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Using Acid Stress Tolerance Indices, Identifying Tef (*Eragrostis tef*) Genotypes that Tolerant Acid Soil

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Abstract: To expand tef agriculture to acidic areas and fulfill the crop's increasing demand, it is critical to identify tef genotypes that are tolerant of acidic soil. Using acid tolerance indices based on grain yield trait, the study's goal was to assess and select tef genotypes resistant to acid soil. The experiment carried out in the Holetta tef research program lath house, 100 tef genotypes were grown in a simple lattice design for two years in both limed and unlimed conditions. The genotypes varied considerably based on whether the soil was limed or not, according to the analysis of variance results. Grain yield was lowered by acid stress on average (20.24%). The most suitable indices for selecting tolerant tef varieties were tolerance index (TOL) and average rank (AR). Genotype 40, 22 and 72 showed superior performance under unlimed whereas G75, G16 and G77 were best under limed condition. Eleven genotypes, namely, G40, G22, G72, G10, G14, G56, G67, G81, G30, G25, G49 and G6 were found among the top high yielding genotypes and showed superior performance in both stress and non-stress conditions.

Key words: Acid Soil · Genotypes · Lime Treated · Stress · Tef and Tolerance

INTRODUCTION

Tef [*Eragrostis tef* (Zucc.) Trotter] is grown on more than 3.1 million hectares in Ethiopia annually [1]. For over 70 million people, it is the most popular cereal and their main source of nutrition. The primary usage of tef grain is for human consumption, which is obtained by baking the grain flour into the well-known "*injera*" cottage bread [2]. Straw (chid) is an important source of food for animals. Tef cultivation is generally expanding due to the high domestic market prices for grain and straw. Tef is a crop that is adaptable to a variety of agro-ecologies and has a fair resistance to moisture stresses of both low (particularly terminal drought) and high (waterlogging). Compared to other cereals, it has a high nutritional value, particularly in iron, calcium and copper [3].

Tef is currently being supported and promoted as a health crop globally due to its slow-release carbohydrate components and gluten-free proteins [4]. The study of tef was first conducted scientifically in the late 1950s. Since then, efforts in basic and applied research have yielded several noteworthy successes. Over 58 improved cultivars are currently available [1]. Even though tef is being cultivated and accepted more widely in Ethiopia, the national yield per unit area (1.914 t/ha) is still low due to a number of biotic and abiotic stresses that affect its' production and productivity.

Abiotic stressors that have a major global impact on crop productivity include soil acidity. As to the findings of Ermias and von Uexkull; acid soils, defined as surface layer pH values less than 5.5, account for 3,950 million hectares worldwide, which represents 30% of all ice-free area and around 40% of arable land [5, 6]. According to Malcolm and Andrew; 659 million ha, or 22% of the 3.01 billion ha of land in Africa, have acidic soil [7]. Over 28.1% of Ethiopia's land is affected by significant soil acidity and 43% of the agricultural land in the three high-potential regions mostly in the highlands is affected [8].

The exchangeable forms of aluminum and hydrogen are linked to soil acidity. Humid locations typically have acidic soils, whereas arid or desert regions typically have alkaline or sweet soils. The behavior of aqueous solutions which are considered acidic when the activity of hydrogen ions is greater than that of hydroxyl ions led to the development of the notion of acidity. Because of crop removal and element leaching, most humid regions have

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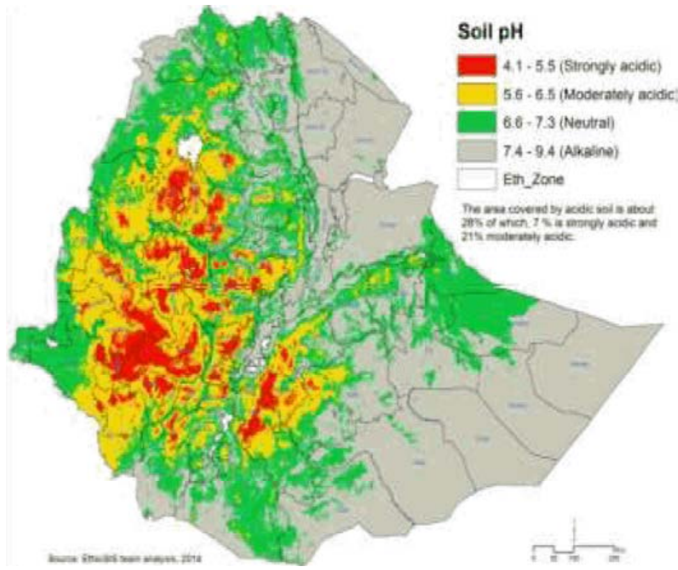

