Research Article

Sugarcane Landraces of Ethiopia: Germplasm Collection and Analysis of Regional Diversity and Distribution

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Sugarcane has been cultivated by smallholder farmers since 16th century in Ethiopia and preceded the commercial production. However, as far as this study is concerned, no exploration and collection have been conducted to know the landraces and study the regional diversity of the crop. Therefore, the objectives of this study were to collect native sugarcane landraces in Ethiopia and to assess phenotypic diversity and analyze regional distribution among landraces collected from different geographical regions. More than 300 sugarcane genotypes were collected. The landraces were analyzed for 21 quantitative stalk and juice quality characters and 16 qualitative characters. Phenotypic diversity among landraces was high, as expressed by the large range of variation for mean quantitative traits and the high (0.80) Shannon–Weaver diversity index. Our results provided experimental evidence on occurrence of geographical variation and significant within-region variation where it was high in the regions of Amhara, Benshangul-Gumuz, and SNNPR. Wide variability of agronomically important characters in sugarcane such as millable stalk count at harvest, single cane weight, and plant height was observed among regions. These characters also demonstrated high correlation with cane and sugar yield and the altitude of the collection sites. Therefore breeders can utilize accessions of regions showing variability for these characters in selection programs and to design breeding strategies to produce varieties with best commercial merits. The present study contributes to updating sugarcane descriptors adopted from USDA-ARS as well as Bioversity passport data for the future collection and evaluation. The paper discussed insinuation of the results with regard to plant breeding, germplasm collection, and conservation as well as the plausible sources for the wide range of variation observed. This is the first study to report landrace sugarcane genetic resources in Ethiopia and information on geographical pattern of variation in Ethiopian local sugarcane germplasm.

1. Introduction

Sugarcane plays a significant role in the Ethiopian socioeconomy. Sugar and its byproduct are used for local consumption and export. The industry created job opportunity for a large number of people. Today in the country sugar consumption outstrips its production. The per capita sugar consumption in Ethiopia is very low (5–6 kg) which is even below the African standard (15 kg) while the world average per capita consumption is 21 kg in 2016. The commercial sugarcane sector in Ethiopia commenced since 1951. Sugar Corporation of Ethiopia currently administers six sugar factories, namely,

Wonji-Shoa, Metahara, Finchaa, Tendaho, Arjo-dedessa, and Kesseme, and nine sugar development projects at Kuraz, Tana Beles, and Welkayit. Sugarcane plantations are expanding with current area coverage of 98,986 hectares and production of 400,000 tons of sugar and 25,388 m³ of ethanol per annum. The new sugar factories planned to have ethanol and cogeneration facilities thereby increasing the production of sugar and coproducts. Accordingly, when all projects are completed the annual sugar production will be boosted to 3.9–4.17 million tons, ethanol production will be 181 million litres and the factories contribute 709 Mega Watt electric power to the national grid. This is 11.8% of sugar production

by the leading sugar producer Brazil with a total amount of 35.3 million tons produced in 2016/17 [1]. Similarly Brazilian ethanol production reached 30.23 billion litres in 2015/16.

Though commercial sugarcane production has a history of six decades, sugarcane had been cultivated in Ethiopia since 16th century. According to the report by central statistics agency (CSA) currently sugarcane is produced in about 31,236.81 ha with 1,565,060.00 holdings in different parts of the country [2]. But the production is not usually used for industrial purposes. It is noticeably used for making confectioneries, household consumption (chewing), selling for immediate cash, and feeding livestock. In some areas, sugarcane is used to prepare local beverage called “Karibo” mainly preferred by Muslim communities, while in others the leaves are used for thatching and as firewood [3]. However, the potential of this sector is not well explored and has not been given due consideration. Furthermore no exploration and germplasm collection have been done to represent and preserve local landraces.

The sugar industry of Ethiopia is so far dependent on introduction of exotic varieties which are not suitably adapted to various agroecologies and local growing conditions. In light of the rapidly increasing commercial sugarcane plantation areas in the country, the demand for improved varieties that suit various agroecologies is increasing. Under such situations, there will be a continuous demand for broad genetic base sugarcane varieties that are high yielding and stable under abiotic and biotic stresses. Therefore the industry is currently launching breeding program, which is long overdue, to produce its own improved varieties. The development of high yielding and stable varieties requires a continuous supply of new germplasm as a source of desirable genes and/or gene complexes. The primary sources of such genes are landraces, introductions, weedy, and wild relatives of crop plants [4, 5]. The availability of such germplasm requires the identification of areas of diversity of various characters of agronomic importance, especially in the local landraces growing within the variable agroecologies of Ethiopia. Therefore, germplasm collection and conservation and the study of genetic diversity of Ethiopian sugarcane landraces are worthwhile since this can broaden the genetic base and provide locally adapted genes for improvement of the crop.

In spite of the great importance of Ethiopian sugarcane landraces for the germplasm genetic base improvement and utilization in the breeding program, no effort has been made so far to collect and preserve this genetic wealth. Furthermore, study of the variation and assessment of extent and geographical pattern of distribution of this landraces is lacking. For effective utilization of germplasm in plant breeding programmes, the information on the extent and patterns of distribution of genetic variation of a crop species is very essential [6–8]. This also can help in devising appropriate sampling procedures for germplasm collection and conservation and obtaining core collection for efficient germplasm management [9, 10].

The objectives of this study were to collect sugarcane landraces in Ethiopia and to assess phenotypic diversity and analyze regional distribution among landraces collected from different geographical areas.

2. Materials and Methods

2.1. Germplasm Collection

2.1.1. Sampling Technique. Sugarcane germplasm were collected during 2010/11 all across Ethiopia in the regional states of Amhara (07/10/2010-09/05/2011), Oromia (26/08/2010-08/07/2011), Southern Nations Nationalities and Peoples Region (SNNPR) (10/08/2010-09/12/2010), Tigray (21/04/2011-09/05/2011), Benshangul-Gumuz (20/12/2010-15/02/2011), Gambella (04/11/2010-28/11/2010), Somali (29/06/2011-26/07/2011), and Harari (02/06/2011-23/06/2011) (Figure 1, Supplemental Table 1). Collection was made from homesteads, farmers’ fields, and local markets. Germplasm was collected using stratified random sampling technique; sampling areas are shown in Figure 1. In each region all zones were sampled. Two to four districts (locally referred to as “Weredas”) were selected from each zone. From each district (depending on size, a district contains several localities or subdistricts) 2-5 subdistricts (locally referred as “Kebeles”) or peasant associations (PAs) were selected. The districts and subdistricts were selected based on long agricultural history and relatively wide areas allocated to sugarcane production. Moreover, purposive sampling was also employed based on information supplied by key informants on the unique and quality sugarcane types grown in these areas. In the selected subdistricts sugarcane clones were collected following the methods proposed in [11]. Each distinct morphotype in a village was randomly sampled. Information on the sampled sugarcane germplasm was recorded and passport data was collected following the method of Bioversity International [12]. Moreover, juice sample was taken from the bottom, middle, and top part of the stalk of each clone and mean percent brix reading was recorded using hand refractometer.

2.1.2. Determination of the Physical and Chemical Properties of Soils in Sugarcane Germplasm Collection Areas. To determine the predominant physical and chemical properties and the fertility status of soils under sugarcane production, samples were collected and analyzed across germplasm collection areas. Georeferencing (latitude and longitude) of the study sites were made with a Garmin GPS. In every germplasm sampling area, a composite soil sample was taken between 0–30 and 30–60 cm depths. Soil samples were analyzed for organic carbon, total nitrogen (N), soil pH, soil electrical conductivity (EC), available phosphorus (P), and available potassium (K) contents using standard procedures [13]. Soil pH was measured potentiometrically using a digital pH meter (Jenway Model-3320, GransmoreGeeen). Soil EC was measured using digital conductivity meter (Jenway Model-4310, GransmoreGeeen). Organic carbon was determined following the wet digestion method described in [14]. Total N was determined using the Kjeldahl procedure [13]. Available phosphorus was determined using the Olsen method [15] and Bray II method [16] for acidic soils. Available K was measured by flame photometry using the sodium acetate extractant method at pH 4.8 [17]. Soil texture was determined by hydrometer method [17].

