more than one indicates above-average susceptibility and vice versa (Poudel et al., 2021). NL 1387 (1.151) followed by Bhirkuti (0.893) were observed for maximum YSI value. YSI determines the stability of the genotypes that is lower the YSI value, the more unstable the genotype or most stress-prone genotype under late sown drought condition, and vice versa. NL 1368 was found to have the highest value of MSTI1. The higher the value of MSTI1, the higher would be the yield under both conditions (Farshadfar & Elyasi , 2012). Bhrikuti (1.76) followed by BL 4919 (1.43) was found to have the highest value of MSTI2. The higher the value of MSTI2, the higher would be the yield stability of genotypes leading to the identification of the most stable genotype across both heat and drought under late sown conditions (Farshadfar & Elyasi , 2012).

Correlation among the stress tolerance indices (STIs) with the yield at late sown (Yp) and drought under late sown condition (Ys) was done to evaluate the association of stress tolerance indices to yield at both conditions. Correlation analysis showed a non-significant correlation between the Yp and Ys (Table 3). This showed the conditions have their effect independently on the genotype performance. A similar result was reported by (Poudel et al., 2021). Therefore, the selection of the genotype at drought under late sown condition based on its performance in late sown was not beneficial because a genotype performing well in one condition was not necessarily to perform well in another.

Table 3. Correlation among Yp, Ys, and STIs

	Yp	Ys	TOL	MP	GMP	YSI	STI	MSTI1	MSTI2	SSI
Yp	1	0.300	.669**	.837**	.780**	-.600**	.763**	.910**	.505*	.600**
Ys	0.300	1	-.509*	.773**	.830**	.553**	.844**	.623**	.954**	-.553**
TOL	.669**	-.509*	1	0.153	0.058	-.973**	0.031	0.336	-0.288	.973**
MP	.837**	.773**	0.153	1	.995**	-0.081	.992**	.962**	.883**	0.081
GMP	.780**	.830**	0.058	.995**	1	0.004	.998**	.932**	.918**	-0.004
YSI	-.600**	.553**	-.973**	-0.081	0.004	1	0.034	-0.228	0.332	-1.000**
STI	.763**	.844**	0.031	.992**	.998**	0.034	1	.932**	.935**	-0.034
MSTI1	.910**	.623**	0.336	.962**	.932**	-0.228	.932**	1	.775**	0.228
MSTI2	.505*	.954**	-0.288	.883**	.918**	0.332	.935**	.775**	1	-0.332
SSI	.600**	-.553**	.973**	0.081	-0.004	-1.000**	-0.034	0.228	-0.332	1

Yield at late sown condition (Yp) and under late sown drought condition (Ys) had significant positive correlation with MP, GMP, STI, MSTI1, and MSTI2 (Table 3). Hence, MP, GMP, STI, MSTI1, and MSTI2 can be used to select a high-yielding genotype under both conditions (Kamrani et al., 2018). Yield at late sown (Yp) was significantly negatively correlated with YSI and significantly positively correlated with SSI and TOL, respectively.

Similarly, Ys had significant negative correlation with TOL and SSI and significant positive correlation with YSI. Hence, a genotype having higher YSI would have a higher yield under a late sown drought condition whereas a genotype with higher TOL and SSI would have a higher yield under a late sown drought condition (Poudel et al., 2021).

Principal Component Analysis (PCA)

The association of grain yield under both conditions with stress tolerance indices were considered a good criterion for the selection of drought under late sown tolerant genotypes (Nouri et al., 2011). Although correlation analysis was found to help the degree of association, Principal component analysis figured out the relationship between all the attributes at once. Therefore, PCA was found to be the best approach than the correlation analysis for the identification of stress tolerant genotypes.

Table 4. Principle component analysis based on Yp, Ys, and STIs

Comp.	Eigen value	Variance %	Cumulative %	Yp	Ys	TOL	MP	GMP	YSI	STI	MSTI1	MSTI2	SSI
PC 1	6.032	60.326	60.326	0.325	0.330	0.036	0.406	0.406	-0.007	0.406	0.388	0.372	0.007
PC 2	3.839	38.400	98.726	0.305	-0.296	0.506	0.033	-0.013	-0.506	-0.028	0.119	-0.187	0.506

PC1= Principal component 1, PC2= Principal component 2

Considering eigenvalue greater than one, the components cumulative explained 98.726% variation of stress tolerance indices (

Table ***4***). PC1 and PC2 explained 60.326% and 38.400% of the total variation. PC1 had highly positive correlation with Ys, MP, GMP, STI, MSTI1, and MSTI2. Therefore, PC1 was a yield potential and stress-tolerant component. Whereas, PC2 was highly positively correlated with Yp, TOL, and SSI. Therefore, PC2 was a stress susceptible component (

Table ***4***). PC1 and PC2 were used on the basis of their correlation with Yp, Ys, and stress tolerance indices (Bahrami et al., 2014; Dorostkar et al., 2015; Kamrani et al., 2018; Puri & Gautam, 2015). Biplot showed the interrelationships among the stress tolerance indices (Figure 2). The genotypes with high PC1 and low PC2 were high yielders at both conditions whereas the genotypes with low PC1 and high PC2 were low yielders under stressed conditions. Therefore, Bhirkuti followed by BL 4919, NL 1368, and NL 1376 were most suitable under both conditions while NL 1387, NL 1179, and Gautam were most susceptible genotypes under drought under late sown condition (Figure 2). The cosine angle between the vectors of the indices gives the correlation among the indices. Two indices were positively correlated if the angle between the indices was less than 90° and correlated negatively when the angle between them was greater than 90° (Poudel et al., 2021).