Source: Behailu Kassahun's Ethiopian ATA Soil Map [8]

acidic or "sour" soils. These elements include potassium, magnesium and calcium. It is convenient to express a soil's degree of acidity or alkalinity in terms of pH values. The pH scale has 14 divisions, or pH units, with values ranging from 1 to 14.

Low soil fertility and acidity are two of the biggest abiotic barriers to tef production [9,10]. Among these limitations, soil acidity is a significant problem, especially in the western regions of Ethiopia [11]. Ermias state that in contrast to most internationally significant cereals, tef has not yet been developed for soil acidity tolerance [5]. According to Wang and Vitorello; nutrient deficiencies, toxicity from aluminum, manganese, hydrogen ions, deficiencies or unavailability of essential nutrients like calcium, magnesium, molybdenum and phosphorus directly affect crop growth and yield in acidic soils [12, 13].

The government extension service has mostly encouraged the use of compost, lime and mineral fertilizers in addition to soil and water conservation techniques to address the issue of acidity in the soil. However, their influence on the management of acid soils has been limited due to variations in agro-ecologies, the endowment of local resources and the restricted ability of small-scale farmers to invest in such choices [14].

Selection, hybridization and other breeding techniques are the most effective and cost-effective ways to create tolerant cultivars and lessen the effects of soil acidity on crop yield. Plant breeders' primary responsibility is to evaluate various genotypes under stress conditions and carry out selection procedures in order to take advantage of genetic variations for the improvement of stress-tolerant cultivars. In order to determine which genotypes are the most stress resistant, numerous selection indices have been developed based on yield under stress and non-stress [15-22].

Recent releases, accessions and regional/local cultivars have not been included in studies conducted thus far. This study aimed to use specific acid tolerance indices to identify tef genotypes that are tolerant to acid stress. Additionally, the most suitable indices for selecting tolerant tef varieties were identified.

MATERIALS AND METHODS

Site of Experiment Material and Design: The experiments (limed and unlimed) were carried out at Holetta Agricultural Research Center in the Lat house for two years in parallel, from 2021 to 2022. The experimental materials include improved tef varieties, core germplasm that originated from 12 zones of Ethiopia, particularly the western part, screened for different purpose and available own our hands as well as local landraces from acid-prone places using a simple lattice design. To calculate the stress indices, the soil acidity was split into two levels in this study. One trial had acid soil (pH less than 4), whereas the other involved lime-treated soil (pH greater than 5.5). The soil sampled from Medakegn, the most acidic district in northwest Ethiopia, had a pH (H_2O) ratio ranging from 1:2.5 specifically 3.9 pH, which is highly acidic.

Table 1: Lists and sources of tef genotypes tested at Holeta Agricultural Research during 2021 and 2022 under lath house conditions on the pot; treated with lime (non-stressed) and un-limed (stressed) soil.