FIGURE 1: A map of Ethiopia showing sugarcane germplasm collection sites (black circles).

TABLE 1: Location information of the test sites.

Location	Latitude	Longitude	Altitude (masl) ^a	Rainfall (mm)	Temperature (°C)	
					Minimum	Maximum
Wonji	8° 31' N	39° 12' E	1550	800	15.3°C	26.9°C
Metehara	8° 51' N	39° 52' E	950	554	17.5°C	32.6°C

^amasl = meters above sea level.
Source: meteorological Stations of respective locations.

2.2. Diversity Study

2.2.1. Plant Materials. A total of 211 sugarcane (*Saccharum* spp.) accessions, consisting of 196 landraces (Supplemental Table 3) and 15 introduced commercial varieties including 2 standard varieties (Supplemental Table 4) were used for this study. The landraces represent collections from all geographical regions across Ethiopia maintained at field conservation garden at Wonji and Metehara Sugar Estates, Sugar Corporation of Ethiopia. Sampling of the landraces was made on representation basis, stratified systematic sampling method to a given range of geographic area, altitudinal ranges, and a range of morphological traits. The introduced materials were commercial varieties under production in different estates where the two were standard varieties.

The 196 landraces were collections from the following regions of Ethiopia: Amhara (47), Benshangul-Gumuz (10), Gambella (3), Harari (2), Oromiya (65), SNNPR (59), Somali (3), and Tigray (7) (Figure 1). The altitude of the collection sites for the landraces used in this study ranged from 454 to 2687 meters above sea level representing the distribution of the crop in Ethiopia. The introduced materials were from Barbados (6), Cuba (1), India (5), Mexico (1), and South Africa (2).

2.2.2. Methods. The plant materials were grown at Wonji and Metehara Sugar Estates of Sugar Corporation of Ethiopia during the 2012/13 growing season. Details of the planting locations are shown in Table 1. Each accession was grown in a single row plot of 5 m long and 1.45 m between rows and 20 cm between plants within a row, with two replications in randomized complete block design.

Uniform crop management practices were applied as recommended for the areas. Urea was applied 2.5 months after planting at a rate of 200 kg·ha⁻¹ at Wonji and 400 kg·ha⁻¹ at Metehara.

Accessions from regions with sample size less than 12 were included in adjacent regions to reduce experimental error due to small sample size. Hence, the two Harari and three Somali accessions were included in Tigray and the three Gambella accessions were included in Benshangul-Gumuz. This reduced the 8 regions of Ethiopia from which the landraces were originally drawn to five. With the introduced materials included, 6 regions of origin were used in the statistical analyses.

Data on 17 quantitative stalk characters was recorded, namely, sprout count 1 and 2 months after planting (SPCIMAP and SPC2MAP), tiller counts 4 and 5 month after planting (TC4MAP and TC5MAP), stalk count 10 months

after planting (STC10MAP), hand refractometer brix reading 10 months after planting (HRBrix10MAP), millable stalk count per hectare (MSCHA), single cane weight (SCW), number of internode (NOI), internode length (IL), stalk height (SH), stalk diameter (SD), leaf length (LL), leaf width (LW), leaf area (LA), cane yield quintal per hectare (CYHA), and sugar yield quintal per hectare (SY). Data on 4 juice quality parameters, i.e., brix percent (Brix%), pol percent (pol %), purity percent (purity %), and sugar percent (SR %), was also recorded. For every accession, ten plants were used for recording data for quantitative characters, which were recorded on plot basis. Count data and cane yield were recorded considering all cane stalks from the whole plot. For quantitative leaf characteristics measurement, a procedure developed in [18] was used.

To categorize each accession morphologically, sugarcane descriptors adopted from USDA-ARS were employed (GRIN, 2004). Data on 16 qualitative traits was recorded, namely, presence or absence of bud cushion (BUDCUSHION), relative degree of bud extension (BUDEXTEND), relative bud shape (BUDSHAPE), relative shape of dewlap (DEWLAP-SHAP), type of outer auricle (AURICLEOUT), presence or absence of stalk corky cracks (STALKCORKC), presence or absence of stalk corky patches (STALKCORKP), relative shape of ligule (LIGSHAPE), presence or absence of stalk growth cracks (STALKCRACK), presence or absence of bud groove (BUDGROOVE), relative plant erectness (ERECT), relative degree of internode alignment (INALIGN), relative internode shape (INSHAPE), colour of the leaves (LEAF-COLOR), colour of the exposed rind (RINDCOLE), and canopy structure (CANOPY). Each accession was scored for the most frequent character-state. Leaf colour and colour of the exposed rind were examined and scored using the Munsell colour chart [19].

2.2.3. Statistical Analyses. First analysis of variance was made for the 21 characters for each location. Homogeneity of the error variances among the locations was assessed in [20] F-max method for each of the 21 characters. The test established the homogeneity of the error variances for all characters except TC4MAP. For TC4MAP logarithmic data transformation, which is recommendable for continuous data, was used to homogenize the error variance. Then, data of all the characters were subjected to test location-accession-related analysis of variance to determine effects of test sites and genotype X environment (G X E) interaction. The results showed the nonsignificance of effects of test sites for SPC1MAP, IL, LW, Pol%, sugar percent (SR%), and the nonsignificance of G X E interactions for SPC2MAP, SCW, Brix%, Pol%, and Brix10MAP. For the other characters both test site effects and G X E interactions were significant ($P < 0.05$).

Analysis of variance was made for 21 quantitative characters following the procedure used in [21, 22]. The mean squares of the regions were tested against pooled mean squares of accessions within regions. The pooled means squares for accessions within regions of origin and the mean squares of accessions within each region were tested against

the pooled within-region error mean squares. Means, ranges for means, and percent coefficients of variation for all the characters were computed for each region of origin and for the entire data. The regional means were compared using Duncan's multiple range testing. Correlations between the characters were computed at three levels. First correlations of the characters were assessed based on the 211 accession means. Then interregion correlation was computed using the means of characters for each region. Finally, a series of intraregion correlation coefficient matrices were obtained for each region using the accession means from that region for the characters.

For qualitative characters, phenotypic frequency distributions were worked out for all the sample germplasm and locations. The Shannon-Weaver diversity index (H') was computed using the phenotypic frequencies to assess the phenotypic diversity for each character for all accessions. The Shannon-Weaver diversity index as described in [23] is given as

$$H' = - \sum_{i=1}^n p_i \log_e (p_i) \quad (1)$$

where p_i is the proportion of accessions in the i^{th} class of an n -class character and n is the number of phenotypic classes of traits. Each H' value was divided by its maximum value ($\log_e n$) and normalized in order to keep the values between 0 and 1. By pooling various characters across the regions, the additive properties of H' were used to evaluate diversity of regions and characters within the population. The average diversity index ($\bar{H}'$) over n traits was estimated as $\bar{H}' = \sum \bar{H}'/n$.

