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Breeding Crops for Tolerance to Acidic Soils in Ethiopia: A Review

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Abstract
Soil acidity and associated low nutrient availability is one of the constraints to crop production on acid soils. In Ethiopia, soil acidity is a well-known problem limiting crop productivity. The management of acid soils should aim at improving the production potential by the addition of amendments to correct the acidity, manipulate the agricultural practices and using acid tolerant crops to obtain optimum crop yields. In this paper, we review some of the most recent applications of different breeding approaches for improving crop yield under acidic soils condition. In addition to this review paper aimed to put together recent achievements made through research on developing soil acid tolerant cereal and food legumes in Ethiopia. These newly released cereal and legume crops gave additional option for our farmers living in acid soil prone areas.

Keywords: Aluminum, breeding, low pH, toxicity, tolerance, soil acidity.
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1. Introduction

Soil acidity is one of the major abiotic constraints affecting crop productivity which is caused by a low potential of hydrogen (pH). It is among the major land degradation problems, which affects ~50% of the worlds potentially arable soils (Kochian *et al.*, 2004). Considerable grain yield reductions of crop under low soil pH have been reported in numerous studies. In Ethiopia currently about 40% of the total arable land was affected by soil acidity, out of this about 27.7 % is moderately acidic and 13.2% is strongly acidic (Adane, 2015). As a result, most of the soils have a pH range of 4.5 to 5.5 and contain low organic matter and also low nutrient availability (Achalu, 2014).

The poor fertility of acidic soils is due to a combination of mineral toxicities (Al, Mn, and Fe) and nutrient deficits caused by the leaching or decreased availability of phosphorus (P), calcium (Ca), magnesium (Mg), sodium (Na), and micronutrients such as molybdenum (Mo), zinc (Zn), and boron (B) (Gupta *et al.*, 2013). In the humid tropics, soils become acidic naturally due to leaching of basic cations under high rainfall conditions. At pH below 5, Al is soluble in water and becomes the dominant ion in the soil solution. In acid soils, excess Al primarily injures the root apex and inhibits root elongation (Sivaguru and Horst, 1998). The poor root growth leads to reduced water and nutrient uptake, and as a result crops grown on acid soils are constrained with poor nutrients and water availability. The net effect of which is reduced growth and yield of crops (Marschner, 2011; Wang *et al.*, 2006).

Crop tolerance of acidic soil has become extremely important in the agricultural development of the humid tropics (Kamprath and Foy, 1985).The use of tolerant crop varieties is considered to be the best complement to non-genetic management option for combating Al-toxicity problem (Rao *et al.*, 1993; Abebe, 2007) This paper reviews crop improvement for tolerance to acidic soils using conventional and molecular technologies. It also reviews the genetic, physiological, and biochemical mechanisms by which plants tolerate low soil pH stress. The adoption of existing and improved acid-tolerant crop genotypes is also taken into account.

2. Formation of Acid Soil

2.1. Distribution of Acid Soil in Ethiopia

Soil acidity and associated low nutrient availability are key constraints to crop production in acidic soils, mainly Nitisols of Ethiopian highlands (Zeleke *et al.*, 2010). Haile *et al.* (2017) estimated that 43% of the Ethiopian cultivated land is affected by soil acidity. Nitosol/Oxisol soils are the main soil classes dominated by soil acidity. These soils are predominantly acidic and have been found that more than 80 % of the landmasses originated from Nitosol are acidic. Some of the well-known areas severely affected by soil acidity in Ethiopia are Ghimbi, Nedjo, Hossana, Sodo, Chencha, Hagere-Mariam and Awi Zone of the Amahara Regional State (ATA, 2014). The extent of soil acidity in Ethiopia is shown in Figure 1. About 28.1% of these soils are dominated by strong acid soils (pH 4.1-5.5) (ATA, 2014). Strongly acidic soils are usually infertile because of the possible Al and Mn toxicities, and Ca, Mg, P, and molybdenum (Mo) defciencies (Barber, 1984).

