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Estimates of genetic parameters and genotype by environment interactions for sugar yield and its components in sugarcane genotypes in Western Kenya

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This study was conducted to estimate broad sense heritability, genetic advance, GE interactions and correlations among quality traits in sugarcane clones in western Kenya. Thirteen sugarcane promising clones and one check cultivar were evaluated plant and ratoon crops in three locations under rain fed conditions using the randomised complete block design with three replications. Analysis of variance showed significant differences in hand refractometer brix, sucrose content (Pol% cane), juice purity, fire content, sugar yield and brix yield. Sucrose content, fibre content, sugar yield and brix yield exhibited significant genotype × location (GL) interactions. The genotype mean squares exceeded the GE interactions for all the quality traits suggesting that more emphasis should be placed on testing clones in many locations than on testing ratoon crops within locations. High genetic coefficient of variation (GCV) was detected for cane yield (8.12%), brix yield (6.39%), sugar yield (5.69%) and sucrose content (3.69%). Broad sense heritability was high for sucrose content (0.712) and moderate for cane yield (0.515), fibre content (0.474), juice purity (0.445) and refractometer brix (0.380). Cane yield (10.3%), brix yield (6.7%), sucrose content (5.5%) and sugar yield (5.4%) showed highest expected genetic advance. The results indicated that these traits may respond positively to selection and present opportunities for improvement through breeding. High genetic correlation (r_g=0.998) between refractometer brix and sucrose content suggest that selection for refractometer brix can be effective in identifying varieties with high sucrose content.

Key words: *Saccharum* spp. heritability, genetic advance, sucrose content, selection, sugar.

INTRODUCTION

Genetic improvement of varieties plays a pivotal role in the development of sugar industries in almost all sugarcane growing countries. Improved cane yields, sucrose content and disease and pest resistance and maintaining acceptable fibre levels for milling are usually the main breeding objectives in most sugarcane breeding programmes (Jackson, 2005). Studies on exploitation of sugarcane as a sustainable energy source are on the increase (Corcodel and Roussel, 2010; Hoang et al., 2015; Priya et al., 2018). An improvement in sucrose

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content in sugarcane has high economic value as it increases sugar yield with very little increase in marginal costs through harvesting, cane transport or milling (Jackson, 2005). Thus gains in sucrose content are economically more beneficial than corresponding increases in cane yield thus increased sucrose content is a key objective of sugarcane breeding programmes.

Breaux (1984) reported that the record increase in sugar recovery in Louisiana was attributed to wide acceptance of high sucrose varieties that were introduced in 1973. The high sucrose content of the varieties was a result of continuous breeding and selection effort since the 1920s (Breaux, 1984; Legendre, 1992). Significant increase in the sucrose content of both experimental clones and cultivars grown in a number of locations throughout the sugarcane-growing region of Louisiana since 1928 was reported by Irvinne and Richards (1983). The average sucrose % cane of experimental varieties rose from 5.54% in 1928 to 13.56% in 1978; while the average sucrose % cane for all adopted cultivars increased from 7.25% in 1928 to 12.7% in 1981. In addition the study showed a strong correlation between the sucrose content of experimental varieties and actual mill recovery (r = 0.79) and sucrose content of commercial varieties and mill recovery (r = 0.80) during the same period. However, further improvement in sucrose content through breeding may be difficult as the sucrose content of parent varieties reaches an apparent plateau (Legendre, 1992; Inman-Bamber, 2014).

The effectiveness of selection for sugar yield and its components depends largely on the genetic variability present in the breeding population and the heritability of the traits. It is necessary to identify traits with high genetic variation. The easiest way to estimate variance components is to test a large number of genotypes for two or more years and at two or more locations (Mayo, 1980). Components of juice quality are largely determined by the genotype but can be significantly influenced by the environment (Tena et al., 2016; Singh et al., 2019). Sucrose content and purity are conventional indicators of maturity commonly used as selection criteria and they are widely investigated in sugarcane breeding programmes (Mariotti et al., 2001). The sugarcane industry in Kenya is largely dependent on a few varieties that have low sucrose content and sugar yield (Jamoza, 2011). In recent years the industry has emphasized development and adoption of high yielding sugar rich varieties. This study aimed to estimate (i) broad sense heritability (ii) potential genetic advance and (iii) correlations among juice quality traits in promising Kenyan sugarcane clones.