3. Results and Discussion

3.1. Collection of Sugarcane Germplasm. In Ethiopia the history of sugarcane cultivation by smallholder farmers preceded that of commercial cultivation. As documented in the history of a monastery in Northern Ethiopia, sugarcane has been grown in the country since the 16th century [2]. In this study, local sugarcane germplasm exploration and collection were conducted all across Ethiopia in the regional states. More than 300 local sugarcane genotypes were collected during 2010/2011 and passport data of the genotypes is presented in Supplemental Table 1. The collected germplasm were planted at five locations across the country with respect to their collection area. These are Wondogenet Agricultural Research Center, Jimma Agricultural Research Center, Mecha Wereda Agricultural Bureau nursery field at Picolo Abay, Sirinka Agricultural Research Center (at Kobo Subcenter), and research field of Haramaya University at Diredawa (Tonny Farm). The clones have been monitored during the 2011/12 season for symptoms of major diseases and insects. These clones were transferred to commercial sugarcane plantation estates at Wonji and Metehara for further selection and maintenance. No major diseases and insect pests were detected in all the germplasm collected except sometimes termites and borer were observed (Supplemental Table 2).

TABLE 2: Mean soil physical and chemical properties of sugarcane fields in the surveyed regions.

Regions	Soil chemical properties						Texture (%)		
	PH	EC(ds/m)	OC %	N%	P (ppm)	K(ppm)	Sand	Silt	Clay
Amhara	7.19	0.176	1.51	0.130	18.90	159.82	21	25	54
Benshangul-Gumz	6.73	0.139	2.85	0.178	3.45	97.74	23	22	55
Gambella	7.43	0.168	1.92	0.170	31.49	457.15	54	18	29
Harari	7.91	0.831	2.30	0.207	10.37	44.50	6	36	58
Oromia	7.16	0.302	2.59	0.236	11.19	237.70	27	22	51
SNNPR	6.96	0.115	1.85	0.180	29.19	472.72	24	28	48
Somali	8.36	0.293	1.21	0.070	3.22	114.90	10	35	55
Tigray	8.18	0.209	1.49	0.113	7.40	45.45	32	33	35

Most of the sampled germplasm had acceptable levels of juice refractometer readings (expressed in degree brix) relative to the history of the ages of the samples (Supplemental Table 1). The number of harvestable/saleable cane stalks obtained in plant cane and ratoon crops and the number of harvestable ratoon crops showed variation region to region and zone to zone and sometimes district (“wereda”)-wise. There is also variation in maturity time of the clones both in plant cane and in ratoon crops (Supplemental Table 2). These are mainly depending on the variety, soil condition, cultural practices, and climatic conditions.

The genotypes collected from the respective zones in the study regions were recorded by their local names. Sometimes similar varieties bear different names at different localities and vice versa. Farmers mentioned a broad range of sugarcane landraces that had been grown in the areas and maintained for generations. Some of the landraces were commonly recognized by most farmers within and across zones of the respective regions, whereas some were rare varieties known only by few farmers. The large number of landraces observed during the current study demonstrates the existence of diverse genetic resources of sugarcane in Ethiopia. The diversity could have evolved presumably due to diverse climatic conditions, low input management systems, high pests and disease pressure, and continuous selection by farmers. Smallholder farmers face diverse environment stresses and have multiple production objectives that affect selection of genotypes [24]. There were no formally released improved sugarcane varieties grown by farmers in the study regions except in few places. This was mainly observed in SNNPR at Wolayta and Kembata-Tembaro zones. These varieties have been informally introduced to these areas by seasonal workers employed at the sugar estates especially at Wonji and Metehara.

The collected landraces would serve to broaden the genetic base of the available sugarcane germplasm. The sugar industry in Ethiopia is currently establishing sugarcane breeding program. Therefore, collection and efficient characterization of germplasm are vital to strengthen the breeding program.

3.1.1. Physical and Chemical Properties of Soils of Sugarcane Germplasm Collection Areas. Table 2 summarizes the physical and chemical properties of soils in the sugarcane

production fields of surveyed areas. Sugarcane production by smallholder farmers in the surveyed areas is conducted across the seasons where harvesting and planting are done as long as there is available moisture. Therefore the soil samples represent the sugarcane production season and the altitudinal ranges of the respective areas.

Generally the organic carbon content of soils in sugarcane producing areas across the country is low to very low (2-4, <2). Amhara, Gambella, SNNP, Somali, and Tigray Regions are in a very low category (<2). Similarly across regions the total N content is low except Harari and Oromia regions where the average total N is medium. This problem should be addressed either with augmenting the soil with inorganic fertilizers or through appropriate management practices like crop residue management. Available phosphorus is high in Amhara, Gambella, and SNNP Regions whereas moderate values were observed in Harari, Oromia, and Tigray Regions. Generally the level of phosphorus in soils of sugarcane producing areas in these regions is adequate. In Benshangul-Gumz and Somali Regions low level of phosphorus was recorded which should be addressed with due attention. Available K is sufficient for normal sugarcane growth in soils of all regions. Relatively lower values of K were recorded in soils of Harari and Tigray Regions. It should be noted that organic carbon, EC, PH, and variability of P and K are affected by rainfall and temperature that are seasonal and the values recorded refer to the season when the soil samples were taken. Generally, Ethiopian soils are deficient in various essential nutrients like boron, nitrogen, phosphorus, potassium, sulfur, zinc, and copper, although severity differs from region to region [25]. Particularly the loss of P and N resulting from the use of dung and crop residues for fuel is demonstrated to be equivalent to the total amount of commercial fertilizer use.

Across regions in Ethiopia, generally clay type of soil dominates followed by silt, except in Gambella Region where the dominant soil texture was sand. Soil management options related to clay soil may address soil related problems in smallholder sugarcane growing areas across Ethiopia.

3.2. Diversity of Sugarcane Landraces

3.2.1. Quantitative Characters

Univariate Statistics. Analysis of variance depicted highly significant differences ($p < 0.01$) between accessions pooled

over the regions for the 21 characters of the 211 sugarcane accessions studied and significant difference for the 6 regions of origin for 6 characters (Table 3). The results suggested the occurrence of significant phenotypic variation between the accessions as a whole. Significant variations of different sugarcane stalk and juice quality characters was also reported in similar studies conducted elsewhere [26, 27]. Region-wise partitioning of the variance indicated significant within-region differences ($p < 0.05$) among the populations within almost all regions for the characters NOI, IL, SH, SD, LL, LW, LA, Brix%, Pol%, Purity%, SR%, MSCHA, SCW, CYHA, and SY; for 8 characters within Tigray; for TC4MAP and TC5MAP within Oromiya and SNNPR. Brix10MAP showed no significant difference within all regions.

In general, within-region variation was greater for stalk diameter, single cane weight, millable stalk count, and cane and sugar yield than for other characters for all the regions. Assuming that a significant portion of the phenotypic variation is genetic, it would be possible to make selection for any of this group of characters within a particular region. It was apparent that the variance between accessions pooled over regions was greater than between regions. Therefore, in order to sample the variation effectively it would be necessary to sample the variable populations from different localities in a region. The study in [28] on genetic diversity among main land USA sugarcane cultivars showed high genetic diversity within populations of different regions than between populations.

Duncan's multiple range testing for regional means for all the characters is shown in Table 4. Relatively much differentiation was observed for stem diameter and juice purity percent compared to other parameters. Important yield components like MSCHA, SCW, SH, and SD have shown higher values in Tigray, SNNPR, and Oromiya regions. High cane and sugar yield were recorded for accessions in Tigray region followed by SNNPR, Oromiya, and introduction which were statistically at par. Statistically similar lower values of cane and sugar yield were recorded in Amhara and Benshangul collections.

