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Evaluation of Tef [*Eragrostis tef* (Zucc.) Trotter] Genotypes for Acid Soil Tolerance Using Stress Indices

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Abstract

Soil acidity stress is one of the yield limiting factors in high rainfall areas of Ethiopia such as the Benishangul-Gumuz region and developing acid tolerant varieties are the most cost-effective method to tackle the problem. Forty-nine tef genotypes were evaluated under two soil regimes, acidic (pH 4.97) and lime-treated (pH 5.90) soils using completely randomized design (CRD) with three replication in the lathouse at Assosa Agricultural Research Centre in 2017 to identify acid stress tolerant genotypes of tef based on selection indices and determine the most appropriate indices. Grain yield (g pot^{-1}) under both soil conditions used in the computation of acid stress indices. The most effective stress indices which were highly correlated with the yield in both environments were stress tolerance index (STI), geometric mean productivity (GMP) and mean productivity (MP). YSI, PCRD, TOL, and SSI identified the stable genotypes with little yield reduction, however, they are not correlated with high yield and selected genotypes which had low in yield potential. Five genotypes, namely DZ-01-3492 (#28), DZ-01-3733(#29), DZ-01-3405(#34) and DaboBanja(#40) with high grain yield under both environments were identified which are the most widely adapted genotypes. In addition, the genotypes adapted for one of the environment were also identified and therefore, recommended for the future breeding program.

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Keywords

Acid tolerance, Soil acidity, Stress indices, Tef genotypes.

Introduction

Tef, *Eragrostis tef* (Zucc.) Trotter is one of the crops that originated and were diversified in Ethiopia (Vavilov, 1951). It has been introduced to different parts of the world through various institutions and individuals. It is the most demanded crop in Ethiopia which serves as a staple food, sources of income and feed of livestock (Seyfu, 1997). It is the healthy crop since it is free of a protein known as gluten which is found in wheat, barley, and rice that can cause celiac disease by aberrant T-cell (Spaenij-Dekking *et al.*, 2005).

Recently, tef has covered over three million hectares of land in Ethiopia (CSA, 2018). From this, 0.025 million hectares holds for Benishangulgumuz region and 0.329 million tons of grain was produced in 2017/18 season (CSA, 2018). Although the cultivation of tef and its acceptance is become increased in Ethiopia but several environmental limitation were facing the production. From these limitations, soil acidity is one of the major problems which are dominated especially in western parts of Ethiopia (Angaw and Desta, 1988). As a case in point, a site-specific study of soils around Assosa and

Wollega revealed that in aggregate, about 67% had pH values less than six and were very strongly to strongly Acidic(Mesfin, 2007). Acid soils cause nutritional disorders, deficiencies or unavailability of essential nutrients such as calcium, magnesium, molybdenum and phosphorus and toxicity of aluminium, manganese and hydrogen ions activity in the soil and perfectly affect the growth and production of crops (Vitorello *et al.*, 2005; Wang *et al.*, 2006).

One of the options to reduce the impacts of soil acidity on crop production is the development of tolerant cultivars through selection, hybridization, and other breeding methods. The main task of plant breeders to exploiting the genetic variations for the improvement of stress tolerant cultivars is evaluating different genotypes under stress conditions and performs selection practices. Many selection indices have been formulated on the basis of yield under stress and non-stress to identify the most stress tolerant genotypes(Fischer and Maurer, 1978; Bouslama and Schapaugh, 1984; Blum *et al.*, 1988; Hossain *et al.*, 1990; Fernandez, 1992). These selection indices have been not used in the identification of acid tolerant tef genotypes. Therefore, this study was designed to identify acid stress tolerant genotypes of tef based on selection indices and determine the most desirable indices that can be applied to select the tolerant tef genotypes.

Materials and Methods

Experimental site, material and design

The experiment was conducted in lathouse of Assosa Agricultural Research Center (AsARC) in BenishangulGumuz Region, Ethiopia during 2017. Experimental material comprising forty-nine tef genotypes collected from different parts of Ethiopia and some improved varieties (Table 1) were kindly obtained from Debre-Zeit agricultural research. The study was including two experiments (two levels of soil acidity) in order to compute the stress indices. One of the experiment belonged to acid soil condition (pH 4.97) and the other was lime treated soil (pH 5.90). In each experiment, all materials were sown by using randomized complete design with three replications on plastic pots and arranged in lat house of Assosa Agricultural Research Center side by side during 2017 season. To increase the soil pH, 2kg of acid soil was treated with 4.71g of fine particles quicklime (CaO) and filled into pots. All pots were watered and incubated for two weeks in the lathouse till to planting. Then, the seed was sown on pot and thinned to five plants per pot at seedling stage. Fertilizer rate of 46 kg $ha^{-1}P_2O_5$in the form of NPS was applied at the time of sowing and 23 kg ha^{-1} N_2 in the form of Urea was applied 30-35 days after planting.

Soil sampling and analysis

Soil samples were randomly taken from the field of AsARC at 0-20 cm depth using Auger sampler in a zigzag line method. A total of ten soil samples were taken and bulked into one composite sample. The sample was dried, grounded using mortar and pestle, sieved through 2 mm mesh and packed in a polyethylene bag. Soil analyses were done for major physio-chemical properties at Assosa Agricultural Research Center.

Stress selection indices and measurement

After harvest, grain yield under acid (Ys) and lime treated soils (Yp) was weighted in grams of grains from all plants per pot. The experiment of acid and lime treated soils were considered as stress and non-stress environments respectively to determine the following selection indices. Let theYp= Average grain yield of a given genotype in the non-stress environment (limed soil); Ys= Average grain yield of a given genotype in the stressed environment (acidic soil); $\overline{Yp}$= Mean yield of all genotypes in a non-stressed environment (limed soil); $\overline{Ys}$= Mean yield of all genotypes in the stressed environment (acidic soil).The following stress indices were computed based on these four measurements.

1. Stress Susceptibility Index (SSI):SSI $= \frac{1-(Ys/Yp)}{1-(\overline{Ys}/\overline{Yp})}$ (Fischer and Maurer, 1978).
2. Stress Tolerance Index(STI): STI $= (Ys*Yp)/(\overline{Yp})^2$ (Fernandez, 1992).
3. Tolerance index (TOL):TOL = Yp - Ys(Hossain *et al.*, 1990).
4. Geometric mean productivity (GMP): GMP $= \sqrt{Ys*Yp}$ (Fernandez, 1992).
5. Mean productivity (MP); MP = $\left(\frac{Yp+Ys}{2}\right)$ (Hossain *et al.*, 1990).