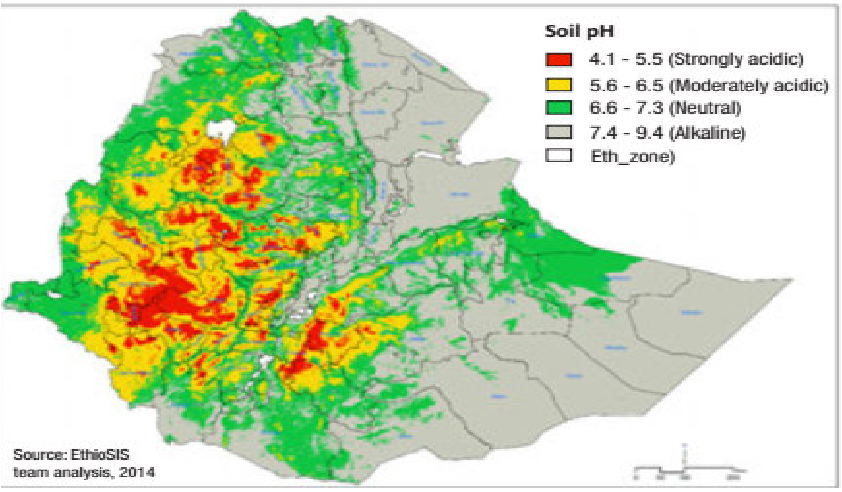

Figure 1. Extent and distribution of soil acidity (ATA, 2014) in Ethiopia

2.2. Causes of Soil Acidity

Soil acidification is a complex set of process resulting in the formation of an acid soil. The amount of Hydrogen cation (H+) activity in the soil solution determines the soil pH and is influenced by edaphic, climatic, and biological factors. High rainfall affects the rate of soil acidification when rainfall washes away bases ($Ca2^{+}$, $Mg2^{+}$, K^{+}, Na^{+}, and carbonate ion (CO3-2)) from the soil. Hydrolysis results in a reduction in soil pH when a metal is dissolved in water, releasing protons. The hydrolytic displacement of base cations and the provision of additional acids from oxidation reactions are the main natural causes of soil acidification, which lead to base-deficient, aerated sands under strong leaching conditions such as high rainfall and drainage (Fey, 2001). Poor agricultural practices (use of ammonium fertilizers and crop removal) also contribute to the acidification of the soil (Rowell, 1998). Continuous application of inorganic fertilizer without soil test, in the end, can increase soil acidity. The use of N fertilizers in ammonia form is a source of acidification (Fageria and Nascente, 2014; Guo *et al.*, 2010). Soil acidification is intensified by the removal of cations through the harvesting of crops and by acid precipitation from polluted air (Ulrich *et al.*, 1980, Hede *et al.*, 2001).

2.3. Toxification of acid soils

Acid soil toxicity is caused by a combination of high solubility of toxic heavy metal elements (iron, copper, manganese, zinc, and aluminum), a lack of essential nutrients (phosphorus, magnesium, calcium, potassium, sodium), and low soil pH (Bian *et al.,* 2013). Low soil pH can therefore generate excesses of aluminum, iron, and manganese, which hamper crop production (Zeigler *et al.*, 1998). As aluminum and iron are released during the acidification/weathering process, they become more accessible on cation exchange sites, in solution, or simply on exposed surfaces. Both ions react readily with phosphate, forming relatively insoluble compounds through a process known as phosphate fixation. High Al and Fe oxides and hydroxide in low soil pH are responsible for P fixation, making it unavailable to plants (Oboru, 2008).

The pH of soils for best nutrient availability and crop yields is considered to be between 6.0 and 7.0, which is the most preferred range by common field crops (Duncan, 2002). A summary of crop relation to soil reaction is given in Table 1. Cotton, alfalfa, oats and cabbage do not tolerate acid soils and are considered suitable to neutral soils with a pH range of 7-8. Wheat, barley, maize, clover and beans grow well on neutral to mildly acid soils (pH 6-7). Grasses tend to tolerate acidic soils better than legumes, so liming to pH 5.5 may control acidity without limiting production. Legumes, however, need more Ca and perform best between pH 6.5 and 7.5. Among crops tolerant to acid soils are millet, sorghum, sweet potato, potato, tomato, flax, tea, rye, carrot and lupine (Somani, 1996).