Higher value of sucrose percent in cane was also observed for accessions from Tigray and the lowest value was in Amhara accessions while other regions were statistically similar. Generally, for most of the characters high value was obtained from accessions in Tigray region followed by SNNPR, Oromiya, and introduction. Therefore, the materials from these regions can be used for selection of cane and sugar yield per se and in breeding program. The local accessions in many of the regions showed superiority over the introduced commercial varieties currently in production for most of the characters including cane and sugar yield (Table 4). This may be due to the adaptation and coevolution of the materials with different stresses for long period of time in the country's agroecology. These locally adapted genes conferring yield advantage could be harnessed through strategic crossing and selection for improvement of the crop. Superiority of local landraces over introduced varieties was reported [29, 30].

The range of variation of the accession means established wide variation between the regions and the accessions within the regions for the characters studied (Table 5). Accordingly,

the maximum score was 41 times the minimum for sprout count one month after planting, 32 for sprout count two months after planting, 25 for tiller count four months after planting, 22 for sugar yield, 20 for cane yield, 12 for millable stalk count, 8 for stalk count 10 months after planting, 7 for single cane weight, 6 for tiller count five months after planting, and 2 for other yield components and sugar quality parameters except hand refractometer brix reading ten months after planting and juice purity percent which scored 1. The same trend was observed between accessions within a particular region. However, accessions within Amhara, Benshangul-Gumuz, and introduction showed wider ranges of variation than those accessions within other regions for the majority of the characters. The wide range of geographic and climatic features of the regions in Ethiopia and the original differentiation and further farmers selection for production niches and uses for hundreds of years may have resulted in the accessions to possess a tremendously high degree of morphological variation. The reason for introduced varieties showing high variation also could be due to broader geographic spectrum from where they were initially acquired and difference in their parental source and genealogical history. It was demonstrated, even with these limited numbers of samples (15 genotypes), that introduction of genetic materials has practically broadened the genetic base of the sugarcane germplasm for the breeding program.

Coefficient of variation measured as the ratio of standard deviation to the corresponding overall mean and expressed as percentage, is useful to compare different characters measured in different units. It is also useful to compare same character in different groups of populations with different sample size, mean, and variance or different characters in different populations. In the current study high coefficients of variation were observed between regions and within each region for sprout as well as tiller counts in the months the data was recorded, stalk count 10 months after planting, and millable stalk count at harvest, cane and sugar yield, single cane weight, and leaf area (Table 6). Though accessions from a particular region were more variable for a specific character compared to other regions, accessions from Amhara, Benshangul-Gumuz, introduction, and SNNPR were more variable than accessions from other regions. This result demonstrated the tremendous variability of sugarcane germplasm from these regions. The accessions from Tigray and Oromiya had low coefficients of variation for many characters, indicating relatively high within-region uniformity. The high coefficients of variation observed for most of the characters agreed well with those reported in [31] for indigenous sugarcane of Brazil. Similar results were also reported in sorghum [32]. The different levels of regional variability of a particular character could be due to differences in forces of selection and/or differences in the intensity of a particular selecting force. It could also be due to random effect and reduced sample parents of parental materials moved differently by various human population migration and the interaction of these with Darwinian forces.

Results of this study suggested the presence of wide range of variations of characters determined by univariate statistics.

TABLE 3: Analysis of variance for 21 quantitative characters in sugarcane germplasm.

(a)											
Source	Df	SPC1MAP	SPC2MAP	TC4MAP	TC5MAP	STC10MAP	MSCHA	SCW	NOI	IL	SH
Regions	5	278.95	1043.87	2273.56	421.85	247.34	406040344.83	0.11	31.86*	2.17	333.41
Pooled accessions within region	205	251.12**	742.25**	4507.22**	2222.15**	2094.51**	5469526874.70**	0.58**	59.89**	9.07**	3791.79**
Accessions within:											
Amhara	46	284.01*	397.63	4045.72	2608.99*	2316.14**	5247254325.00**	0.53**	79.31**	10.74**	4241.16**
Benshangul-Gumuz	12	107.31	484.30	2993.62	1483.23	642.99	3460963080.00*	0.74**	52.61*	4.97*	1707.61
Introduced	14	239.37	3457.97**	3683.82	1118.60	2145.59**	5329303698.00**	0.47**	39.37**	3.28	1280.88
Oromiya	64	272.41	413.89	5959.95**	5959.95**	1869.41**	5607864397.30**	0.48**	58.56**	9.44**	3652.29**
SNNPR	58	216.99*	565.63	3899.04*	2339.09**	2411.29**	5429342255.00**	0.73**	55.43**	9.16**	4760.74**
Tigray	11	341.57	1850.22	3890.79	1133.88	2325.57**	8175666309.00**	0.59**	44.06	11.20**	3084.55**
Pooled error within region	205	144.27	471.05	1999.79	992.06	301.81	740676567.85	0.14	13.94	1.62	986.72
See the Materials and Methods for the abbreviations of the characters.											
***Significant at p < 5% and 1* levels, respectively.											
(b)											
Source	SD	LL	LW	LA	CYHA	Brix%	Pol%	Purity%	SR%	SY	Brix10MAP
Regions	0.28*	410.8*	2.23**	44178.66**	151602.4	5.15*	4.14	5.94	2.1	2944.52	1.5
Pooled accessions within region	0.33**	425.46**	1.66**	22034.24**	2341159**	5.41**	6.3*	12.88**	4.05**	42710.67**	3.2
Accessions within:											
Amhara	0.5**	467.51	2.27**	28865.04**	2015788**	6.33**	7.63**	14.63**	4.96**	37736.62**	3.65
Benshangul-Gumuz	0.28	795.04**	1.66	27744.3	1166906*	10.81**	13.1**	22.71**	8.33**	21387.39**	4.16
Introduced	0.27*	359.8	1.26**	24368.23**	1039912*	12.42**	15.02**	23.62*	9.69**	23690.7**	3.3
Oromiya	0.21**	407.4**	1.17**	14910.3*	2383219**	4.86**	5.02**	9.69*	3.08**	44628.65**	3.48
SNNPR	0.4**	404.76**	1.96**	24593.05**	2656260**	3.13*	3.97**	12.08	2.7**	45654.39**	2.5
Tigray	0.13**	144.25	0.93	12225.9	4732780**	2.04	2.04	3.96	1.23	84299.56**	2.19
Pooled error within region	0.08	178.55	0.61	9846.73	274134	2	2.16	7.04	1.4	5043.69	3.36

TABLE 4: Regional means for 21 characters in sugarcane germplasm.

(a)

Regions	SPCIMAP ^b	SPC2MAP	TC4MAP	TC5MAP	STCI0MAP	Brix10MAP	MSCHA	SCW	NOI	IL	SH
Amhara	13 ^c	28 ^{bc}	67 ^{bc}	63 ^b	48 ^c	15.16	67588 ^c	1.42 ^b	28.65 ^a	7.96 ^c	219.87 ^c
Benshangul-Gumuz	11 ^c	23 ^c	56 ^c	56 ^b	44 ^c	15.01	68780 ^c	1.58 ^a	28.37 ^a	8.65 ^{ab}	240.22 ^b
Introduced	11 ^c	31 ^b	68 ^{bc}	64 ^b	57 ^b	15.38	99521 ^a	1.44 ^b	27.23 ^b	8.76 ^{ab}	234.69 ^b
Oromiya	18 ^b	28 ^{bc}	84 ^a	76 ^a	58 ^b	15.31	83178 ^b	1.65 ^a	29.57 ^a	8.48 ^{ab}	243.47 ^b
SNNPR	17 ^b	31 ^b	79 ^{ab}	66 ^b	57 ^b	15.09	78179 ^b	1.69 ^a	28.69 ^a	8.37 ^b	234.53 ^b
Tigray	24 ^a	40 ^a	91 ^a	84 ^a	72 ^a	15.18	106078 ^a	1.64 ^a	29.58 ^a	8.84 ^a	253.42 ^a
Entire data	16	29	58	69	55	15.19	79885	1.59	28.88	8.39	235.45

^bSee the Materials and Methods for the abbreviations of the characters.Means of each character followed by the same letter were not significantly different at $p < 0.05$ according to Duncan's multiple range test.