6. Yield stability index (YSI); YSI = Ys/Yp (Bouslama and Schapaugh, 1984).
7. Stress resistance index (SRI); SRI = $\frac{Ys \times (Ys/Yp)}{\overline{Y}s}$ (Blum *et al.*, 1988).
8. % Reduction (PCRD); PCRD = $\left(\frac{Yp - Ys}{Yp}\right) x\,100$ (Choukan *et al.*, 2006).

Results and Discussions

The mean performance of genotypes

The mean performances of genotypes under acid soil stress and limed soil environment are presented in Table 4. Grain yield (g pot^{-1}) ranged from 0.69 to 2.71 under acid soil condition and from 0.77 to 3.94 under limed soil condition. The highest grain yield was obtained from genotype DZ-01-3724 (#32) followed by genotypes DZ-01-3492 (#28), DZ-01-1722 (#17), DZ-01-3704 (#41), DZ-01-3405 (#34), DZ-01-1841A (#25), DZ-01-855 (#19) and the local check (#49) in acid soil stress condition.

Similarly, genotype DZ-01-3492 (#28), DZ-01-3535 (#37), DaboBanja (#40), DZ-01-305 (#9), DZ-01-3497 (#36), DZ-01-3405 (#34) and the local check (#49) gave maximum grain yield under limed soil condition. Genotype DZ-01-3492 (#28) ranked 2nd and 1st under acid and limed soil condition respectively (Table 5); however, it's percent reduction was relatively high (33.5%) (Table 3). Moreover, genotype DZ-01-3724 (#32) which was ranked the first under stress condition and ranked 16th under no stress had low (2.63%) percent reduction in yield indicating the relative consistency of the performance of this genotype over the two environments. DZ-01-1722 (#17) ranked 3rd under soil acidity stress but 12th under no stress and had yield reduction of 21.6%. DZ-01-3704 (#41) ranked 4th and 22nd under stress and no stress, respectively, but had low yield reduction (6.7%).

Improved varieties, Ambo toke (#45) (1.98 and 1.70), Estuib (#46) (1.26 and 2.27) and Quncho (#47) (1.64 and 1.93), gave low grain yield (g pot^{-1}) under both acid and lime-treated soil conditions. The local check, '*Kontal'* had higher mean of grain yield (2.07 and 3.33), ranking 8th and 6th under acid and lime-treated soil conditions indicating its relatively better and consistent performance as compared to the improved varieties. DaboBanja which is a landrace grown under severely acidic soils of Amhara region showed relatively better performance over the improved varieties Ambo toke (#45), Estuib (#46), Quncho (#47), Kora (#48) and local check (#49). It ranked 3rd under no stress and 10th under stress but had high yield reduction (43.6%). The study of Ermias (2015) indicated that DaboBanja landrace had better tolerance to soil acidity than all tested improved varieties except Dima. Tef varieties released so far have not been bred specifically for acid tolerance.

Stress susceptibility index (SSI)

Stress susceptibility index (SSI) estimates the degree of susceptibility or reduction in yield of a genotype under stress condition. Negative values of this index are obtained whenever yield under stress is higher than yield under lime treated. Lower values of SSI indicate a little reduction of yield under stress as compared to yield and higher stability and the vice versa. The genotype that showed SSI less than one are more tolerant of stress conditions (Khan and Mohammad, 2016). The lowest SSI values were observed for genotype DZ-01-1841A (#25) (-0.52), with grain yield 2.19 and 1.86 g pot^{-1}; Ambo toke (#45) (-0.49) with grain yield 1.98 and 1.70 g pot^{-1}; DZ-01-16 (#6) (-0.31) with grain yield 0.85 and 0.77 g pot^{-1}; Kora (#48) (-0.09) with grain yield 1.99 and 1.93 g pot^{-1} and DZ-01-3724 (#32) (0.08) with grain yield 2.71 and 2.78 g pot^{-1}under acid stress and lime-treated soil environments, respectively (Table 4). Thus according to SSI, these genotypes were relatively less reduction in yield under acid stress condition.

The mean yield of the 10 genotypes with the lowest SSI was 1.82 and 1.84 g pot^{-1} under soil acidity stress and lime-treated, respectively (Table 2). There was no considerable yield reduction due to stress (0.22%). The mean SSI of these genotypes was 0.01. The mean yield of the most unstable genotypes with the highest SSI was 1.09 and 2.43 g pot^{-1} under stress and limed, respectively with yield reduction of 55.43 and their mean SSI was 1.64 (Table 3). Selection based on low SSI favors high yield under stress. Of the genotypes with low SSI and were stable, only DZ-01-855 (#19), DZ-01-1841A (#25), DZ-01-3724 (#32) and DZ-01-3704 (#41) ranked 7th 6th 1st and 4th by yield under stress. All others are ranked 12th to 45th by yield under acidity stress. All of them had ranks from 16th to 49th by yield under lime treated soil condition (Table 5). None of the 10 genotypes that gave the highest yields under lime treated were selected by SSI. SSI seems to identify genotypes with high yield under acid stress, but low yield under no stress. Two of the 10 most unstable genotypes (high SSI), DZ-01-3497 (#36) and DZ-01-3535 (#37) ranked 5th and 2nd, respectively by yield under no stress. The others ranked from 14th to 47th by yield under no stress and from 19th to 49th by yield under stress (Table 5). SSI seems inappropriate for selecting high yielding genotypes under no stress. Ranking of genotypes by PCRD and YSI is identical to their ranking by SSI.

Stress tolerance index (STI)

The highest stress tolerance were for genotypes DZ-01-3492 (#28) (1.74), DZ-01-3724 (#32) (1.27), DaboBonja (#40) (1.25), DZ-01-3405 (#34) (1.24), DZ-01-305 (#9) (1.17), DZ-01-1722 (#17) (1.16), and local check (#49) (1.16) (Table 2), whereas the least ten STI values were found for genotypes DZ-01-16 (#6) (0.11), DZ-01-3747 (#44) (0.18), DZ-01-306 (#10) (0.21), DZ-01-1234 (#22) (0.24) and DZ-01-3738 (#30) (0.26) (Table 3).