Table 3. Crop relation to soil reaction (pH)

Crop	Optimum pH for best growth	Crop	Optimum pH for best growth
Alfalfa	7.0-8.0	Sugar beet	5.8-7.0
Cotton	7.0-8.0	Millets	5.5-7.5
Oats	7.0-8.0	Sorghum	5.5-7.5
Cabbage	6.0-6.5	Sweet potato	4.5-6.5
Wheat	6.0-7.0	Potato	4.5-6.5
Barley	6.0-7.0	Tomato	5.5-7.5
Maize	6.0-7.2	Lupin	4.5-6.0
Faba bean	6.0-8.0	Mango	5.0-6.0
Field pea	6.0-7.0	Papaya	6.0-6.5
Chickpea	7.0-8.0	Avocado	5.0-8.0
Lentil	6.5-8.0	Pineapple	4.5-6.5
Soybean	6.2-7.0	Flax	5.0-7.0
Beans	5.5-8.0	Tea	4.0-6.0
Onion	5.8-6.5	Carrot	5.5-7.0
Sugarcane	5.0-8.5	Rye	5.0-7.5

Source: Somani (1996)

3. Management of Acid Soil

Liming is a major and effective practice to overcome soil acidity constraints and improve crop production on acid soils. Soil acidity can be corrected easily by liming the soil, or adding basic materials to neutralize the acid present. The most economical liming materials and relatively easy to manage are calcitic or dolomitic agricultural limestone (Pilbeam and Morley, 2007; Rengel, 2011).

Integrated soil fertility management (ISFM) is one of the approaches to manage and improve soil health and fertility status (Agegnehu and Amede, 2017). ISFM is one of the components of the management of acid soils. Farmyard manure (FYM) and crop residues are among organic plant nutrient sources, which could ameliorate the physical and chemical properties of soils. The addition of organic fertilizers to acid soils has been effective in reducing phytotoxic levels of Al resulting in yield increases. The possible alternative of using organic sources such as crop residues, manures, compost and biochar are substitutes for lime (Agegnehu and Amede, 2017; Sharma *et al.*, 1990). Similar study showed that the residual effects of manure and compost applications signifcantly increased electrical conductivity (EC), pH levels, plant-available P and NO_3-N concentrations (Eghball *et al.*, 2004). The use of acid-tolerant crop cultivars constitutes an efficient and permanent alternative to increase yields in acidic soils (Horst *et al.*, 1997).

3.1. Acid soil tolerance mechanism in crop

Aluminum tolerance can be divided into mechanisms that facilitate Al exclusion from the root apex **(**external tolerance mechanisms or apoplastic mechanisms) and mechanisms that confer the ability to tolerate Al in the plant symplasm **(**internal tolerance mechanisms or symplastic mechanisms**)** (Kochian, 1995; Kochian *et al.,* 2004).

Several external tolerance mechanisms have been suggested, of which the most important are: 1) exudation of organic acids (Pellet *et al.*,1995; Magalhaes *et al.*, 2007); 2) immobilization at the cell wall (Taylor, 1991; Kochian, 1995); 3) exudation of phosphate (Taylor, 1991; Ryan *et al.*, 1993); 4) active Al efflux across the plasma membrane (Taylor, 1991); 5) production of root mucilage (Henderson and Ownby, 1991); 6) Al exclusion via alterations in rhizosphere pH (Taylor, 1991; Kochian, 1995), and 7) selective permeability of the plasma membrane (Taylor, 1991). The Al-activated mechanism of malate exudation is well described in wheat (Sasaki *et al.*, 2004), rye (Ligaba *et al.*, 2006), whereas the mechanism of Al tolerance in maize, soybean, sorghum, and barley involves mainly citrate release (Maron *et al.*, 2010). In addition to malate, citrate exudation has also been reported to contribute to Al tolerance in wheat and rye (Yokosho *et al.*, 2011).

The most important internal tolerance mechanisms are Al-binding proteins, chelation in the cytosol, compartmentation in the vacuole, evolution of Al tolerant enzymes, and elevated enzyme activity (Taylor, 1991). Substantial experimental evidence supports the synthesis of Al-binding proteins (Somers *et al.*, 1996).

3.2. Genetic Mechanisms of Aluminum Tolerance

Fourteen genes from seven different species are known to contribute to $Al3^+$ tolerance and resistance and several additional candidates have been identified (Table 2). Some of these genes account for genotypic variation within species and others do not (Ryan *et al.*, 2011). As explained below, a thorough understanding of both the genetics and physiology of resistance was pivotal for finally identifying the first $Al3^+$ resistance genes.