(b)

Regions	SD	LL	LW	LA	Brix	Pol	Purity	Yield	CYHA	Sugar yield
Amhara	2.68 ^{bc}	127.92	4.35 ^b	420.40	18.99	17.66 ^b	92.84 ^{cd}	12.59 ^b	996.44 ^c	129.63 ^c
Benshangul-Gumuz	2.74 ^{ab}	127.54	4.48 ^{ab}	431.10	19.14	17.83 ^{ab}	92.95 ^{bcd}	12.73 ^{ab}	048.88 ^c	137.23 ^c
Introduced	2.61 ^c	131.04	4.40 ^{ab}	450.10	19.24	17.85 ^{ab}	92.61 ^d	12.70 ^{ab}	1417.92 ^b	185.72 ^b
Oromiya	2.80 ^a	128.56	4.46 ^{ab}	429.56	19.21	18.01 ^{ab}	93.77 ^{ab}	12.91 ^{ab}	1451.90 ^b	190.78 ^b
SNNPR	2.83 ^a	129.53	4.64 ^a	451.23	19.04	17.81 ^{ab}	93.49 ^{abc}	12.75 ^{ab}	1407.65 ^b	181.89 ^b
Tigray	2.81 ^a	126.6	4.37 ^b	417.92	19.39	18.21 ^a	93.87 ^a	13.07 ^a	1907.29 ^a	249.83 ^a
Entire data	2.76	128.69	4.48	434.47	19.12	17.87	93.36	12.78	1336.73	174.37

TABLE 5: Range of variation of accession means for 21 quantitative characters in sugarcane germplasm by region of origin.

(a)

Regions	SPCIMAP ^a	SPC2MAP	TC4MAP	TC5MAP	STC10MAP	Brix10MAP	MSCHA	SCW	NOI	IL	SH
Amhara	1-36	5-51	20-164	26-141	16-124	13.22-17.28	15345-185862	0.38-2.00	21.50-39.25	5.20-11.23	158.83-290.43
Benshangul-Gumuz	4-21	10-52	23-103	22-84	30-67	13.31-16.73	36207-138621	1.07-2.68	22.00-36.50	6.91-10.04	201.40-278.58
Introduced	2-30	4-126	33-134	44-95	33-109	13.51-17.26	41379-166207	0.91-2.04	19.00-31.00	7.68-10.84	192.33-256.68
Oromiya	2-41	5-48	17-235	22-133	20-112	12.24-17.19	29655-177586	0.87-2.53	19.00-40.75	5.49-11.83	187.45-313.95
SNNPR	3-39	15-74	12-191	22-119	16-111	13.19-16.66	16724-170345	0.36-2.64	19.50-42.25	5.46-11.37	152.45-297.28
Tigray	11-39	14-94	41-156	58-115	31-102	13.73-16.58	41724-153793	1.11-2.12	25.25-35.00	6.26-10.33	195.15-281.75
Entire data	1-41	4-126	7-178	22-141	16-124	12.24-17.28	15345-185862	0.36-2.68	19.00-42.25	5.20-11.83	152.45-313.95

^a See the Materials and Methods section for the abbreviations of the characters.

(b)

Regions	SD	LL	LW	LA	CYHA	Brix	Pol	Purity	Yield	Sugar yield
Amhara	1.70-3.27	103.85-154.93	2.00-5.56	166.91-555.68	168.00-337.75	15.60-22.12	14.19-20.79	86.55-96.14	9.85-14.94	21.00-465.50
Benshangul-Gumuz	2.17-3.08	107.30-158.63	3.61-5.65	296.33-543.24	372.50-1907.50	14.26-21.12	12.51-20.07	86.25-95.22	8.53-14.53	45.50-246.75
Introduced	2.12-3.04	110.20-147.63	3.30-5.56	340.76-665.12	475.75-2424.50	13.93-20.82	12.14-19.91	87.09-95.98	8.22-14.48	51.25-337.00
Oromiya	2.08-3.27	87.53-147.65	3.25-5.78	287.22-554.93	401.25-2920.75	14.20-20.92	13.22-19.85	88.65-97.56	9.44-14.43	51.00-389.50
SNNPR	1.71-3.34	110.05-173.75	2.95-6.20	241.76-645.29	194.25-3262.00	15.49-21.03	13.56-20.02	85.07-96.75	9.03-14.50	23.25-439.75
Tigray	2.52-3.20	117.20-136.55	3.72-5.42	346.10-548.47	485.75-3339.00	17.55-20.20	16.41-19.16	92.21-95.68	11.76-13.85	64.00-433.00
Entire data	1.70-3.34	87.53-173.75	2.00-6.20	166.91-665.12	168.00-337.75	13.93-22.12	12.14-20.79	85.07-97.56	8.22-14.94	21.00-465.50

TABLE 6: Percent of coefficient of variation for 21 quantitative characters in sugarcane germplasm by region of origin.

(a)

Regions	SPCIMAP	SPC2MAP	TC4MAP	TC5MAP	STC10MAP	Brix10MAP	MSCHA	SCW	NOI	IL	SH
Amhara	104.31	95.60	79.50	65.58	52.54	13.14	53.87	25.18	16.72	16.81	13.89
Benshangul-Gumuz	121.05	103.44	103.99	80.75	58.60	13.75	59.80	21.64	15.91	15.92	15.69
Introduced	116.15	80.77	71.98	60.11	42.85	14.13	39.34	23.41	13.13	15.73	16.43
Oromiya	81.27	73.58	71.87	48.68	40.98	12.39	39.96	23.04	14.92	16.74	13.35
SNNPR	72.12	81.17	66.27	49.75	35.63	13.92	42.49	26.20	13.68	15.14	15.14
Tigray	55.85	84.35	64.60	45.33	24.53	12.15	26.04	18.02	16.53	12.14	11.21
Entire data	75.49	74.10	58.70	45.97	31.40	12.06	34.07	23.32	12.93	15.18	13.34

(b)

Regions	SD	LL	LW	LA	CYHA	Brix	Pol	Purity	Yield	Sugar yield
Amhara	8.78	14.02	21.81	29.86	58.56	8.92	10.40	2.89	11.70	60.33
Benshangul-Gumuz	14.48	12.97	20.31	27.72	55.50	10.25	10.87	2.85	11.60	56.00
Introduced	13.99	10.66	15.91	20.79	46.80	5.89	7.60	3.76	9.87	51.34
Oromiya	10.35	10.93	18.70	23.86	45.57	6.54	6.92	2.80	7.80	45.86
SNNPR	11.93	11.56	16.59	23.05	49.89	7.52	8.37	3.45	9.56	50.65
Tigray	7.37	10.01	25.41	31.93	33.43	6.43	6.85	2.11	7.43	32.15
Entire data	9.91	10.38	17.52	22.84	39.17	7.40	8.22	2.84	9.26	40.73

This is in agreement with previous studies on sugarcane germplasm [33–35].

This is the first study to report information on geographical pattern of variation in Ethiopian local sugarcane germplasm which has been lacking so far. Our results provided experimental evidence on occurrence of geographical variation and significant within-region variation where it was high in the regions such as Amhara, Benshangul-Gumuz, and SNNPR.