The five genotypes with the highest STI were 2nd 1st 10th 5th and 15th by yield under stress and 1st 16th 3rd 6th and 4th by yield under lime treated (Table 5). DZ-01-3492 (#28), DZ-01-3405 (#34), DZ-01-3733 (#29), and DaboBanja (#40) gave high yield under both environments (ranked 1st to 10th). DZ-01-3724 (#32) and DZ-01-1722 (#17) are adapted to acidic soil while DZ-01-305 (#9) and DZ-01-3497 (#36) are adapted to lime-treated soil. All these genotypes were among the highest yielding at either or both environments. Seven of the highest yielding genotypes under stress and eight of the highest yielding genotypes under lime treated and four of the five genotypes with high yield under both environments were identified by this index. The ten genotypes with the lowest STI were among the lowest yielding at both soil environments.

Stress tolerance index (STI) is used to identify genotypes that have high yield under both stress and non-stress environment. However, these genotypes were unstable with yield reduction of 34.3% and SSI of 1.01 (Table 3). The larger the value of STI for a genotype under stress environment, the higher is its stress tolerance and yield potential(Fernandez, 1992). Therefore, those genotypes which had high STI estimates can be considered as the most tolerant to soil acidity stress.

Tolerance index (TOL)

Tolerance index (TOL) is the difference of yield under non-stress and stress conditions(Hossain *et al.*, 1990) therefore, the greater the value of TOL, the larger the yield reduction under stress and the higher the stress sensitivity of the genotype, the lower its stability and *vice versa*. Accordingly, the most tolerant genotypes were for DZ-01-1841A (#25) (-0.33), Ambo Toke (#45) (-0.28), DZ-01-16 (#6) (-0.08), Kora (#48) (-0.06), and DZ-01-3724 (#10) (0.04) gave high yield under stress and none gave high yield under lime treated soil (Tables 2 and 4). The most acid stress sensitive genotypes according to the TOL were DZ-01-3535 (#37) (2.13), DZ-01-3692 (#43) (1.69), DZ-01-305 (#9) (1.68) and DZ-01-3497 (#36) (1.67). Genotypes DZ-01-3492 (#28), and DaboBanja (#40) were high yielding over both soil environments while DZ-01-3497 (#36), DZ-01-3535 (#37), and DZ-01-3533 (#38) were high yielding only under lime treated and were unstable.

For most of the tested genotypes ranking by TOL was very similar to a ranking by SSI for high yielding genotypes but was different for low yielding genotypes. Nine of the 10 genotypes with lowest TOL also had low SSI while only four of the genotypes with lowest TOL did also have low SSI. The negative value of TOL showed greater yield under stress than non-stress conditions (Javed *et al.*, 2011). Low TOL, therefore, did not lead to high yield in both environments. To the contrary, high yield reduction (high TOL) identified genotypes with high yield under no stress. TOL is biased and not favorable for selection of genotypes under stress environment. It had failed to select genotypes with proper yield under both soil environments.

Mean productivity (MP)

Mean productivity is the average of genotype yield under non-stress and stress conditions, and its higher values indicate its higher yield potential under both environments. Thus the genotypes with the highest MP values were DZ-01-3492 (#28) (3.28), DaboBanja (#40) (2.84), DZ-01-305 (#9) (2.77), DZ-01-3405 (#34) (2.77), DZ-01-3724 (#32) (2.75), local check (#49) (2.70), and DZ-01-3733 (#29) (2.66) (Table 2). All genotypes with the highest MP gave high yield under both environments (ranked 1st to 10th) except DZ-01-305 (#9), DZ-01-3497 (#36) and DZ-01-3535 (#37), which gave high yield only under no stress, ranking 15th 19th and 29th, respectively under acidity stress and DZ-01-3724 (#32) and DZ-01-1722 (#17) which gave high yield under acid but ranked 16th and 12th under limed (Table 5). Eight of the highest yielding genotypes under lime treated and seven of the 10 highest yielding genotypes under acid were identified by MP. All five genotypes that gave high yield under both soil conditions were identified by MP. Selection by high MP led to high yield under both environments, with some bias towards high yield under non-stress environment. However, these genotypes were unstable with yield reduction of 36.4% (Table 2).

The lowest MP values were those of genotypes DZ-01-16 (#6) (0.81), DZ-01-306 (#10) (1.11), DZ-01-3747 (#44) (1.13), DZ-01-1234 (#22) (1.32), DZ-01-3738 (#30) (1.35) and DZ-01-383 (#24) (1.39) (Table 3). These genotypes were given low yields under both environments and were also unstable with yield reduction of 32.2% under stress.

Geometric mean productivity (GMP)

The geometric mean is similar to STI and MP in discriminating genotypes and its higher values indicate higher crop tolerance under stress. The highest GMP was recorded from genotype DZ-01-3492 (#28) (3.21), DZ-01-3724 (#32) (2.75), DaboBanja (#40) (2.73), DZ-01-3405 (#34) (2.71), DZ-01-305 (#9) (2.64), DZ-01-1722 (#17) (2.63), and local check (#49) (2.63) (Table 4). All gave high yield under both environments except DZ-01-305 (#9), DZ-01-1512 (#26), and DZ-01-3497 (#36) which were adapted to the non-stress environment and DZ-01-3724 (#32) and DZ-01-1722 (#17) which were adapted to stress environment. All five genotypes, DZ-01-349 (#28), DZ-01-3733 (#29), DZ-01-3405 (#34), DaboBanja (#40) and the local check (#49), that gave high yield under both environments were identified by GMP and MP. Similar genotypes were identified by both GMP and MPand differed in only two genotypes, DZ-01-3535 (#37) which was selected only by MP and ranked 29th under stress while DZ-01-1512 (#26) was selected only by GMP and ranked 14th under stress. Percent reduction in these genotypes was 34.3%. Average ranks by yield under stress and no stress of the 10 genotypes selected by MP were 10.1 and 6.3; these mean ranks were 8.6 and 7.1, respectively for GMP and STI (Table 2). Both MP and GMP are a little biased towards high yield under non-stress.

Stress resistance index (SRI)

The highest SRI were recorded for genotypes DZ-01-3724 (#32), (DZ-01-3492 (#28), DZ-01-3704 (#41), Ambo Toke (#45) and Kora (#48) (Table 2), while the lowest SRI were recorded for genotypes DZ-01-1311 (#18), DZ-01-3535 (#37), DZ-01-3753 (#31), DZ-01-3692 (#43) (Table 3). High SRI identified one widely adapted genotype, DZ-01-3492 (#28) and five genotypes with high yield under stress but not under no stress environment. These genotypes ranked from 1st to 7th and from 12th to 40th, respectively, under stress and no stress except genotype DZ-01-3492 (#28) which had high yield under both environments. From the ten worst genotypes identified by low SRI, genotype DZ-01-3535 (#37) gave high yield and ranked 2nd under no stress. The remaining genotypes were low yielding under both stress and non-stress environments. High SRI identified genotypes with relatively high stability but was biased towards selecting high yielding genotypes under stress environment.