Table 2. Summary of genes involved in $Al3^+$ resistance or tolerance

Species	Gene	Protein function	Evidence	Reference
$Al3^+$ resistance genes that explains genotypic variation				
Wheat	TaALMT1	Malate transport	Segregation, function	Sasaki *et al*., 2004
Arabidopsis	AtALMT1	Malate transport	Homology, function, mutational	Hoekenga *et al.,* 2006
Sorghum	SbMATE1	Citrate transport	Segregation, function	Magalhaes *et al.,* 2007
Barley	HvAACT1	Citrate transport	Segregation, function	Furukawa *et al.,* 2007
Rye	ScALMT gene cluster	Malate transport	Segregation, homology	Collins *et al.,* 2008
Maize	ZmMATE1	Citrate transport	Segregation, function	Maron *et al.,* 2010
$Al3^+$ resistance genes that do not explain genotypic variation				
Arabidopsis	AtMATE	Citrate transport-efflux	Mutational	Liu *et al*., 2009
Arabidopsis	AtSTOP1	C2H2-type Zn finger transcription factor	Mutational	Iuchi *et al.,* 2007
Rice	OsSTAR1 and OsSTAR2	UDP-glucose transport	Mutational	Huang *et al*., 2009
Rice	ART1	C2H2-type Zn finger transcription factor	Mutational	Yamaji *et al*., 2009
Arabidopsis	ALS3	Partial ABC protein-function unclear	Mutational	Larsen *et al*., 2005
Arabidopsis	ALS1	Partial ABC protein-function unclear	Mutational	Larsen *et al*., 2007
Arabidopsis	AtSTAR1	Partial ABC protein-function unclear	Mutational	Huang *et al*., 2010
Likely $Al3^+$ resistance genes				
Wheat	TaMATE1	Citrate transport-efflux	Segregation, homology (no mutational or functional data)	Ryan *et al*., 2009
Brassica napus	BnALMT1 BnALMT2	Malate transport-efflux	Homology, function (no mutational or segregation data)	Ligaba *et al.,* 2006
Rye	ScMATE2	Citrate transport-efflux	Homology, biology (no functional or segregation data)	Yokosho *et al*., 2010

Source: Ryan et al., 2011

3.3. Screening Strategies for Aluminum Tolerance

Different screening methods have been used to evaluate Al tolerance: nutrient solution culture (Baier *et al*., 1996), soil bioassays (Stolen and Andersen, 1978; Ring *et al*., 1993), cell and tissue culture (Conner and Meredith, 1985) and field evaluations (Johnson *et al*., 1997). Laboratory- and greenhouse-based techniques for screening for Al tolerance are widely used because they are quick, highly accurate, non-destructive, and can be applied at early developmental plant stages. Field-based techniques are more laborious (Carver and Ownby, 1995).

3.4. Nutrient solution culture

Solution culture is the most common screening medium for Al tolerance which provides easy access to the root system, strict control over nutrient availability and pH, and non-destructive measurements of tolerance (Carver and Ownby, 1995). Different assays have been applied to identify Al tolerant and Al sensitive genotypes, of which the most widely used, are hematoxylin staining of root tips and root growth measurement (Baier *et al*., 1996; Carver and Ownby, 1995). Plant parameters such as root and top dry weight, height, tiller number, and number of spikelets per ear have also been used to evaluate Al tolerance (Mugwira et al., 1978). Aluminum-induced callose (1,3-b-DGlucan) synthesis after short Al treatment in nutrient solution has been reported to correlate well with Al tolerance (Horst *et al*., 1997). Results obtained using the nutrient solution technique has proven to be highly relevant to acidic field conditions. Genotypes classifed as Al tolerant based on the nutrient solution evaluation very often show improved agronomic performance under acid soil and Al stress (Baier et al., 1995).

3.5. Soil bioassays

Soil bioassays have a distinct advantage over nutrient solution culture when Al tolerance may be influenced by soil dependent external factors (Ring *et al.*, 1993). The use of soil media has received less attention than solution media for Al tolerance evaluation, and relatively few examples of its use can be found in the literature (Stølen and Andersen, 1978).

3.6. Field evaluation

The ultimate and most direct method of evaluating for Al tolerance is by measuring economic yield (forage or grain) under field conditions. Field evaluation is normally conducted in two duplicate tests: one in an unamended and naturally acid plot, and the other in a lime-amended plot. The data are reported as the ratio of grain yield in the unamended plot to that in the lime amended plot to adjust for differences in yield potential without acid soil stress (Carver and Ownby, 1995; Johnson *et al.*, 1997).