The overall patterns of similarity or difference between regions seemed to depend on environmental factors such as rainfall, temperature, length of growing season, and altitude. Wide variability of millable stalk count at harvest, single cane weight, and plant height was observed among regions where these characters demonstrated high correlation with cane and sugar yield (Table 7). Therefore breeders can utilize accessions of regions showing variability for these characters in selection programs and to design breeding strategies to produce varieties with best commercial merits.

Bivariate Statistics. Correlation coefficients worked out on the 21 quantitative characters are shown for the entire data (Table 7), between regions (Table 8), and within regions (data not shown). Results of the association studies for the entire data showed that cane and sugar yield had highly significant positive correlation with most of the quantitative stalk characters and juice quality parameters. However, the association of tiller counts 4 and 5 months after planting, stalk count 10 months after planting, millable stalk count at harvest, single cane weight, and plant height with cane and sugar yield was stronger, suggesting these component characters as main contributing factor to cane and sugar yield. In fact sugar yield is the product of cane yield and sucrose percent cane surely being influenced with components affecting cane yield. Similar trend was reported by earlier sugarcane workers [36, 37]. In sugarcane, the cane and sugar yields are considered to be the complex characters. The information on the phenotypic interrelationship of cane yield and sugar yield with their component character per se would be of immense help to sugarcane breeders.

Stem diameter had significant positive association with both cane and sugar yield indicating the significance of this trait in improving both cane and sugar yields. Similar reports have been made by earlier sugarcane workers [37, 38]. Stalk diameter was also positively and significantly correlated with plant height. It is one of the traits that are related to lodging resistance [39] and the positive associations with height would help in reducing the chance of lodging as height increases. Among the physiological attributes included in the study, leaf area had highly significant positive association with cane yield. Similar observation was also made in [37]. Sucrose percent, which is an important juice quality attribute, had highly significant positive association with sugar yield and simultaneously cane yield also had highly significant association with sugar yield. Based on the magnitude of correlation coefficient values it can be said that cane yield is much more important than sucrose percent in determining the sugar yield and the same has also been reported by other sugarcane workers [37, 40]. Similar to observations made in

[37, 41], results of the current study showed that all the quality parameters like sucrose percent, pol percent, brix percent, and purity percent were significantly correlated in positive direction. This indicated any of these juice quality traits could be considered for selection leading to the simultaneous improvement in the remaining quality traits.

Ten of the 21 characters also showed significant positive correlations with altitude of the collection sites (Table 7). As described in [42], ecological characteristics have influenced the genotypic constitution of landraces during domestication and hence a relationship exists between the agroecology in the collection site and the morphological characteristics of the landraces. Thus positive correlation between collection site variables and plant characteristics would imply that the variation between accessions may be related to agroecological variations among the collection sites [43].

The correlation coefficient between number of internodes and altitude was negative and significant indicating that other environmental factors (other than altitude) and/or nonenvironmental factors might account for the variation for this particular character. Since temperature decreases with an increase of altitude in Ethiopia [44, 45], it is more likely that temperature has exerted strong selection pressure in number of internodes in the genotypes. Information on the relationships between environmental factors of the collecting sites and morphophysiological variation of germplasm could enhance the understanding of evolutionary adaptive patterns, which could assist germplasm collectors and users [46].

Character associations between region and within region also followed similar fashion like that of the entire data. Number of sprout, tiller, and stalk counts and sugar quality parameters showed significant positive correlations with cane and sugar yield.

Though not significant and strong the correlation of leaf length and width and leaf area (leaf area = leaf length X leaf width X 0.75) with cane and sugar yield was negative in the interregion correlations. This kind of relationship was also exhibited between these leaf characteristics and yield components like tiller and stalks counts, plant height and single cane weight, and stalk diameter and sugar quality parameters. This may have been attributed to the variation of temperature with altitude and other environmental factors across the regions resulting in such type of relationship. Such relationship also calls for the need to have enough data on environmental variables of the collection sites such as temperature and rainfall. If germplasm collection is required to meet its objectives effectively and efficiently. Unfortunately, data on such useful environmental variables like temperature and rainfall are lacking in the passport data of the current Ethiopian sugarcane germplasm collections. The significance of environmental factors of the collection sites as very important determinants in structuring morphophysiological variations was reported in tetraploid wheat [22, 47, 48].

Association of characters among yield, its components, and other economic traits is important for the interpretation of the patterns of variation and making selection in breeding program and combining several desirable attributes. It

TABLE 7: Simple correlation coefficients between 21 quantitative characters and the characters with altitude of collection sites based on the mean for 211 sugarcane accessions.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
A	1.00																					
B	0.57**	1.00																				
C	0.63**	0.38**	1.00																			
D	0.54**	0.24**	0.71**	1.00																		
E	0.56**	0.32**	0.79**	0.72**	1.00																	
F	0.06	0.07	-0.03	-0.09	-0.07	1.00																
G	0.43**	0.30**	0.70**	0.69**	0.88**	-0.156*	1.00															
H	0.19**	0.10	0.27**	0.31**	0.32**	-0.17*	0.37**	1.00														
I	0.22**	-0.01	0.10	0.05	0.01	0.17*	-0.11	-0.10	1.00													
J	0.06	0.13	0.22**	0.31**	0.31**	-0.14*	0.48**	0.53**	-0.68**	1.00												
K	0.28**	0.17*	0.41**	0.48**	0.48**	-0.05	0.60**	0.68**	0.01	0.71**	1.00											
L	0.06	0.04	0.11	0.11	0.11	-0.17*	0.16*	0.71**	-0.02	0.24**	0.35**	1.00										
M	0.12	-0.06	0.17*	0.19**	0.14*	-0.07	0.18**	0.28**	-0.08	0.25**	0.24**	0.21**	1.00									
N	-0.08	-0.11	-0.12	-0.06	-0.15*	-0.19**	-0.10	0.44**	-0.06	0.15*	0.16*	0.54**	0.14*	1.00								
O	-0.001	-0.06	0.01	0.03	-0.03	-0.20**	0.04	0.47**	-0.08	0.23**	0.24**	0.50**	0.57**	0.87**	1.00							
P	0.14*	0.11	0.19**	0.21**	0.20**	0.02	0.29**	0.45**	-0.08	0.29**	0.36**	0.46**	0.14*	0.25**	0.25**	1.00						
Q	0.19**	0.12	0.22**	0.22**	0.21**	0.03	0.28**	0.44**	-0.03	0.27**	0.37**	0.46**	0.14*	0.23**	0.23**	0.97**	1.00					
R	0.27**	0.09	0.21**	0.15*	0.14*	0.01	0.12	0.21**	0.12	0.09	0.24**	0.25**	0.06	0.10	0.11	0.49**	0.67**	1.00				
S	0.21**	0.12	0.23**	0.21**	0.21**	0.04	0.26**	0.42**	-0.00	0.25**	0.36**	0.44**	0.13	0.21**	0.22**	0.94**	0.99**	0.75**	1.00			
T	0.42**	0.29**	0.63**	0.63**	0.80**	-0.18**	0.91**	0.68**	-0.14*	0.58**	0.71**	0.39**	0.26**	0.08	0.20**	0.39**	0.38**	0.17*	0.36**	1.00		
U	0.43**	0.29**	0.63**	0.63**	0.80**	-0.17*	0.91**	0.68**	-0.14*	0.57**	0.71**	0.40**	0.26**	0.07	0.20**	0.45**	0.44**	0.22**	0.43**	0.10**	1.00	
V	0.14*	0.17*	0.15*	0.11	0.21**	-0.09	0.22**	0.18**	-0.17*	0.18**	0.10	0.18**	0.08	0.09	0.11	0.10	0.10	0.03	0.09	0.25**	0.25**	1.00

A=SPC1MAP; B=SPC2MAP; C=TC4MAP; D=TC5MAP; E=STC10MAP; F=Brix10MAP; G=MSCHA; H=SCW; I=NOI; J=IL; K=SH; L=SD; M=LL; N=LW; O=LA; P=Brix; Q=Pol; R=purity; S=yield; T=CYHA; U=sugar yield; V = Altitude.