In general, suitable genotypes for acidic, lime treated and both soil environments were determined based on various selection indices since the determination of tolerant genotypes based on a single criterion is not consistent. MP, GMP and STI identified five widely adapted genotypes (DZ-01-3492 (#28), DZ-01-3733 (#29), DZ-01-3405 (#34), DaboBonja (#40) and the local check (#49)). The other genotypes selected under stress by Ys or under no stress by Yp were the ones adapted to the specific environment. All these specifically adapted genotypes were also among the 10 highest yielding genotypes identified by MP and GMP, except DZ-01-3533 (#38), which was specifically adapted to the non-stress environment. Nine of the 10 highest yielding genotypes identified by MP and GMP were identical. DZ-01-1512 (#26), specifically adapted to non-stress environment, was identified only by GMP while DZ-01-3535 (#37) which was also adapted to non-stress environment was identified only by MP. Two of the genotypes with high yield only under stress (DZ-01-1722 (#17) and DZ-01-3724 (#32)) were identified by both MP and GMP. Two of the genotypes with high yield only under no stress (DZ-01-305 (#9) and DZ-01-3497 (#36)) were also identified by both MP and GMP. STI selected the same genotypes that were identified by GMP.

SSI, PCRD, TOL,andSRI selected 4, 4, 3 and 6, of the 10 genotypes that gave high yield under stress. They selected stable genotypes with the lowest yield reductions under stress. These indices seem to be biased towards selecting a few relatively high yielding genotypes adapted to stress environments. The majority of the genotypes selected by SSI, YSI and PCRD and some selected by SRI, however, were stable but low yielding under both environments, ranking from 25th to 49th (Table 5) except one genotype (DZ-01-3492 (#28)) selected by SRI which was widely adapted.

Several authors noted that STI, GPM and MP are more suitable indicator for evaluating drought stress tolerance for wheat genotypes (Golabadi *et al.*, 2006; Javed *et al.*, 2011; Mokhtar *et al.*, 2012) for rapeseed genotypes (Shirani Rad and Abbasian, 2011) for Safflower (Seyed *et al.*, 2013). Talebi (2009) reported that cultivars producing a high yield in both drought and well-watered conditions can be identified by STI, GMP and MP values. Similarly, GMP, STI, and MP indices were used as best indices to select salt tolerance of rice genotypes (Seyyed *et al.*, 2012). Contrary (Farshadfar *et al.*, 2001) noted that SSI and TOL are more indicators to select stress tolerant genotypes. But selection based on TOL often leads to genotype which has a low yield.

Table.1 List of germplasms and released varieties of tef used in the experiment

No.	Genotype	Area of collection	No.	Genotypes	Area of collection
1	DZ- 01-1531	-	26	DZ-01-1512	-
2	DZ-01-1821	West Showa	27	DZ-01-2086	Awi
3	DZ-01-1908	West Wollega	28	DZ-01-3492	Jimma
4	DZ-01-2111A	West Wollega	29	DZ-01-3733	South West Showa
5	DZ-01-280	DebreZeit	30	DZ-01-3738	South West Showa
6	DZ-01-16	DebreZeit	31	DZ-01-3753	South West Showa
7	DZ-01-1676A	West Wollega	32	DZ-01-3724	Minjar
8	DZ-01-272	East Showa	33	DZ-01-3394	Jimma
9	DZ-01-305	East Showa	34	DZ-01-3405	Jimma
10	DZ-01-306	East Showa	35	DZ-01-3486	Jimma
11	DZ-01-1551	-	36	DZ-01-3497	Jimma
12	DZ-01-1482	East Gojjam	37	DZ-01-3535	Jimma
13	DZ-01-1809	West Showa	38	DZ-01-3533	Jimma
14	DZ-01-1573A	-	39	DZ-01-3507	Jimma
15	DZ-01-999	West Showa	40	DaboBanja	Awi
16	DZ-01-728	Ambo	41	DZ-01-3704	Minjar
17	DZ-01-1722	Jimma	42	DZ-01-3688	South West Showa
18	DZ-01-1311	ArsiNegele	43	DZ-01-3692	South West Showa
19	DZ-01-855	East Showa	44	DZ-01-3747	South West Showa
20	DZ-01-1978	West Wollega	45	Ambo toke	Released in 1999
21	DZ-01-1769A	-	46	Estuib	Released in 2008
22	DZ-01-1234	Central Tigray	47	Quncho	Released in 2006
23	DZ-01-229	DebreZeit	48	Kora	Released in 2014
24	DZ-01-383	DebreZeit	49	Local check	Assosa
25	DZ-01-1841A	East Wollega			

Table.2 The ten top ranking genotypes by grain yield under lime treated (Yp) and under acidic soil (Ys) and by various stress indices

Rank	Ys	Yp	GMP	MP	YSI	SSI	PCRD	TOL	STI	SRI
1	32‡	28	28	28	25	25	25	25	28	32
2	28	37	32	40	45	45	45	45	32	25
3	17	40	40	9	6	6	6	6	40	45
4	41	9	34	34	48	48	48	48	34	41
5	34	36	9	32	32	32	32	10	9	48
6	25	34	17	49	10	10	10	32	17	19
7	19	49	49	29	41	41	41	41	49	17
8	49	29	29	17	14	14	14	14	29	28
9	29	38	36	36	19	19	19	3	36	11
10	40	26	26	37	3	3	3	47	26	39
Means										
Ys	2.27	1.99	2.17	2.12	1.82	1.82	1.82	1.76	2.17	2.23
Yp	3.01	3.45	3.34	3.39	1.84	1.84	1.84	1.78	3.34	2.53
GMP	2.60	2.61	2.68	2.67	1.83	1.83	1.83	1.77	2.68	2.36
MP	2.64	2.72	2.75	2.76	1.83	1.83	1.83	1.77	2.75	2.38
YSI	0.79	0.58	0.66	0.64	1.00	1.00	1.00	1.00	0.66	0.91
SSI	0.63	1.25	1.01	1.08	0.01	0.01	0.01	0.01	1.01	0.26
PCRD	21.17	42.26	34.31	36.36	0.22	0.22	0.22	0.43	34.31	8.71
TOL	0.74	1.46	1.17	1.27	0.02	0.02	0.02	0.02	1.17	0.31
STI	1.15	1.16	1.21	1.21	0.61	0.61	0.61	0.58	1.21	0.97
SRI	1.12	0.72	0.90	0.87	1.12	1.12	1.12	1.09	0.90	1.25
Rs	5.5	13.2	8.6	10.1	19.3	19.3	19.3	21.1	8.6	7.4
Rns	13.4	5.4	7.1	6.3	36.4	36.4	36.4	38.0	7.1	22.7