MATERIALS AND METHODS

Experimental sites and genotypes

The test genotypes, experimental sites and methodology applied to obtain estimates were as described by Jamoza et al. (2014). In brief, 13 clones (KEN01-24. KEN01-26, KEN01-41, KEN01-279, KEN01-345, KEN01-592, KEN01-819, KEN01-848, KEN01-1009, KEN01-1104, KEN01-1108, KEN01-1139 and KEN01-1294) representing eight crosses involving 15 parents and one commercial variety (N14) were chosen for study and evaluated in plant and first ratoon crops between August 2007 and June 2010. They were grown at three locations in western Kenya namely: Kibos (34° 48'E, 0° 04'N) 1,184 m above sea level on clay loam soil with long term mean annual rainfall of 1,490 mm. The temperatures range from 15.3 to 30°C; Mumias (34° 30'E, 0° 21'N) at 1,314 m above sea level, receives 2,194 mm annual rainfall with a temperature range of 16.4 to 30.9°C and has free draining loam soils; and Nzoia (34° 40'E, 0° 35'N) situated at 1,445 m above sea level, receives average annual rainfall of 1,650 mm with a temperature range of 13 to 32°C and has sandy clay loam soils. The randomised complete block design with three replications was used at each location. The following cane quality data were collected in both crops.

Field brix

Hand held refractometer (0-32^{o}) was used to determine brix of 5 millable stalks taken randomly from each plot in the field at harvest.

Sugarcane analysis

At harvest millable stalks in each plot were cut at ground level, well topped and hand stripped to remove the trash and green leaves. Twelve millable stalks were randomly taken from each plot, bundled, tied, labelled and transported to the laboratory for juice and fibre analysis. Juice was extracted from six stalk samples using a simple three roller cane press (Milligan et al., 1990a). The juice was filtered through Whatman filter paper No.1 and 100 ml portions of the filtrate used to determine brix (percent soluble solids w/w) using a bench refractometer as described in the Laboratory Manual for South African Sugar Factories (Anon, 1985). For the determination of Pol % juice approximately 300 ml samples of the extracted juice were placed in a beaker and clarified using 3 g of sub lead acetate. The mixture was then filtered using Whatman filter paper No. 91. Polarimetric readings of the clarified juice were obtained using a digital automated sucromat while sucrose content (Pol% cane) was calculated from the values of Pol % juice and fibre content (BSES, 1970).

The other six stalks from the harvested sample for each cane variety were used to determine fibre content following the procedure described by Clayton (1971). Six pieces were cut from different (top, middle, and bottom) portions of the stalks in order to obtain a subsample equivalent to one whole stalk. The pieces were further cut into smaller pieces (approx. 3 cm) then shredded in a laboratory hammer mill (shredder). The shredded samples were well mixed and then 200 g subsamples were placed in pre weighed fibre bags and washed alternately in cold and hot water to remove all sugars (mainly sucrose, fructose and glucose). The samples thus processed were dried in an air oven at 105°C for 24 h to constant weight. The fibre content was calculated directly from the 200 g fresh weight and dry weight as:

$$Fibre\ content\ \% = \frac{weight\ of\ dried\ sample}{weight\ of\ fresh\ sample} * 100$$

Purity of juice was computed as:

$$Purity\ \% = \frac{Pol\ \%\ cane}{Brix\ \%\ cane} * 100$$

Other derived quality characters were computed as follows:

Table 1. Mean squares for quality traits combined over the plant and first ratoon crops and three locations (Mumias, Nzoia and Kibos) in 2007-2010.