The two most important problems observed when evaluating for Al tolerance in the feld are the presence of fungal pathogens such as take-all (incited by *Gaeumannomyces graminis* var. *tritici*), in which infection is often favored by the application of lime to low pH soils (Johnson *et al.*, 1997), or spatial variability of pH in the surface and subsurface soil layers (Carver and Ownby, 1995). There are several examples of evaluating for Al tolerance in the field, but they are more expensive and laborious (Stølen and Andersen, 1978; Baier *et al.*, 1995; Johnson *et al.*, 1997).

3.7. Hematoxylin staining method

The hematoxylin staining method is an extremely powerful tool for observing tolerance without laborious quantitative measurements. The hematoxylin dye forms complexes with tissue Al that has been immobilized as AlPO 4 by phosphate on or immediately below the root surface (Ownby, 1993). There are several variations of the hematoxylin method. Polle *et al.* (1978) used the hematoxylin-staining pattern of root tips as an indicator of Al tolerance. As the intensity of staining increases, reflecting a higher level of Al uptake, the level of tolerance decreases. Another procedure using hematoxylin, the modifed-pulse method, evaluates Al tolerance based on the ability of Al tolerant seedlings to continue root growth after a short pulse treatment with high Al concentrations (Aniol, 1984). Aluminum sensitive seedlings do not show root re-growth because their apical meristem has been damaged. This method can be applied to determine Al tolerance through either measuring root regrowth (Gallego and Benito, 1997) or evaluating seedlings on a 1 to 3 scale (tolerant, medium tolerant, and susceptible) based on their ability to present root regrowth (Riede and Anderson, 1996).

3.8. Root growth method

The root growth method considers two Al tolerance parameters: root growth (RG) and a root tolerance index (RTI) (Baier *et al.*, 1995). The RG parameter is measured root growth under Al stress while RTI is root growth under Al stress compared to root growth without Al stress. A low-ionic-strength nutrient solution combined with a low Al concentration is used, as evidence suggests that Al tolerance studies should be conducted using solutions containing ionic strength and Al activity approximating soil composition (Blamey *et al.*, 1991). Assessment of Al tolerance based on root growth and RTI has been used extensively in genetic and molecular studies (Baier *et al.*, 1996; Riede and Anderson, 1996; Somers *et al.*, 1996).

4. Successes in Breeding for Low Soil pH Tolerant Crops in Ethiopia

4.1. Soil acidity tolerant food legume crop

Fifteen common bean varieties were evaluated for acid soil tolerance at Jimma research center and Mettu Research sub center (Hurumu trial site). The analysis of variance showed that the main effect of amendments, varieties and years, and the interaction effect of amendments by different varieties and years had a significant effect on grain yield and biomass of common bean. At Mettu the highest (2703.7 kg/ha) mean grain yield of common bean was obtained from SER 119 variety under both lime and phosphorus treated main plot and the highest (1864.4 kg/ha) mean grain yield of common bean was obtained from the same varieties under control soil condition. The highest (6.44t/ha) above ground biomass was obtained from SER 119 variety under both lime and phosphorus treated plot, while the highest (4.17t/ha) above ground biomass was obtained from Awash-1 variety under control soil conditions at Mettu (Table 10).Common bean varieties SER 119 & Awash-1 gave the best performance for most of the traits tested and these are promised varieties among the other (Table 10).

Table 10: Mean values of common bean yields and above ground biomass as affected by interaction of amendments, varieties and year at Mettu.