‡ Numbering of genotypes (1 to 49)

Where Ys = Grain yield of each genotype under acid stress, Yp = Grain yield of each genotype under no stress, GMP = Geometric mean productivity, MP = Mean Productivity, YSI = Yield stability index, SSI = Stress susceptibility index, TOL= Tolerance index, PCRD = Percent reduction, STI = Stress tolerance index, SRI = Stress resistance index, Rs = Mean rank of stress, Rns = Mean rank of non-stress

Table.3 The ten bottom ranking genotypes by grain yield under lime treated (Yp) and under acidic soil (Ys) and by various stress indices

Rank	Yp	Ys	GMP	MP	YSI	SSI	PCRD	TOL	STI	SRI
40	25‡	31	14	7	36	36	36	28	14	18
41	30	7	7	23	31	31	31	5	7	37
42	23	10	20	14	20	20	20	13	20	31
43	45	2	12	12	30	30	30	2	12	43
44	3	20	24	24	44	44	44	38	24	2
45	12	6	30	30	2	2	2	40	30	20
46	14	24	22	22	24	24	24	36	22	30
47	44	30	10	44	43	43	43	9	10	24
48	10	22	44	10	37	37	37	43	44	44
49	6	44	6	6	22	22	22	37	6	22
Means										
Yp	1.56	1.81	1.64	1.60	2.43	2.43	2.43	3.28	1.64	2.36
Ys	1.30	0.95	0.99	1.01	1.09	1.09	1.09	1.71	0.99	1.12
GMP	1.40	1.29	1.25	1.26	1.62	1.62	1.62	2.36	1.25	1.62
MP	1.43	1.38	1.31	1.31	1.76	1.76	1.76	2.50	1.31	1.74
YSI	0.85	0.58	0.65	0.68	0.45	0.45	0.45	0.52	0.65	0.48
SSI	0.43	1.24	1.02	0.95	1.64	1.64	1.64	1.43	1.02	1.54
PCRD	14.64	42.01	34.53	32.23	55.43	55.43	55.43	48.26	34.53	51.92
TOL	0.26	0.86	0.65	0.59	1.34	1.34	1.34	1.57	0.65	1.24
STI	0.35	0.29	0.27	0.27	0.48	0.48	0.48	0.97	0.27	0.46
SRI	0.74	0.35	0.42	0.44	0.30	0.30	0.30	0.57	0.42	0.34
Rs	33.5	44.5	42.8	42.0	40.4	40.4	40.4	23.0	21	42.2
Rns	44.4	37.3	41.8	42.9	25.9	25.9	25.9	8.30	38	28.4

‡ Numbering of genotypes (1 to 49)

Where, Ys = Grain yield of each genotype under acid stress, Yp = Grain yield of each genotype under no stress, GMP = Geometric mean productivity, MP = Mean Productivity, YSI = Yield stability index, SSI = Stress susceptibility index, TOL= Tolerance index, PCRD = Percent reduction, STI = Stress tolerance index, SRI = Stress resistance index, Rs = Mean rank of stress, Rns = Mean rank of non stress

Table.4 Average grain yield of 49 tef genotypes under acid and lime-treated soil conditions with their respective indices

No.	Ys	Yp	SSI	TOL	STI	GMP	MP	PCRD	YSI	SRI
1	1.35	2.37	1.27	1.02	0.54	1.79	1.86	42.96	0.57	0.48
2	1.08	2.49	1.68	1.41	0.45	1.64	1.78	56.70	0.43	0.29
3	1.45	1.68	0.40	0.23	0.41	1.56	1.57	13.69	0.86	0.78
4	1.63	2.38	0.93	0.75	0.65	1.97	2.01	31.37	0.69	0.69
5	1.67	3.01	1.32	1.35	0.84	2.24	2.34	44.69	0.55	0.57
6	0.85	0.77	-0.31	-0.08	0.11	0.81	0.81	-10.43	1.10	0.58
7	1.17	1.89	1.13	0.73	0.37	1.49	1.53	38.38	0.62	0.45
8	1.67	2.08	0.58	0.41	0.58	1.86	1.88	19.71	0.80	0.83
9	1.93	3.61	1.38	1.68	1.17	2.64	2.77	46.54	0.53	0.64
10	1.09	1.13	0.10	0.04	0.21	1.11	1.11	3.24	0.97	0.66
11	2.03	2.66	0.70	0.63	0.91	2.32	2.34	23.81	0.76	0.96
12	1.27	1.60	0.60	0.33	0.34	1.42	1.43	20.46	0.80	0.63
13	1.56	2.93	1.39	1.38	0.77	2.14	2.25	46.93	0.53	0.51
14	1.42	1.59	0.32	0.17	0.38	1.50	1.50	10.71	0.89	0.78
15	1.92	2.82	0.95	0.91	0.91	2.33	2.37	32.11	0.68	0.81
16	1.22	1.99	1.14	0.77	0.41	1.56	1.60	38.59	0.61	0.46
17	2.33	2.97	0.64	0.64	1.16	2.63	2.65	21.57	0.78	1.13
18	1.24	2.20	1.29	0.96	0.46	1.65	1.72	43.70	0.56	0.43
19	2.18	2.50	0.38	0.32	0.92	2.33	2.34	12.80	0.87	1.18
20	0.98	2.16	1.61	1.17	0.36	1.46	1.57	54.40	0.46	0.28
21	1.50	2.42	1.13	0.92	0.61	1.91	1.96	38.10	0.62	0.58
22	0.75	1.88	1.78	1.13	0.24	1.19	1.32	60.11	0.40	0.19
23	1.24	1.81	0.93	0.57	0.38	1.50	1.53	31.43	0.69	0.53
24	0.84	1.95	1.68	1.11	0.27	1.28	1.39	56.85	0.43	0.22
25	2.19	1.86	-0.52	-0.33	0.69	2.02	2.03	-17.71	1.18	1.60
26	1.94	3.12	1.12	1.19	1.02	2.46	2.53	37.99	0.62	0.74
27	1.68	2.41	0.90	0.73	0.68	2.01	2.05	30.29	0.70	0.73
28	2.62	3.94	0.99	1.32	1.74	3.21	3.28	33.50	0.66	1.08
29	2.06	3.26	1.08	1.19	1.13	2.59	2.66	36.64	0.63	0.81
30	0.83	1.86	1.63	1.03	0.26	1.25	1.35	55.28	0.45	0.23
31	1.21	2.38	1.46	1.17	0.48	1.69	1.79	49.30	0.51	0.38