N#	Genotypes	Sources
1	*DZ-01-99*	*Asgori (released)*
2	*DZ-01-196*	*Magna (released))*
3	*DZ-01-354*	*Enatite (released)*
4	*DZ -01-787*	*Wolenkomi (released)*
5	*DZ-Cr- 44*	*Menagesha (released)*
6	*DZ- Cr -82*	*Melko (released)*
7	*DZ-Cr -255*	*Gibe (released)*
8	*DZ-01-974*	*Dukem (released)*
9	*DZ -Cr -358*	*Ziquala (released)*
10	*DZ -01-2053*	*Holeta key (released)*
11	*DZ -01-1278*	*Ambo toke (released)*
12	*DZ -01-1285*	*Koya (released)*
13	*PGRC/E 205396*	*Ajora (released)*
14	*DZ -01-1868*	*Yilmana (released)*
15	*DZ -01-2423*	*Dima (released)*
16	*DZ -Cr-387(RIL-355)*	*Quncho (released)*
17	*DZ -01-1880*	*Gudru (released)*
18	*DZ -23-Tafi-Adi-72*	*Kena (released)*
19	*DZ -01-3181*	*Etsub (released)*
20	*DZ -Cr-438(RIL133B)*	*Kora (released)*
21	*ACC 214746A*	*Werekiyu (released)*
22	*DZ -Cr-438(RIL7)*	*Abola (released)*
23	*DZ -Cr-438(RIL 91A)*	*Dagem (released)*
24	*DZ -Cr-429 RIL 125*	*Negus (released)*
25	*DZ -Cr-442RIL 77c*	*Filagot (released)*
26	*DZ -Cr-457 RIL181*	*Tesfa (released)*
27	*DZ-Cr-419*	*Heber-1(released)*
28	*DZ-01-401*	*Areka-1(released)*
29	*ACC #225931*	*Abay (released)*
30	*ACC 236952*	*Dursi (released)*
31	*DZ-01-256*	*Jitu (released)*
32	*DZ-Cr-458 RIL 18*	*Ebba (released)*
33	*DZ-Cr-429 RIL 29*	*Washera (released)*
34	*DZ-Cr-497 RIL 133*	*Bishoftu (released)*
35	*DZ-Cr-37*	*Tseday (released)*
36	*DZ-01-2054*	*Gola (released)*
37	*DZ-01-1281*	*Gerado (released)*
38	*DZ-01-1681*	*Key Tena (released)*
39	*DZ-01-1821*	*Zobel (released)*
40	*DZ-01-146*	*Genat (released)*
41	*HO-CR-136*	*Amarach (released)*
42	*ACC -205953*	*Mechare (released)*
43	*DZ- CR-387*	*Gemechis (released)*
44	*DZ-Cr-385(RIL 295*	*Simada (released)*
45	*DZ-Cr-387(RIL273*	*Lakech (released)*
46	*DZ-Cr-409*	*Boset (released)*
47	*DZ-Cr-453(RIL 120B*	*Bora (released)*
48	*DZ-Cr-428*	*Mena (released)*
49	*DZ-01-899*	*Gimbichu (released)*
50	*DZ-01-2675*	*Dega Tef (released)*
51	*Dabo Banja tef*	*Hawi zone (as a check)*
52	*HOH-TFS-187*	*pvt 2018 code 69*
53	*HOH-TFS-220*	*pvt 2018 code 12*
54	*HOH-TFS-014*	*pvt 2018 code 2*

Table 1: Continue

N#	Genotypes	Sources
55	*HOH-TFS-285*	*pon 2018 code 18*
56	*HOH-TFS-094*	*pon 2018 code 14*
57	*HOH-TFS-224*	*pon 2018 code 51*
58	*HOH-TFS-036*	*pon 2018 code 10*
59	*HOH-TFS-190*	*pon 2018 code 39*
60	*HOH-TFS-138*	*pvt 2018 code 6*
61	*HOH-TFS-242*	*pvt 2018 code 14*
62	*HOH-TFS-302*	*pvt 2018 code 19*
63	*HOH-TFS-227*	*pvt 2018 code 52*
64	*HOH-TFS-291*	*pvt 2018 code 43*
65	*HOH-TFS-177*	*pvt 2018 code 8*
66	*HOH-TFS-300*	*pvt 2018 code 18*
67	*HOH-TFS-262*	*pvt 2018 code 15*
68	*HOH-TFS-009*	*pon 2018 code 53*
69	*HOH-TFS-071*	*pon 2018 code 28*
70	*HOH-TFS-255*	*pon 2018 code 55*
71	*HOH-TFS-233*	*pon 2018 code 9*
72	*HOH-TFS-026*	*pon 2018 code 4*
73	*HOH-TFS-040*	*pon 2018 code 13*
74	*HOH-TFS-193*	*pon 2018 code 6*
75	*HOH-TFS-171*	*pon 2018 code 36*
76	*HOH-TFS-090*	*pon 2018 code 1*
77	*HOH-TFS-202*	*pon 2018 code 2*
78	*HOH-TFS-117*	*pon 2018 code 71*
79	*HOH-TFS-015*	*pon 2018 code 20*
80	*Medakegn tef*	*Local around medakegn*
81	*Holeta tef check*	*Local around Holeta*
82	*Dembecha Ac#15*	*Cultivar/west Gojam*
83	*Dembecha Acc#16*	*Cultivar/west Gojam*
84	*Dembecha Acc#17*	*Cultivar/west Gojam*
85	*Dembecha Acc#18*	*Cultivar/west Gojam*
86	*Machake Acc#20*	*Cultivar/west Gojam*
87	*Quarit Acc#24*	*Cultivar/west Gojam*
88	*Quarit Acc#25*	*Cultivar/west Gojam*
89	*Mecha Acc#26*	*Cultivar/west Gojam*
90	*Mecha Acc#27*	*Cultivar/west Gojam*
91	*Mecha Acc#002*	*Cultivar/west Gojam*
92	*Dangila Acc#003*	*Cultivar/Awi*
93	*Bonja Acc#005*	*Cultivar/ Awi*
94	*Bonja Acc#006*	*Cultivar/ Awi*
95	*Figata Acc#007*	*Cultivar/ Awi*
96	*Figata Acc#008*	*Cultivar/ Awi*
97	*Guagusa Acc#009*	*Cultivar/ Awi*
98	*Sekala Acc#012*	*Cultivar/west Gojam*
99	*Sekala Acc#013*	*Cultivar/west Gojam*
100	*Sekala Acc#014*	*Cultivar/west Gojam*