	Years	Yield Kg/ha				Agb t/ha			
Varieties		L	C	P	LP	L	C	P	LP
SER 119	Year 1	1181.7	396.3	1080.9	2159.5	2.22	0.69	1.817	4.12
	Year 2	1704	673.8	2257.5	2703.7	3.85	1.34	5.33	6.44
Naser	Year 1	1001.5	782.8	747.4	1637.1	2.08	1.217	1.53	2.68
	Year 2	1880.5	790.8	1648.7	2474.6	3.98	1.85	3.47	5.187
SER 125	Year 1	821.3	633.4	874.3	1604.7	1.29	1.29	1.767	3.01
	Year 2	1031.6	563.1	1977.8	2306.4	2.59	1.85	4.86	5.60
Gofat	Year 1	786.2	516.9	606.9	1529.3	1.203	0.93	0.93	2.36
	Year 2	1041.3	620.2	1632.6	2266.7	2.17	1.34	3.10	4.54
Roba	Year 1	579.2	239.7	501.9	1169.1	1.063	0.713	1.017	2.94
	Year 2	1526.1	730.3	1701.8	2235.4	3.33	1.57	3.89	5.74
Awash-1	Year 1	392.8	454.4	530.2	1038.3	0.74	1.44	1.157	2.5
	Year 2	1444.3	1864.4	2204.7	1963.2	3.053	4.17	3.98	5.69
Ayenew	Year 1	756	639.3	844.6	1277.8	1.94	1.29	1.48	2.13
	Year 2	1814.3	785.8	1730.1	2073	3.98	1.89	4.26	4.95
Meka	Year 1	1054.4	619.6	503.4	1090.1	1.75	1.217	1.02	2.13
	Year 2	1624.4	1322.7	2021.1	1893.4	3.33	2.68	4.44	4.17
Iboda	Year 1	516.1	429.1	346.9	966.8	1.017	0.88	0.65	2.92
	Year 2	675.6	452	1819.2	1864.4	1.62	1.34	3.98	4.35
GLP 2	Year 1	937	563.2	735.4	1428.2	1.94	1.34	1.20	3.75
	Year 2	1310.7	816.5	1264.2	1812.5	3.15	2.45	3.33	4.54
Dimtu	Year 1	755	477.8	369.8	968	1.85	1.25	0.697	2.17
	Year 2	1538.8	951.5	1552.5	1686.5	4.07	2.50	3.70	4.95
Goberasha	Year 1	658.8	242.2	317.1	996.5	1.62	0.557	0.603	1.99
	Year 2	980	541.3	940.2	1460.1	2.17	1.20	2.127	3.79
Bashbash	Year 1	586	329.4	540.1	1103	1.34	0.65	1.25	2.27
	Year 2	1174.6	556.7	932.2	1364	2.77	1.44	2.96	3.47
Awash Melka	Year 1	450.6	468	257.5	924.4	1.34	1.16	0.69	2.54
	Year 2	1340.8	327.2	547.7	853.5	2.930	1.46	1.250	2.31
Dame	Year 1	887.3	676.7	484.8	1058.2	1.660	1.67	1.157	2.22
	Year 2	980.5	703.5	1314.7	1183.7	3.057	1.99	3.007	4.44
LSD			**520.23**				**1.48**		
CV			**29.86**				**37.55**		

Where, L=lime alone, p=phosphorus alone, LP= both lime and phosphorus treated, C=control Agb= above ground biomass, LSD=list significant different, CV= coefficient of variation, year1=2017, year2=2018
Source: JARC Progress Report 2019

Acid soil tolerant sweet lupin (*Lupinus angustifolius*) varieties SWL-001(walala) were released by Holeta Agricultural Research Center (Fekadu, 2018). Currently this variety is under production in some areas where highland pulse crops are out of production due to soil acidity. So, scaling up of sweet lupin especially in acid prone areas should be given a great emphasis.

A research conducted at Jimma agriculture research center, Mettu and Haru Research sub center on fifteen soybean genotypes evaluated for acid soil tolerance identified HAWASSA-04 variety and genotype BRS268 as a promising acid tolerant genotypes. The presence of significant interaction of genotypes and amendment for yield indicates the differential response of genotypes to soil acidity, thus implying the possibility of selecting genotypes that perform, exceptionally to low Phosphorus or alumunium toxicity and high P conditions. HAWASSA-04 variety and Genotypes: PI567046A and PI423958 with respective mean grain yield of 2047.2, 2050, and 1981.6 kg ha^{-1}under the combined amendment of P and lime gave the highest grain yield during 2017 and PI423958 gave high grain yield (2310.1kg/ha) during 2018 respectively, while the lowest grain yield (510.50 kgha^{-1}) was recorded on genotype SCS-1 under the control main plots (Table 7). Tolessa (2018) research results also indicated that, the existence of significant genotype x amendment interactions for all root, nodule and yield and yield components parameters imply the presence of differential response of Soybean genotypes for different soil amendments. Soybean genotype PI567046A & HAWASSA-04 variety gave the best performance for most of the traits tested and these are promised genotypes among the other tested. Tolerance index and mean productivity value indicated that Soybean genotype PI567046A and variety HAWASSA-04 performed well for most of the traits and selected as tolerant (Tolessa, 2018).