Table.4 Continued

No.	Ys	Yp	SSI	TOL	STI	GMP	MP	PCRD	YSI	SRI
32	2.71	2.78	0.08	0.07	1.27	2.75	2.75	2.63	0.97	1.63
33	1.75	2.76	1.08	1.01	0.81	2.20	2.25	36.52	0.63	0.69
34	2.20	3.33	1.00	1.13	1.23	2.71	2.77	33.90	0.66	0.90
35	1.82	2.26	0.58	0.44	0.69	2.02	2.04	19.50	0.81	0.91
36	1.77	3.44	1.44	1.67	1.02	2.47	2.60	48.64	0.51	0.56
37	1.51	3.64	1.73	2.13	0.92	2.35	2.58	58.55	0.41	0.39
38	1.74	3.18	1.34	1.44	0.93	2.35	2.46	45.18	0.55	0.59
39	1.93	2.51	0.69	0.58	0.82	2.20	2.22	23.21	0.77	0.92
40	2.05	3.64	1.29	1.59	1.25	2.73	2.84	43.63	0.56	0.72
41	2.31	2.47	0.20	0.17	0.96	2.39	2.39	6.74	0.93	1.33
42	1.59	2.15	0.77	0.56	0.57	1.85	1.87	26.09	0.74	0.73
43	1.21	2.90	1.72	1.69	0.59	1.88	2.06	58.21	0.42	0.31
44	0.69	1.57	1.66	0.88	0.18	1.04	1.13	56.26	0.44	0.19
45	1.98	1.70	-0.49	-0.28	0.56	1.83	1.84	-16.50	1.17	1.43
46	1.26	2.27	1.32	1.01	0.48	1.69	1.76	44.56	0.55	0.43
47	1.64	1.93	0.44	0.29	0.53	1.78	1.79	14.85	0.85	0.87
48	1.99	1.93	-0.09	-0.06	0.64	1.96	1.96	-2.94	1.03	1.27
49	2.07	3.33	1.12	1.27	1.16	2.62	2.70	38.00	0.62	0.79
Grand mean	1.61	2.44	0.93	0.82	0.70	1.97	2.03	31.44	0.69	0.71

Ys: grain yield of each genotype under stress, Yp: grain yield of each genotype under normal, SSI: Susceptibility index, TOL: Tolerance index, STI: Stress tolerance index, GPM: Geometric productivity mean, MP: Mean productivity, PCRD: Percent reduction, YSI: Yield stability index, SRI: Stress resistance index

Table.5 Ranking of 49 tef genotypes in respect to different soil acidity stress tolerance indices

No.	Ys	Yp	SSI	STI	TOL	GMP	MP	YSI	PCRD	SRI	Mean rank
1	33	27	32	31	30	31	30	32	32	36	37
2	43	21	45	36	43	36	34	45	45	44	44
3	31	44	10	37	9	37	39	10	10	19	25
4	26	25	20	24	22	24	25	20	20	24	23
5	24	11	36	17	41	17	16	36	36	32	29
6	45	49	3	49	3	49	49	3	3	30	32
7	41	38	30	41	20	41	40	30	30	38	41
8	23	33	13	28	13	28	28	13	13	14	18
9	15	4	38	5	47	5	3	38	38	27	21
10	42	48	6	47	5	47	48	6	6	26	31
11	11	18	17	16	18	16	15	17	17	9	9
12	34	45	14	43	12	43	43	14	14	28	33
13	28	13	39	20	42	20	19	39	39	35	34
14	32	46	8	40	8	40	42	8	8	18	26
15	17	15	22	15	25	15	14	22	22	16	15
16	38	34	31	38	23	38	37	31	31	37	38
17	3	12	15	6	19	6	8	15	15	7	3
18	37	30	34	35	27	35	36	34	34	40	40
19	7	20	9	14	11	14	16	9	9	6	4
20	44	31	42	42	36	42	38	42	42	45	45
21	30	23	29	26	26	26	26	29	29	31	30
22	48	39	49	46	33	46	46	49	49	49	49
23	36	42	21	39	16	39	41	21	21	34	36
24	46	35	46	44	32	44	44	46	46	47	47
25	6	40	1	22	1	22	24	1	1	2	5
26	14	10	27	10	37	10	11	27	27	20	17
27	22	24	19	23	21	23	22	19	19	22	19
28	2	1	23	1	40	1	1	23	23	8	6
29	9	8	26	8	38	8	7	26	26	15	12
30	47	40	43	45	31	45	45	43	43	46	46
31	40	25	41	33	35	33	32	41	41	42	43
32	1	16	5	2	6	2	5	5	5	1	1
33	20	17	25	19	28	19	18	25	25	25	22

Table.5 Continued

No.	Ys	Yp	SSI	STI	TOL	GMP	MP	YSI	PCRD	SRI	Mean rank
34	5	6	24	4	34	4	4	24	24	12	7
35	18	29	12	21	14	21	23	12	12	11	13
36	19	5	40	9	46	9	9	40	40	33	27
37	29	2	48	13	49	13	10	48	48	41	35
38	21	9	37	12	44	12	12	37	37	29	28
39	15	19	16	18	17	18	20	16	16	10	11
40	10	3	33	3	45	3	2	33	33	23	16
41	4	22	7	11	7	11	13	7	7	4	2
42	27	32	18	29	15	29	29	18	18	21	24
43	39	14	47	27	48	27	21	47	47	43	42
44	49	47	44	48	24	48	47	44	44	48	48
45	13	43	2	30	2	30	31	2	2	3	10
46	35	28	35	34	29	34	35	35	35	39	39
47	25	36	11	32	10	32	33	11	11	13	20
48	12	36	4	25	4	25	27	4	4	5	8
49	8	6	28	7	39	7	6	28	28	17	14

Ys: Grain yield of each genotype under stress, Yp: Grain yield of each genotype under limed, SSI: Susceptibility index, TOL: Tolerance index, STI: Stress tolerance index, GPM: Geometric productivity mean, MP: Mean productivity, YSI: yield stability index, PCRD: Percent reduction, SRI: Stress resistance index.