Where ACC- Accession derived released tef varieties, DZ- Debre Zeit, 01- Variety released through selection, Cr- Variety released through Cross /hybridization, HO- Holeta released tef variety, HOH-TFS- Holeta Habte tef germplasm selected and PGRC/E- Plant Genetic Resource Conservation of Ethiopia.

Table 2: Description of the selected acid soil stress indices

Tolerance Index	Formula	References	Remarks / Pattern of Selection
Tolerance Index (TOL)	TOL = Yp -Ys	[29]	The highest TOL values indicate the greatest yield reduction caused by stress, while the lowest values show tolerance.
Stress Susceptibility Index (SSI)	$SSI = \frac{Yp - Ys}{Yp*(1-[\frac{\mu Ys}{\mu Yp}])}$	[15]	High stress susceptibility is indicated by SSI values >1, while values < 1 indicate high yield stability.
Stress Tolerance Index (STI)	$STI = \frac{Yp * Ys}{(\mu Ys)^2}$	[19]	Maximum values STI stands for stress-tolerant genotype.
Geometric Mean Index (GMP)	$GMP = \sqrt{YpxYs}$	[19]	Highest GMP values indicate a genotype's high yield potential both under stress and in the absence of stress.
Mean Productivity (MP)	$MP = \frac{Yp + Ys}{2}$	[29]	The highest MP values indicate a genotype's stress tolerance and yield potential.
Yield stability Index (YSI)	$YSI = \frac{Ys}{Yp}$	[16]	High YSI values indicate stable under stress and non-stress genotypes.
Yield Index (YI)	$YI = \frac{Ys}{\mu Ys}$	[30]	Highest Value
Harmonic Mean (HM)	$HM = \frac{2(Yp * Ys)}{(Ys + Yp)}$	[31]	Highest Value
Relative Stress *Index* (RSI)	$RSI = \frac{(Ys/ Yp)}{(\mu Ys/\mu Yp)}$	[32]	Highest Value

Where; Yp and Ys are yields of a given genotype under non-stress and under stress soil conditions respectively. ìYs is mean yield of all test genotypes under stress conditions whereas ìYp is mean yield of all genotypes under non-stress soil conditions.

All of the components for each experiment were simultaneously seeded on plastic pots and put side by side. Using a lime requirement formula below and the area of the pot, 2.6 kg of acid soil filled in a 0.0314m^2 area pot was treated with 16 grams of fine particles quicklime ($CaCO_3$) to raise the pH of the soil.

Before planting, every pot of the soil was watered and allowed to incubate for four weeks. Plants were minimized to five per container when they reached the seedling stage. The light red soil type was advised to use 40% N and 60% P_2O_5 fertilizer, along with other management practices.

Based on research recommendations in the study region, fertilizers were applied once at planting at a rate of 46kg P_2O_5 and 22kg N per hectare from NPS (Nitrogen, Phosphorus and Sulphur) formulation and Urea source, respectively. The N:P:S ratios for nitrogen, P_2O_5 and sulfur are, respectively, 19:38: 7. With the exception of the lime treatment, both experimental sets were generally managed similarly.