*See the Materials and Methods for the abbreviations of the characters.

* and **: significant at $p < 5\%$ and 1% levels, respectively.

TABLE 8: Interregion simple correlation coefficients among 21 quantitative characters (based on the mean of the 6 regions of origin).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
A	1.00																				
B	0.80	1.00																			
C	0.81	0.71	1.00																		
D	0.91*	0.82*	0.88*	1.00																	
E	0.86*	0.95**	0.86*	0.92*	1.00																
F	0.00	0.30	0.45	0.40	0.41	1.00															
G	0.55	0.84*	0.64	0.71	0.89*	0.60	1.00														
H	0.65	0.21	0.60	0.43	0.40	-0.32	0.10	1.00													
I	0.80	0.32	0.57	0.70	0.43	-0.20	0.03	0.65	1.00												
J	0.29	0.41	0.29	0.33	0.53	0.22	0.74	0.30	-0.09	1.00											
K	0.69	0.51	0.57	0.65	0.69	0.06	0.64	0.67	0.48	0.83*	1.00										
L	0.74	0.26	0.57	0.48	0.39	-0.44	0.00	0.95**	0.80	0.09	0.56	1.00									
M	-0.52	-0.17	0.03	-0.34	-0.12	0.55	0.12	-0.29	-0.73	0.02	-0.37	-0.49	1.00								
N	-0.01	-0.25	0.17	-0.25	-0.14	-0.39	-0.30	0.66	0.01	-0.04	0.02	0.55	0.31	1.00							
O	-0.40	-0.18	0.04	-0.40	-0.12	0.19	0.06	0.06	-0.65	0.16	-0.18	-0.17	0.89*	0.66	1.00						
P	0.57	0.67	0.51	0.69	0.77	0.40	0.88*	0.24	0.23	0.87*	0.87*	0.14	-0.21	-0.38	-0.22	1.00					
Q	0.81*	0.70	0.71	0.85*	0.84*	0.24	0.76	0.56	0.57	0.73	0.95**	0.50	-0.39	-0.17	-0.31	0.92*	1.00				
R	0.91*	0.52	0.81*	0.81	0.67	-0.06	0.32	0.84*	0.90*	0.21	0.70	0.89*	-0.48	0.23	-0.32	0.43	0.75	1.00			
S	0.88*	0.68	0.75	0.87*	0.83*	0.14	0.67	0.66	0.69	0.63	0.93**	0.64	-0.46	-0.08	-0.35	0.83*	0.98**	0.85*	1.00		
T	0.85*	0.90*	0.85*	0.88*	0.99*	0.36	0.89*	0.49	0.42	0.65	0.79	0.44	-0.13	-0.06	-0.07	0.83*	0.90*	0.70	0.88*	1.00	
U	0.84*	0.90*	0.85*	0.89*	0.98**	0.37	0.90*	0.48	0.42	0.65	0.80	0.43	-0.13	-0.08	-0.08	0.84*	0.91*	0.70	0.88*	1.00**	1.00

A=SPC1MAP; B=SPC2MAP; C=TC4MAP; D=TC5MAP; E=STC10MAP; F=Brix10MAP; G=MSCHA; H=SCW; I=NOI; J=IL; K=SH; L=SD; M=LL; N=LW; O=LA; P=Brix; Q=Pol; R=purity; S=yield; T=CYHA; U=sugar yield.

*See the Materials and Methods for the abbreviations of the characters.

* and **: significant at $p < 5\%$ and 1% levels, respectively.

suggests the advantage of a scheme of selection for more than one character at a time. The correlation between characters may arise from linkage or from developmental genetic interactions, with or without a purely phenotypic component. It could arise also due to differential phenotypic plasticity of characters themselves. Within the limit of experimental error and environmental effects, high correlation coefficients between characters may show that the characters share some common element of genetic control (i.e., pleiotropy, linkage) between genes or else from independently controlled characters responding similarly to geographic variation in selection pressures [49]. The interregion correlation coefficient between the characters measures the consistency of their patterns of regional variation, while the intraregion correlation coefficient measures the association arising from genetic factors but is not affected by regional variation [50]. Since this study showed significant positive correlations intraregionally for some character combinations, it would seem that common genetic control might be playing a role in bringing about correlations between the various characters. It appeared that different response to regional variation was playing a greater role than different genetic control as shown by the many more significant and moderate to high correlation coefficients intraregionally than interregionally.

3.2.2. Qualitative Characters. The frequency distribution for the 16 qualitative characters of germplasm samples by regions in Ethiopia and of the exotic accessions is shown in Supplemental Table 5. For the purpose of avoiding redundancy and improving readability the discrete characters are presented by grouping related traits together.

Bud Cushion and Relative Degree of Bud Extension. Evaluation of the presence and absence of bud cushion revealed that great proportion (70%) of sugarcane landraces from Ethiopia do not have bud cushion. Majority of the sample germplasm in all regions belong to this phenotypic class. Approximately one-half (53%) of the collection have their bud extended above the growth ring followed by those (41%) having bud touching the growth ring.

Relative Bud Shape. Among the phenotypic classes for this character, tall deltoid was dominant (31%) followed by ovate (17%) and narrow ovate (12%). While local accessions in most regions had tall deltoid bud shape, 50% of the introduced accessions belong to two phenotypic classes round with central germ pore (30%) and 20% having pentagonal bud shape. Equal proportions (19%) of the samples from Benshangul-Gumuz were Ovate and Ovate with emarginate basal wing.

Canopy Structure, Relative Plant Erectness, Colour of the Leaves, and Colour of the Exposed Rind. Out of the eight phenotypic classes observed, compact tip droopy was the most frequent (35%). Open semidroopy and open droopy classes had fairly equal distribution. With regard to relative plant erectness, seventy-five percent of the germplasm were found to fall in two phenotypic classes, erect (41%) and almost

erect (34%), for the whole region and country. Most of the accessions (90%) showed light green or green leaf colour, but 20% from introduced collections were greenish yellow. Among phenotypic classes for colour of the exposed rind, brownish yellow, yellow, brown, and yellowish green were the most frequent with fairly equal distribution.

Relative Shape of Dewlap. Double crescent had larger frequency (22%) while squarish, descending, and flaring type of dewlap shape had fairly equal proportions. Seventeen percent of germplasm from Tigray region had squarish deltoid dewlap shape.

Relative Degree of Internode Alignment and Internode Shape. Forty-four percent of the sample germplasm were slightly zigzag while there was almost equal frequency for straight and zigzag internode alignment for the entire region and country. Straight or nearly straight (slightly zigzag) internode alignment of cane stalks is a very important character for mechanized farming and postharvest handling in sugarcane [51]. Forty percent of the collections were observed having concave-convex type of internode shape while 29% was cylindrical and 14% conoidal. Other classes had fairly equal proportion.

Type of Auricle and Relative Shape of Ligule. An equal proportion of the germplasm totally constituting 84% of the collection belong to four phenotypic classes, namely, those with no auricle and others with transitional and short and lanceolate auricles. Sixteen percent of the collections also showed equal frequency for the remaining classes. Benshangul-Gumuz and Tigray regions had each equal 13% accessions with falcate type of auricle. Sixty-seven percent of the collections belong to three ligule shape classes, crescent with lozenge (27%), broad-crescent (21%), and linear-crescent (19%). The germplasm had almost equal proportion for the other phenotypic classes of this character. Nineteen percent of the accessions from Benshangul-Gumuz region had deltoid shape of ligule.