Table.6 The yields of various selection indices as compared to the yield of Yp and Ys

Group	% of no stress	% of Stress
No Stress	100.0	87.7
Stress	87.2	100.0
GMP	96.8	95.6
MP	98.3	93.4
YSI	53.3	80.2
SSI	53.3	80.0
TOL	51.6	77.5
PCRD	53.3	80.2
STI	73.3	95.6
SRI	53.3	98.2

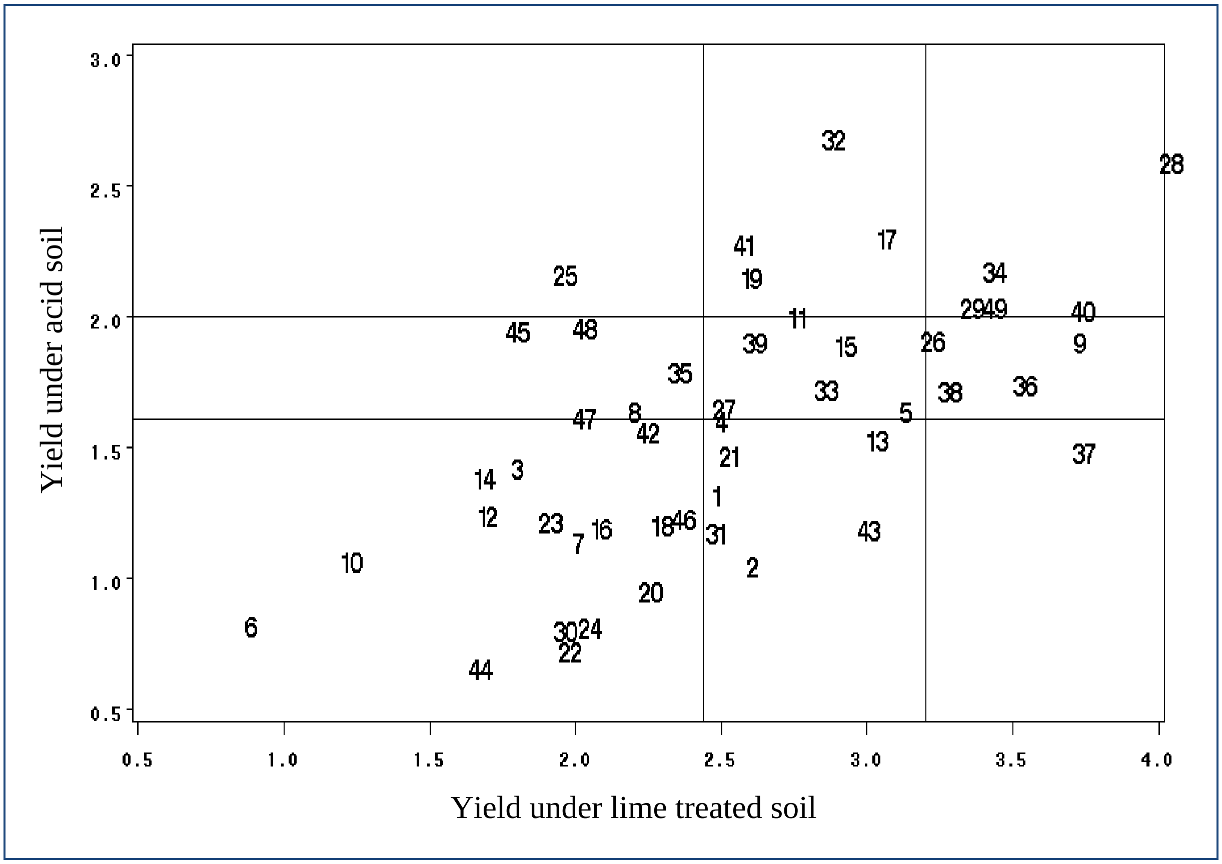
Where GMP = Geometric mean productivity, MP = Mean Productivity, YSI = Yield stability index, SSI = Stress susceptibility index, TOL = Tolerance index, PCRD = Percent reduction, STI = Stress tolerance index, SRI = Stress resistance index

Table.7 The simple correlation between ranks of indices of tef genotypes studied under acid and limed soil

	Yp	Ys	MP	GMP	SSI	YSI	TOL	STI	SRI
Yp	1.00	0.59^{**}	0.88^{**}	0.92^{**}	-0.33^{*}	-0.33^{*}	-0.70^{**}	0.88^{**}	0.16
Ys		1.00	0.85^{**}	0.89^{**}	0.49^{**}	0.49^{**}	0.10	0.89^{**}	0.87^{**}
MP			1.00	0.99^{**}	0.01	0.01	-0.40^{**}	0.99^{**}	0.51^{**}
GMP				1.00	0010	0.10	-0.32^{*}	1.00	0.58^{**}
SSI					1.00	1.00	0.87^{**}	0.10	0.83^{**}
YSI						1.00	0.87^{**}	0.10	0.83^{**}
TOL							1.00	-0.32^{*}	0.54^{**}
STI								1.00	0.28^{**}
SRI									1.00

*, **, ***: significant at 5%, 1% and 0.1% of probability level, respectively. Ys: Yield of genotypes under stress; Yp: Yield of genotypes under non-stress; GMP = Geometric mean productivity, MP = Mean Productivity, YSI = Yield stability index, SSI = Stress susceptibility index, TOL = Tolerance index, PCRD = Percent reduction, STI = Stress tolerance index, SRI = Stress resistance index

Figure.1 Scatter-gram showing the categorization of tef genotypes based on their yield in a comparison of acid soil stress and non-stress conditions



Comparison of stress indices

The grain yields of genotypes selected by various stress indices as compared to grain yield of genotypes by high yield under no stress (Yp) or by high grain yield under stress (Ys) are presented in Table 6. Selections from MP and GMP gave almost equal yield to the Yp selections (98.3 and 96.8 %, respectively) when tested under no stress. They also gave 95.6 and 93.4% of Ys selections. STI selections give the same result as GMP selections. These three indices (MP, GMP, and STI) can, therefore, be used to identify genotypes with high yield under both environments. Those selected under stress (Ys) gave 87.2% of the 10 genotypes selected under no stress. Yp selections also gave 87.7% of Ys selections. This indicates that the two environments had a positive correlation.