Sample of Soil, Collection of Data and Interpretation: Soil samples were collected at random from farmer's fields in the acid-prone midakegn woreda of western Shewa using an Auger sampler in a zigzag line method. The samples were collected from extremely acidic areas at depths ranging from 0 to 20 cm. A 100-gram composite sample was taken after all samples had been bulked and composited in order to analyze the soil's primary physical and chemical characteristics.

Following air drying, disaggregation and sieving through a 2 mm sieve, the samples were examined. The soil laboratory at the Holeta Agricultural Research Center conducted the soil analysis.

As a result, each set of experiments was carried out independently for two years in parallel under ideal conditions with acidic soil (unlimed). According to Kamprath's instructions, extraction and titration were used to estimate exchangeable acidity, which was used to calculate the non-stress $CaCO_3$ or lime requirement [23].

$$LR\left(CaCO3\left(\frac{kg}{ha}\right)\right) = \frac{EA(cmol\ kgsoil) \times A\ (m) \times A(m2) \times \rho b(g\ cm3)}{2} \times LF$$

whereas ρb= Soil bulk density, LF= Liming Factor or adjustment factor (LF=1.5) is determined based on crop response, A= Area of experimental land, DS= Depth of Soil (0.15m), EA= Exchangeable Acidity and LR= Lime Rate.

After harvest, information was collected from each pot regarding the grain yield (g/plot) and its average was translated to kg/ha for statistical analysis. Tolerance indices, or relative values, were calculated using the ratio of the measured parameters under limed (stressed) versus limed (non-stressed) conditions. Mean separation by Fisher's least significant difference test, Duncan test and analysis of variance were carried out for both limed and unlimed data using SAS Version 9.3. Using those indices, principal component analysis and the Pearson correlation coefficient were carried out along with grain yield under stress and non-stress. Pearson states that the correlation coefficient can be used to determine the overall degree of linear association between the indices and the grain yield trait [24].

Biplot analysis is an even better method than correlation analysis to identify superior genotypes for both stress and non-stress environments and to evaluate relationships among all attributes at once [25-27]. The values of various indices and yield under both conditions were pre standardized to means of zero and variances of unity before principal component analysis to avoid bias due to differences in values or measurement scales [28]. A new online program called iPASTIC produces the acidity indices by calculating a number of yield-based stress tolerance and susceptibility indices [21]. The genotypes that are most resistant to acidity in severely acidic soil conditions are indicated by the minimum Average Rank (AR) value. In addition to this, it can also perform correlations and principal component analyses for yield-based stress indices and grain yield.

RESULTS AND DISCUSSION

Variance Analysis: Grain yield data analysis revealed highly significant ($P \leq 0.001$) differences between genotypes under unlimed conditions, but no significant differences under lime treated one. The overall mean grain yield under limed soil was 394.03 kg ha^{-1} (48.3 to 1918.3 kg ha^{-1}), indicating a yield reduction of 20.24%, as in comparison with 314.3 kg ha-1 (10.0 to 880.8 kg ha^{-1}) for unlimed acid soil one. An accessible web-based tool that aggregates all of these indices into a single source is the Plant Abiotic Stress Index Calculator [21]. It was used to calculate the indices and the percentage of relative change owing to stress relative to the non-stress environment for a set of genotypes.

The yield-based indices' results are displayed in Table 3, along with each genotype's relative stress-induced change. The genotypes G75, G16 and G77 exhibited the highest mean performance compared to G51 (the control), with grain yield (Yp) ranging from 48.33 to 1918.33 kg ha^{-1}. Grain yield (Ys) varied between 10 and 880.83 ha^{-1} under acid stress, with the eleven highest yielding genotypes being G40, G22, G72, G10, G14, G56, G67, G81, G30, G25, G49 and G6. The tested genotypes, G6, G43, G50, G46, G12, G72 and the others, exhibited the least amount of variation from the controls when compared to the relative change (RC) resulting from acidity stress (Table 3).