Stalk Corky Cracks, Corky Patches, Growth Cracks, and Bud Groove. Eighty-nine percent of the germplasm across regions had no stalk corky cracks with only eleven percent exhibiting this character. All the germplasm in Gambella, Harari, and Somali had no stalk corky cracks. On the other hand, eighty-one percent of the germplasm for the whole region showed the presence of stalk corky patches. All the local germplasm in Benshangul-Gumuz, Gambella, and Tigray had stalk corky patches whereas 75% of the germplasm from Harari Region, 67% from Somali Region, and 24% from Oromia Region had no stalk corky patches. In the entire region 75% of the germplasm had no stalk growth cracks with only 25% showing this character. Sixty-three percent of the germplasm were found to have bud groove. However, most of the samples in Harari (75%), Amhara (63%), and Oromia (53%) Regions had no bud groove.

The results of this study indicated the wide distribution of phenotypic classes for the characters considered which indicates the existence of different races and combination

of races in local genotypes of different regions in Ethiopia. This diversity of germplasm based on phenotypic markers can help sugarcane breeders in identifying the identity of genotypes as well as maintaining genetic diversity. Differences in morphological characters of different sugarcane varieties have been reported [52]. Piscitelli [53] showed important exomorphological qualitative characters of sugarcane variety that are not influenced by environmental factors and thus can be used as a selection tool in any breeding program.

The amount of phenotypic diversity estimates based on the Shannon–Weaver diversity index (H') are shown in Table 9. The 16 characters differed in their distribution as well as the amount of variation. Individual traits showed a different pattern of variation among accessions. Estimates of H' for individual characters varied from 0.49 for stalk corky cracks to 1.00 for bud groove with an overall mean of 0.80. Most of the characters were highly polymorphic whereas relative plant erectness and presence or absence of stalk corky patches scored moderate values. The high diversity values for the characters showed a wide variability among genotypes. According to [54] this index is also used in genetic resource studies as a convenient measure of both allelic richness and allelic evenness when using genetic data.

The highest diversity computed was on presence or absence of bud groove with a diversity index of 1.00, indicating that this character is very variable in the local sugarcane germplasm. On the other hand, the descriptor computed with the lowest diversity index value (0.49) was the presence or absence of stalk corky cracks indicating that this character is selected in the development of the genotypes. In agreement with the present study, [55] working on *S. officinarum* accessions from the world collection of sugarcane germplasm obtained a low index of 0.25 and 0.35 for presence or absence of stalk corky patches and cracks, respectively.

Their report also showed high diversity index values for internode alignment, growth cracks, internode shape, bud cushion, bud extension, bud groove, and ligule shape. Similarly, [56] experimenting on field collections of sugarcane accessions in Philippine reported high Shannon–Weaver diversity for stalk growth cracks, bud cushion, stalk corky patch, stalk corky cracks, bud extension, and auricle outer shape. Unlike the present study they have reported high index for stalk corky cracks. Medium index values were reported for stalk internode shape and low index values for ligule shape and bud shape. High variability of sugarcane varieties for dewlap shape was also reported in [57].

The H' pooled across characters by region ranged from 0.79 in Oromiya to 0.85 in Tigray with an overall average of 0.81 (Table 8). Most of the regions showed high Shannon–Weaver diversity index. The populations that had the highest H' were that of Tigray and introduction. The H' averaged over regions for different characters was found to range from 0.44 for presence or absence of stalk corky cracks to 0.94 for relative degree of internode alignment and bud groove with an overall average of 0.81 (Table 9).

Assessment of the Shannon–Weaver index also showed sensitivity to both the number of descriptor classes and the

distribution within phenotypic classes in each region. Among regions, the mean values for the Shannon–Weaver index are not significantly different, but differences were found when individual characters were considered. These observations suggest that some regions have high diversity for particular traits while in other regions selective pressures might have reduced the variation to certain genotypes.

4. Conclusions

The large number of landraces observed during the current study demonstrates the existence of diverse genetic resources of sugarcane in Ethiopia. The landraces would serve to broaden the genetic base of the available sugarcane germplasm. Generally, distribution of the overall phenotypic diversity among sugarcane landraces in Ethiopia is uneven. Our results showed that there was a wide range of variation that existed in the local sugarcane landraces studied both at regional and within region levels. Selection and differentiation of types might have taken place along a geographical pattern perhaps associated with climate and use. The present study contributes to updating sugarcane descriptors adopted from USDA-ARS as well as Bioversity passport data for the future collection and evaluation. As Ethiopian Sugar Corporation is in the course of launching breeding program, the observed substantial variation of landraces would enable sugarcane breeders to design and practice breeding and selection programs to improve the crop.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

These supplementary materials contain different tables supporting the results of the study. These include passport data of sugarcane germplasm collected and related information on the materials, local sugarcane germplasm collected and used for morphological diversity study, introduced sugarcane

TABLE 9: Shannon-Weaver Diversity Indices (H') and mean and standard error ($\pm SE$) of landraces in each region based on 16 discrete characters.

Characters	Amhara	Benshangul-Gumuz	Introduced	Oromia	SNNP	Tigray	EL ^b	Total
Presence or absence of bud cushion (BUDCUSHION)	0.83	0.95	0.95	0.89	0.82	0.98	0.90	0.88
Relative degree of bud extension (BUDEXTEND)	0.77	0.79	0.93	0.74	0.72	0.87	0.80	0.78
Relative bud Shape (BUDSHAPE)	0.78	0.96	0.89	0.81	0.85	0.78	0.84	0.78
Canopy structure (CANOPY)	0.89	0.98	0.95	0.81	0.78	0.96	0.89	0.84
Relative shape of dewlap (DEWLAPSHAP)	0.87	0.94	0.92	0.90	0.82	0.96	0.90	0.86
Relative plant erectness (ERECT)	0.80	0.82	0.50	0.67	0.71	0.88	0.73	0.64
Relative degree of internode alignment (INALIGN)	0.96	0.76	0.98	0.97	0.98	1.00	0.94	0.98
Relative internode shape (INSHAPE)	0.86	0.69	0.95	0.77	0.83	0.91	0.83	0.82
Color of the leaves (LEAFCOLOR)	0.87	0.71	0.90	0.64	0.74	0.71	0.76	0.76
Type of outer auricle (AURICLEOUT)	0.80	0.92	0.87	0.79	0.83	0.93	0.86	0.82
Relative shape of ligule (LIGSHAPE)	0.86	0.94	0.82	0.85	0.90	0.83	0.87	0.83
Presence or absence of stalk corky cracks (STALKCORKC)	0.44	0.54	0.35	0.55	0.51	0.25	0.44	0.49
Presence or absence of stalk corky patches (STALKCORKP)	0.66	0.00	0.72	0.79	0.59	0.87	0.60	0.69
Presence or absence of stalk growth cracks (STALKCRACK)	0.66	1.00	0.88	0.62	0.88	0.99	0.84	0.80
Color of the exposed rind (RINDCOLE)	0.85	0.96	0.89	0.84	0.86	0.76	0.86	0.85
Presence or absence of bud groove (BUDGROOVE)	0.95	1.00	0.72	1.00	1.00	0.99	0.94	1.00
Means	0.80±0.03	0.81±0.06	0.83±0.04	0.79±0.03	0.80±0.03	0.85±0.05	0.81±0.03	0.80

^bEL=average of entire location.

varieties used for morphological diversity study, and frequency distribution for 16 qualitative characters in sugarcane by regions in Ethiopia and country of sources of introduced genotypes. (*Supplementary Materials*)

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