Table: 7. The interaction effect of amendments and Soybean genotypes on yield under lime and Phosphorus treated and untreated acid soil condition during 2017 and 2018 main cropping season.

Genotypes	YLD (kg)/ha 2017				YLD kg/ha 2018			
	L	C	P	LP	L	C	P	LP
HAWASSA-04	1576.8^{cde}	1553.1^{de}	2120.0^{a}	2047.2^{ab}	1123.3^{h-s}	1278.9^{f-o}	2088.1^{ab}	1712.3^{b-f}
PI567046A	1943.9^{ab}	1069.9^{k-q}	1534.5^{def}	2050.0^{ab}	1334.7^{e-n}	1058.3^{j-u}	1634.5^{b-g}	1548.1c-j
PI423958	682.80^{t-y}	528.20^{xy}	1552.7^{de}	1981.6^{ab}	1413.3^{e-m}	1651.8^{b-g}	2310.1^{a}	1910.9^{a-d}
JMALM/PR142-15-SC	1214.5^{g-m}	1121.3^{i-p}	1615.9^{cd}	1832.6^{bc}	904^{n-w}	977.3^{m-v}	1971.5^{a-c}	1632.3^{b-g}
JM-HAR/DAV-15-SA	737.50^{s-y}	691.00^{t-y}	1287.7^{f-l}	1830.4^{bc}	706.6^{s-x}	1223.7^{f-p}	1592.1^{c-h}	1212.1^{g-q}
JM-PR142/H3-15-SB	1328.3^{e-j}	1027.2^{m-r}	1475.8^{d-g}	1641.2^{cd}	706.6^{s-x}	995.6^{l-v}	1821.3^{a-e}	1486.3^{c-l}
H-7	772.50^{r-y}	821.80^{q-w}	1173.3^{h-n}	1483.2^{def}	728.6^{p-x}	1074.2^{i-u}	1540.3^{c-k}	1473.6^{d-l}
BRS268	1143.5^{i-o}	1319.8^{e-k}	1473.3^{d-g}	1321.9^{e-k}	1096.5^{i-t}	1218.5^{g-q}	1556.7^{c-i}	1348.4^{e-n}
JM-H3/SCS-15-SG	956.50^{n-s}	1096.5^{i-p}	1344.5^{e-i}	1428.7^{d-h}	819^{o-x}	902.5^{n-w}	1517.9^{c-k}	1341.7^{e-n}
JM-CLK/CRFD-15-SA	935.00^{n-t}	643.50^{v-y}	898.40^{o-v}	1408.4^{d-h}	588.9^{u-x}	1112^{h-s}	1393^{e-n}	1132.3^{h-q}
JM-ALM/H3-15-SC-1	653.20^{u-y}	637.50^{v-y}	1130.4^{i-p}	1215.5^{g-m}	659.7^{s-x}	973.5^{m-v}	1432.4^{d-m}	1107.4^{h-s}
JM-CLK/G99-15-SC	783.80^{r-x}	818.20^{q-w}	1180.6^{h-n}	1123.0^{i-p}	436.7^{wx}	780.1^{p-x}	1048.2^{k-v}	741.4^{p-x}
SCS-1	619.00^{wxy}	510.50^{y}	967.40^{m-s}	1174.3^{h-n}	562.4^{v-x}	721.4^{r-x}	1464^{d-m}	1074^{i-u}
JM-CLK/G99-15-SB	1076.2^{j-q}	757.00^{s-y}	906.10^{o-u}	1121.1^{i-p}	474.6^{wx}	833.6^{o-x}	1060.4^{j-t}	1067.7^{i-u}
JM-DAV/PR142-15-SA	934.70^{n-t}	915.40^{o-t}	878.10^{p-w}	1060.0^{l-q}	407.6^{x}	783.9^{p-x}	1389^{e-n}	608.2^{t-x}
Mean	1185.45				1179.4			
	CV (a) 10.51 CV (b)= 6.24				17.49			

Where, L= Lime treated alone, P= Phosphorus treated alone, LP= Lime and phosphorus treated, YLD = yield, AGB= above ground biomass, CV= Coefficient of variation, C= Control, RP= reduction percentage, Note: Means with the same letters are statistically not significant ($p>0.05$) different from each other.