Table 3: The tef genotypes' results on the grain yield acidity indices

Genotype	Yp	Ys	RC	MP	GMP	HM	SSI	STI	YI	YSI	RSI
G6	106.67	549.17	-414.83	-442.50	327.92	242.03	178.64	-22.52	0.41	1.78	5.15
G43	101.67	432.50	-325.40	-330.83	267.09	209.70	164.64	-17.66	0.31	1.40	4.25
G50	74.17	265.00	-257.29	-190.83	169.59	140.20	115.90	-13.96	0.14	0.86	3.57
G46	93.33	330.00	-253.58	-236.67	211.67	175.50	145.51	-13.76	0.21	1.07	3.54
G12	48.33	160.00	-231.06	-111.67	104.17	87.94	74.24	-12.54	0.05	0.52	3.31
G72	240.83	795.83	-230.45	-555.00	518.33	437.79	369.76	-12.51	1.33	2.57	3.30
G66	147.50	387.50	-162.71	-240.00	267.50	239.07	213.67	-8.83	0.40	1.25	2.63
G68	140.00	365.83	-161.31	-225.83	252.92	226.31	202.50	-8.76	0.36	1.18	2.61
G56	255.00	645.00	-152.94	-390.00	450.00	405.56	365.50	-8.30	1.15	2.09	2.53
G81	251.67	635.00	-152.31	-383.33	443.34	399.76	360.47	-8.27	1.11	2.05	2.52
G4	141.67	313.33	-121.17	-171.66	227.50	210.69	195.12	-6.58	0.31	1.01	2.21

*Where; G- Genotype, Yp-Yield under limed, Ys-Yield under unlimed, RC- Relative change due to stress, TOL-Tolerance index, GMP-Geometric mean productivity, MP-Mean productivity, STI-Stress tolerance index, SSI- Stress susceptibility index, HM-Harmonic mean, YI-Yield index, YSI-Yield stability index and RSI-Relative stress index.

Table 4: The grain yield acidity indices rank results of tef genotypes

Genotype	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI	SR	AR	SD
G22	21.0	2.0	7.0	3.0	3.0	2.0	20.0	3.0	2.0	20.0	20.0	103.0	9.4	8.7
G40	6.0	1.0	30.0	2.0	1.0	1.0	34.0	1.0	1.0	34.0	34.0	145.0	13.2	15.8
G10	31.0	4.0	14.0	8.0	7.0	7.0	24.0	7.0	4.0	24.0	24.0	154.0	14.0	9.9
G67	45.0	7.0	10.0	15.0	13.0	11.0	19.0	13.0	7.0	19.0	19.0	178.0	16.2	10.5
G30	39.0	9.0	15.0	12.0	9.0	9.0	23.0	9.0	9.0	23.0	23.0	180.0	16.4	9.7
G72	72.0	3.0	1.0	13.0	23.0	32.0	6.0	23.0	3.0	6.0	6.0	188.0	17.1	20.9
G14	9.0	5.0	53.0	4.0	4.0	3.0	49.0	4.0	5.0	44.0	44.0	224.0	20.4	21.7
G49	21.0	11.0	44.0	7.0	6.0	6.0	39.0	6.0	11.0	39.0	39.0	229.0	20.8	16.0
G56	67.0	6.0	4.0	24.0	33.0	33.0	9.0	33.0	6.0	9.0	9.0	233.0	21.2	19.3
G25	55	10	8	30	30	30	14	30	10	14	14	245	22.3	14.2
G84	44	15	28	28	21	20	29	21	15	29	29	279	25.4	8.2
G51	4	51	92	10	14	21	85	14	51	80	80	502.0	45.6	34.2

*Where, G- Genotypes, Yp-Yield under limed, Ys-Yield under unlimed, TOL-Tolerance index, GMP-Geometric mean productivity, MP-Mean productivity, STI-Stress tolerance index, SSI- Stress susceptibility index, HM-Harmonic mean, YI-Yield index, YSI-Yield stability index and RSI-Relative stress index.

Table 5: Grain yield under limed (Yp) and unlimed (Ys) acidic soil with different tolerance indices according to Pearson correlation coefficients.