YSI, TOL, PCRD, SSI and SRI selections do not perform well under no stress (51.6 to 53.3%). These are not appropriate indices to identify genotypes that give high yield under no stress. SSI, PCRD, and YSI (80.2%) have relatively high yield under soil acidity stress. They can be used with some success for identification of genotypes with relatively high yield under soil acidity stress. SRI selections (98.2%), gave high yields under soil acidity stress and can be used under stress.

It can, therefore, be concluded that MP, GMP, and STI can be used to identify genotypes with wide adaptation (high yield under both stress and no-stress environments). YSI, SSI, and PCRD can be used with some success to identify high yielding genotypes for stress environments but are inappropriate for selection under no stress. Such selections give similar yield under both environments, are very stable with no yield reduction under stress. TOL cannot be used as selection criteria for any environment. Highly stable genotypes with low TOL are low yielding in both environments.

Correlation of indices

To determine the most desirable acid soil tolerance criteria, the correlation between Yp, Ys, and indices of acid soil tolerance were computed and presented in Table 7. Rank correlations between yields and selection indices have shown that Ys had a highly significant positive correlation with GMP (0.89***), STI (0.89***), SRI (0.89***). Similarly Yp had highly significant positive correlation with GMP (0.88***), MP (0.92***) and STI (0.88***). It had a negative correlation with SSI and YSI (-0.33*), TOL (-0.70***), and non-significant correlation with SRI (0.16). This corroborates the conclusion already made, that MP, GMP, and STI can be used for selecting high yielding genotypes for both stress and non-stress environments. There was a very close correlation (1.00*** to 0.99***) between these three indices. SRI can only be used under stress environments, while TOL is not appropriate for any environment. YSI and SSI may be used under stress with some success, but are inappropriate under non-stress environments. There was a positive correlation between Yp and Ys; five of the 10 highest yielding genotypes were common in both environments.

Similarly, Javed *et al.* (2011) reported a positive and significant association of Yp and Ys with MP, GMP and STI. These were better predictors of potential yield under no stress (Yp) and stress (Ys) than TOL and SSI. Gholipouri *et al.*, (2009) reported that grain yield under stress condition showed a negative association with TOL and with SSI. Thus, SSI might be a suitable index to identify genotypes with low yield and tolerant to stress because under stress yield decreased with increasing SSI (Javed *et al.*, 2011). In our study, Ys had a positive correlation (0.49**) with SSI. On the other hand, the lack of significant correlation between TOL and Ys (r = 0.10) indicated that TOL cannot be used to identify genotypes with high yield under stress. TOL was less helpful in selecting high yielding drought tolerant genotypes (Seyyed *et al.*, 2012). According to Mehrdad *et al.*, (2011), MP, SSI and TOL did not have a significant correlation with yield under stress and cannot be used to select drought-tolerant cultivars. The authors found a positive correlation between STI and GMP indices on one hand, and yield under stress and under no stress on the other and concluded that these indices were the most suitable indices for selecting high yielding cultivars under both drought stress and non-stress conditions.

Category of genotypes based on mean yield under stress and no stress

Mean yields of 49 tef genotypes under soil acidity stress are plotted against their yield under lime treated and acid soils (Figure 1). Genotypes DZ-01-1841A (#25), DZ-01-3704 (#32), DZ-01-3704 (#41) DZ-01-855 (#19) and DZ-01-1722 (#17) were among the 10 highest yielding genotypes under soil acidity stress but were not among the 10 highest yielding genotypes under no stress (Table 2). They ranked 40th 16th 12th 20th and 22nd under no stress. Similarly genotypes DZ-01-3535 (#37), DZ-01-305 (#9), DZ-01-3497 (#36), DZ-01-3533 (#38) and DZ-01-1512 (#26) gave high yield under no stress but gave relatively low yield under stress. They ranked 29th 15th 19th 21st and 14th under stress. Five genotypes, namely, DZ-01-3492 (#28), DZ-01-3733 (#29), DZ-01-3405 (#34), DaboBanja (#40), and the local check (#49) gave high yield under both environments and can be recommended for wide adaptation. Of special interestgenotypesDZ-01-1841A (#25) and DZ-01-3535 (#37) which gave below average yields in the environment where they were not selected. DZ-01-1841A (#25) was among the highest yielding genotypes under stress but ranked 40th under no stress while DZ-01-3535 (#37) was among the highest yielding genotypes under no stress but ranked 29th under stress. DZ-01-3704 (#32) with the highest yield under stress is also of interest.

Genotypes DZ-01-16 (#6), DZ-01-306 (#10), DZ-01-3747 (#44) gave low yield under both environments. They ranked from 42th to 49th under stress and from 47th to 49th under no stress. These genotypes were relatively stable and had low yield reduction except genotype DZ-01-3747 (#44) which had high (56.3 %) yield reduction (Table 4). However, the yield potentials of these genotypes are very low.

Summary and conclusion are as follows

Based on mean performance of the genotypes and most of the stress indices, five genotypes from the ten superior genotypes, namely, DZ-01-3492 (#28), DZ-01-3733 (#29), DZ-01-3405 (#34), DaboBanja (#40) and the local check (#49) which were gave high yield both under acid and lime treated soils and were widely adapted and hence can be utilized for both acid soil stress and no stress environments.

Another five genotypes (D-01-1841A (#25), DZ-01-3704 (#32), DZ-01-3704 (#41), DZ-01-855 (#19) and DZ-01-1722 (#17)) were gave high yield only under acid soil stress while DZ-01-3535 (#37), DZ-01-305 (#9), DZ-01-3497 (#36), DZ-01-3533 (#38) and DZ-01-1512 (#26)) gave high yield only under no stress soil condition.

From stress indices, mean productivity (MP), geometric mean productivity (GMP) and stress tolerance index (STI) categorized the genotypes in the similar fashion and they are strongly correlated with high grain yield under stress and non-stress conditions. These three stress indices were the most suitable indices in selecting desirable genotypes in both environments. On the other hand, YSI, PCRD, TOL, and SSI identified stable genotypes with little yield reduction under stress. However, they had no suitable correlation with yield under both soil environments. They cannot, therefore, be used as desirable selection indices under these soil acidity levels. SRI also identified genotypes with high yield only under soil acidity stress and it is less effective in selecting genotypes under lime treated soil.

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