4.2. Soil acidity tolerant cereal crops

Case studies showing seed yield improvements of some Oat genotypes under acidic soil conditions at Holeta agriculture research center are summarized in Table 5. The candidate varieties along with collected oat accessions were planted on acid soils in multi-locations. Analysis of variance revealed that 79Ab 382 80 SA 94 showed the highest mean seed yield under unlimed soil conditions as compared to other accessions (Table 5). This newly released food oat variety known with local name "Sorataf" gave additional option for our farmers and emerging food agro industries. Therefore, popularization and seed multiplication of this newly released food oat variety should be given a great emphasis especially on acid prone areas of Ethiopia (Fekadu, 2018).

To identify acid tolerant high yielding and promising bread wheat varieties an experiment was conducted at Holeta. The candidate varieties along with one hundred fifty bread wheat accessions collected from National Program Coordinating Centre (Kulumsa) were planted on acid soils in multi-locations under unlimed conditions. Analysis of variance revealed that ETBW 6785 showed the highest mean grain yield across testing locations as compared to other accessions (Fekadu, 2018).

Table 5. Performance of oat varieties in different locations of Ethiopian highlands (2014 -16)

Variety	PLH (cm)	PLN (cm)	BM (Kg/ha)	HLW	TSW	MD	GYLD (Kg/ha)
SRCPX 80 AB 2252	121.82	25.17	11241.0	46.19	35.24	151	2959.6
SRCPX80AB 2291	120.23	28.37	12111.4	50.11	32.46	147	3111.3
SRCPX80 AB 2806	125.01	25.23	11409.5	49.72	34.62	148	2784.0
79AB 382 80 SA 94	96.95	19.45	10655.2	48.63	27.87	143	3228.1
79AB 3825 80 SA 95	128.51	25.07	12742.9	48.32	32.17	146	3065.6
79 CP 84 80 SA 130	129.18	26.25	12091.4	48.52	38.31	148	3214.9
Mean	120.28	24.92	11708.57	48.57	33.44	147	3059.29
CV (%)	5.22	7.51	21.09	3.71	8.98	1.6	28.19
LSD	3.85	1.15	1519.6	1.20	1.85	4.3	535.44

Source: HARC Progress Report 2016

Forty nine tef genotypes were tested under acidic (pH 4.97) and limed (pH 5.90) soils in the lathouse at AsARC in 2017 to assess the extent of genetic variability for acid soil tolerance and identify tef genotypes that perform well under such stress. 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), Dabo Banja (#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 recommendable for both acid stress and no stress (Misgana *et al.*, 2018).

To identify acid tolerant high yielding and promising triticale varieties an experiment was conducted at Holeta. The candidate varieties along with one hundred forty triticale accessions were planted on acid soils in multi-locations under unlimed conditions. Analysis of variance revealed that ETCL 161 showed the highest mean grain yield across testing locations as compared to other accessions (Fekadu, 2018).

Conclusion

Soil acidity has become a great threat in food production through limiting the production potential of the crops because of low availability of nutrients, basic cations and excess hydrogen (H^+) and aluminium (Al^{3+}) in exchangeable forms. The practice of liming acid soils to mitigate soil acidity and reduce phytotoxic levels of Al and Mn has been recognized as necessary for optimal crop production in acid soils. However, these methods have limited practicality for resource poor farmers to apply high rates of lime as well as mineral fertilizers, mainly due to their low purchasing capacity, low availability of lime, high cost of mineral fertilizers and lime transportation, has kept lime and mineral fertilizers from reaching smallholder farmer's fields. Hence, the use of Crop varieties that are tolerant to acidic soils and produce reasonable good yield is paramount importance. Over the past decade, several researchers around the world have focused their efforts on identifying and characterizing the mechanisms employed by crop plants that enable them to tolerate Al toxic levels in acid soils. The two distinct classes of Al tolerance mechanisms are those that operate to exclude Al from the root apex and those that allow the plant to tolerate Al accumulation in the root and shoot symplasm. Plant genetic resources are a rich source of valuable traits that could be used to improve crop species. The presence of crops genetic diversity in Ethiopia is an opportunity for tolerance to low soil pH would increase the potential for the development of high-yielding cultivars with high levels of tolerance to low soil pH as well as toxicities of Al, Fe, and Mn. More research should be devoted to crop tolerance to acid soil. To raise the level of adoption of improved crop cultivars under acidic soils, farmers should be involved in the selection process through participatory breeding and selection approaches.

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