Variables	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Yp	1.00	0.15	0.78	0.84	0.70	0.60	0.48	0.72	0.15	-0.39	-0.39
Ys	0.15	1.00	-0.50	0.66	0.75	0.78	-0.47	0.71	1.00	0.49	0.49
TOL	0.78	-0.50	1.00	0.33	0.14	0.03	0.72	0.18	-0.50	-0.65	-0.65
MP	0.84	0.66	0.33	1.00	0.94	0.88	0.11	0.94	0.66	-0.03	-0.03
GMP	0.70	0.75	0.14	0.94	1.00	0.98	0.04	0.94	0.75	0.05	0.05
HM	0.60	0.78	0.03	0.88	0.98	1.00	0.04	0.91	0.78	0.06	0.06
SSI	0.48	-0.47	0.72	0.11	0.04	0.04	1.00	0.08	-0.47	-0.97	-0.97
STI	0.72	0.71	0.18	0.94	0.94	0.91	0.08	1.00	0.71	-0.02	-0.02
YI	0.15	1.00	-0.50	0.66	0.75	0.78	-0.47	0.71	1.00	0.49	0.49
YSI	-0.39	0.49	-0.65	-0.03	0.05	0.06	-0.97	-0.02	0.49	1.00	1.00
RSI	-0.39	0.49	-0.65	-0.03	0.05	0.06	-0.97	-0.02	0.49	1.00	1.00

*Where Yp-Yield under limed, Ys-Yield under unlimed, TOL-Tolerance index, GMP-Geometric mean productivity, MP-Mean productivity, STI-Stress tolerance index, SSI- Stress susceptibility index, HM-Harmonic mean, YI-Yield index, YSI-Yield stability index and RSI-Relative stress index.

Less tolerant genotypes are those with lower TOL index values. As a result, the most acidity-tolerant genotypes were G72, G6, G56, G81, G43, G22, G25, G67 and G66, while the most acidity-sensitive genotypes were G75, G77, G24, G76, G13, G57 and G99. The STI, MP, GMP and HM indices are all high for tolerant genotypes and they function well in both stressful and non-stressful conditions. G40, G22, G14, G35, G16, G49, G10 and G3 were the genotypes in this instance with the highest values for these indices. Fischer and Maurer state that the SSI only identifies genotypes that exhibit very slight reductions under stressful conditions relative to no stressful conditions [15]. The majority of genotypes (SSI = 1) were displayed in Table 3, with the lowest values being G6, G43, G50, G46, G12, G72 and G66.

Three indices, YI, YSI and RSI, can be used to assess genotypic stability under stressful and non-stressful conditions. These genotype-based indices have been applied to a wide range of crops, such as durum wheat [33], bread wheat [34], barley [35], safflower [36], chickpea [37] and potato [38] as stated by Pour-Aboughadareh and his colleagues [21]. Similar ranking patterns were obtained by RSI and YSI when characterizing tolerant genotypes; the highest values were found for G6, G43, G50, G46, G12, G72 and G66.

As demonstrated here, identifying tolerant genotypes solely by means of an index may not always be straightforward. Pour-Aboughadareh and his colleagues pointed out that we can use Average Rank (AR) to estimate for all indices and select genotypes that may be more superior; the lower the value, the more superior the genotype [21]. The most acidity-tolerant genotypes in this instance under severe acidity conditions were G22 (AR = 9.4), G40 (AR = 13.2), G10 (AR = 14.0), G67 (AR = 16.2), G30 (AR = 16.4), G72 (AR = 17.1), G14 (AR = 20.4), G49 (AR = 20.8), G56 (AR = 21.2), G25 (AR = 22.3) and G84 (AR = 25.4) (Table 4).

Grain Yield and Stress Indices Correlation: It was found that while YSI and RSI are negatively correlated with crop performance under Yp, MP, TOL, GMP, STI, HM, SSI and YI are positively correlated based on actual index values and ranking patterns across all genotypes. The other indices, with the exception of TOL and SSI, were positively correlated with grain yield under Ys (Table 5). These indices may be used to identify genotypes with high potential yield and acid tolerance, as evidenced by the highly significant correlations they show between them and yield under both control and acidic conditions. Moreover, the high