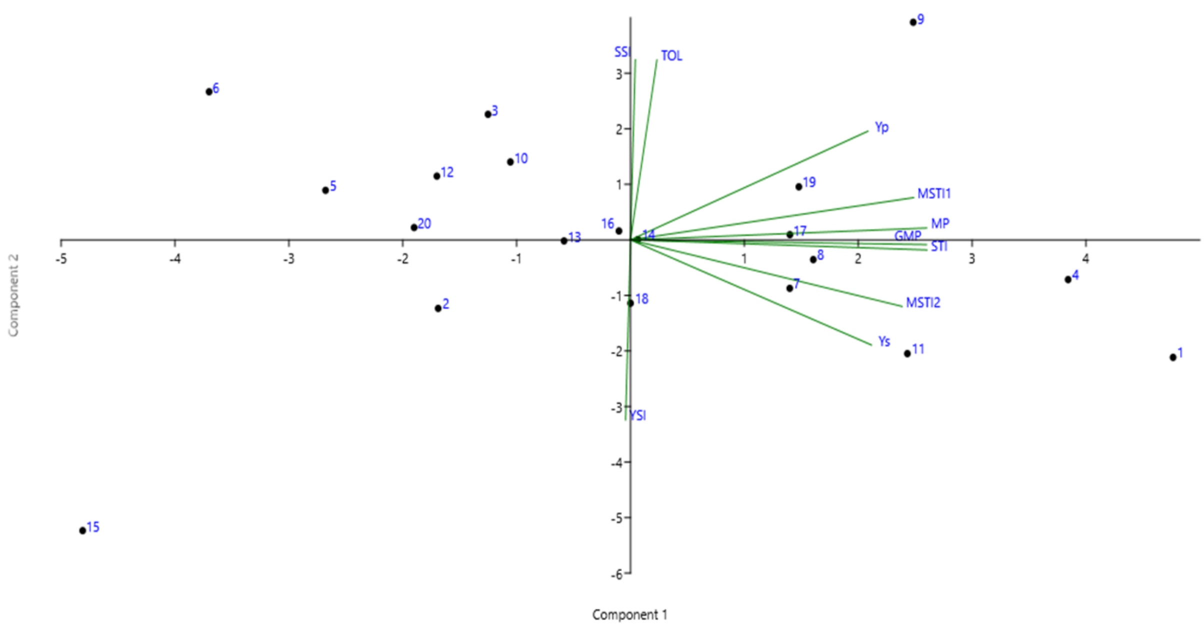

Figure 2. Biplot based on correlation of principle components with Yp, Ys, and stress tolerance indices

Biplot showed, Yp and Ys are positively correlated with MP, GMP, STI, MSTI1, and MSTI2 while negatively correlated with TOL, SSI, and YSI (Figure 2). The genotypes with high PC1 and low PC2 were high yielders at both conditions whereas the genotypes with low PC1 and high PC2 were low yielders under stressed conditions.
Therefore, Bhirkuti followed by BL 4919, NL 1368, and NL 1376 were most suitable under both conditions while NL 1387, NL 1179, and Gautam were most susceptible genotypes under drought under late sown condition (Figure 2).

CONCLUSION

Late sown and drought conditions cause a significant reduction in yield. The effect of heat stress and drought is different in comparison to their individual effects but the simultaneous effect of these late sown and late sown drought stresses conditions and their tolerance is not studied yet properly. Therefore, identification of late sown drought tolerant genotype would help to achieve optimum yield of wheat to feed the global population. The average yield loss of wheat genotypes under late sown drought condition was found to be 23.67% as compared to late sown condition. NL 1368 and Bhirkuti was found to have highest yield under late sown and drought under late sown condition. Yield under late sown (Yp) and yield under late sown drought condition (Ys) were significantly positively correlated to MP, GMP, STI, MSTI1, and MSTI2. Principal component biplot analysis showed, Yp and Ys both were positively correlated with MP, GMP, MSTI1, and MSTI2. Hence, MP, GMP, STI, MSTI1, and MSTI2 can be used in the selection of high-yielding genotypes under both conditions. Bhrikuti, BL 4919, NL 1368, and NL 1376 were found to have the high yield potential under both late sown and late sown drought condition. Hence, these can be used in further breeding programs for yield improvement in wheat.

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AUTHOR CONTRIBUTIONS

Shivalal Nyaupane conceptualized the research, performed analysis, and prepared the manuscript and publication. Radhakrishna Bhandari and Mukti Ram Poudel prepared the manuscript and the manuscript was proofread by all the authors.

COMPETING INTERESTS

The authors declare they have no conflict of interest. The manuscript has not been submitted for publication in other journal.

ETHICS APPROVAL

Not applicable.

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