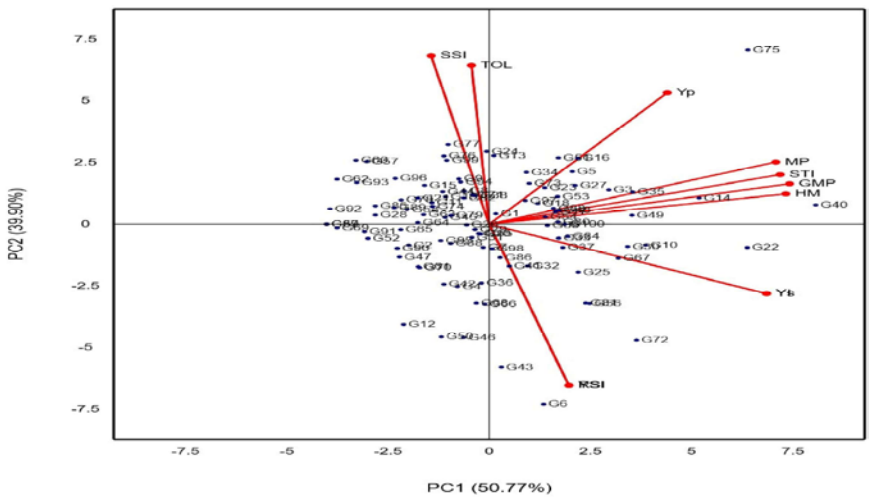

Fig. 1: Biplot based on two components obtained from PCA using Yield under limed (Yp), Yield under unlimed (Ys), Tolerance index (TOL), Geometric mean productivity (GMP), Mean productivity (MP), Stress tolerance index (STI), Stress susceptibility index (SSI), Harmonic mean (HM), Yield index (YI), Yield stability index (YSI) and Relative stress index (RSI).

Table 6: The seven principal components accounted for 100% of the variation, according to the principal component analysis result. Eigen vectors and principal component analysis values for grain yield under limed (non-stressed) and unlimed (stressed) soil conditions.

Factors (Indices)	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Yp	0.24	0.35	0.41	-0.19	-0.19	-0.01	-0.09
Ys	0.38	-0.18	-0.25	-0.28	-0.23	0.06	-0.02
TOL	-0.02	0.42	0.52	0.01	-0.02	-0.05	-0.07
MP	0.39	0.17	0.17	-0.30	-0.27	0.03	-0.08
GMP	0.41	0.11	0.00	0.43	-0.08	-0.27	0.75
HM	0.40	0.08	-0.15	0.62	0.01	-0.12	-0.64
SSI	-0.08	0.45	-0.30	0.20	-0.20	0.78	0.12
STI	0.39	0.13	-0.02	-0.19	0.86	0.21	0.05
YI	0.38	-0.18	-0.25	-0.28	-0.23	0.06	-0.02
YSI	0.11	-0.43	0.39	0.18	-0.02	0.35	0.02
RSI	0.11	-0.43	0.39	0.18	-0.02	0.35	0.02
Eigenvalue	5.58	4.39	0.80	0.13	0.07	0.01	0.00
Variability (%)	50.77	39.90	7.31	1.22	0.66	0.12	0.03
Cumulative %	50.77	90.67	97.98	99.20	99.85	99.97	100.00

*Where PC- Principal component, Yp-Yield under limed, Ys-Yield under unlimed, TOL-Tolerance index, GMP-Geometric mean productivity, MP-Mean productivity, STI-Stress tolerance index, SSI- Stress susceptibility index, HM-Harmonic mean, YI-Yield index, YSI-Yield stability index and RSI-Relative stress index.

level of correlation among these indices implies that they can be employed interchangeably for the purpose of genotype selection that is tolerant.

Principal Component Analysis: Nine yield-based indices and 90.67% of the variance in yield performance were explained by the first two principal components with eigenvalues >1 according to the correlation matrix. This suggests that the variation in the data was sufficiently explained by the two principal components. PC1 was positively affected by the yield of Yp and Ys as well as all other indices, in contrast to PC2, which was positively influenced by Yp, TOL, MP, GMP, HM and SSI (Table 6). Therefore, selecting for genotypes that are acid-tolerant based on high PC1 and intermediate PC2 values may be helpful. A few genotypes were discovered, including G22, G40, G49, G10, G72, G84 and others, which identified as superior genotypes (Fig. 1).

CONCLUSIONS

The percentage of yield loss under acid soil stress (20.24%) as compared to non-stress or limed experiments in the current study demonstrated the severity of acid soils in tef growing areas. Additionally, this study showed that tef exhibits sufficient levels of genetic variation in both stressed and unstressed acid soil environments, suggesting the possibility of future genetic advancements in tef.

For farmers with limited resources, creating and utilizing genotypes resistant to acid soil would be an economical and sustainable approach. In light of this, it is necessary to use the high-yielding and tolerant tef genotypes that have already been identified for additional adaptation research as well as concurrent breeding line extraction for later crossing projects and variety development.

Additionally, the national tef breeding program ought to make good use of the variations present in tef as a general through further screening under critical acid soil environments.

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