Source	DF	Hand refractometer Brix (°)	Sucrose content (Pol % cane)	Juice purity (%)	Fibre content (%)	Estimated sugar yield (tha^{-1})	Brix yield (tha^{-1})
Location (L)	2	11.706**	48.628**	553.605**	108.297**	244.957**	279.526**
Rep (location)	6	1.482**	11.864**	37.885**	2.419*	142.943**	264.371**
Crop-year (Y)	1	0.6**	2.177	889.842**	1.232	356.215**	854.386**
Genotype (G)	13	3.608**	6.142**	16.481**	2.874**	36.701**	92.687**
G x L	26	1.136	1.283*	5.932	1.511*	25.993*	55.397*
G x Y	13	0.794	1.386*	5.108	0.76	15.747	34.77
L x Y	2	50.549**	0.791	148.655**	1.767	242.565*	858.954**
G x L x Y	26	0.41	0.905	3.652	0.666	8.17	15.289
Error	162	0.486	0.715	6.842	0.889	14.209	31.359
Mean	-	20.851	13.367	87.056	16.224	13.556	21.142
CV%	-	3.344	6.328	3.0	5.812	27.808	26.487
R^2	-	0.746	0.738	0.734	0.702	0.62	0.618

*, ** = significant at p≤0.05 and p≤0.01, respectively.

Estimated sugar yield tha^{-1} = Sucrose content (Pol % cane) × cane yield (tha^{-1}) × 100

Brix yield tha^{-1} = Brix % cane × cane yield (tha^{-1}) × 100

Statistical data analysis

All the data were submitted to analysis of variance and covariance, estimation of genetic, genotype by environment interaction and error variance components, broad sense heritability, genetic advance and correlations as described by Jamoza et al. (2014). The genotypes were assumed to be fixed while genotype by environment interactions and environments were random (Chang, 1996; Brown and Glaz, 2001).

RESULTS

Combined analysis of variance for quality components over three locations and two crops

Mean squares for the traits are shown in Table 1. Genotypes exhibited significant (p ≤ 0.01) differences for hand refractometer brix, sucrose content, juice purity, fire content, estimated sugar yield and brix yield. Locations played a significant (p ≤ 0.01) role in the phenotypic expression of all the quality traits. However, years or crops significantly (p ≤ 0.01) influenced genotypes only for hand refractometer brix, juice purity, estimated sugar yield and brix yield. Significant (p ≤ 0.01) genotype × location (GL) interactions were detected for sucrose content, fibre content, estimated sugar yield and brix yield. Location × crop-year (LY) effects were significant for hand refractometer brix, juice purity, estimated sugar yield and brix yield. Genotype × crop-year interactions (GY) were only significant (p ≤ 0.05) for sucrose content. However, genotype × location × crop-year (GLY) interactions were not significant (p ≤ 0.01) for any of the traits studied. For all the traits mean squares for genotypes were larger than GL (1.4 - 4.5 times), GY (2.3 - 4.5 times), GLY (4.3 - 8.8 times) and error (2.4 - 4.8 times) mean squares.

Genetic variability, heritability and genetic advance

Genetic variabilities (GCV) for sucrose content, juice purity, fibre content and sugar yield were higher in first ratoon than plant crop (Table 2). Differences between GCV and phenotypic coefficient of variation (PCV) for all traits were large indicating the influence of environmental factors in the traits. Heritability for the traits ranged from 0.376 for juice quality and sugar yield to 0.685 for refractometer Brix in the plant crop and from 0.321 to 0.81 in the ratoon crop. Expected genetic gains for all the traits in both crop years were less than 10% with sucrose content, sugar yield and Brix yield recording 3.2, 7.9 and 8.1% respectively. Genetic gain for sucrose content and fibre content were much

Table 2. Variance components and heritability for sugar yield and related traits in 14 sugarcane genotypes evaluated in Kibos, Mumias and Nzoia for plant crop (PC) (2007-2009) and first ratoon crop (FR) (2009-2010).

Trait	σ^2_g		σ^2_{gl}		σ^2_e		GCV		PCV		h^2		GA%	
	PC	FR	PC	FR	PC	FR	PC	FR	PC	FR	PC	FR	PC	FR
Refractometer Brix (°)	0.212	0.106	0.173	0.019	0.359	0.611	2.211	1.557	2.673	2.031	0.685	0.588	3.2	2.1
Sucrose content (Pol% cane)	0.119	0.474	0.192	0.119	0.609	0.646	2.603	5.114	3.774	5.684	0.476	0.810	3.2	8.1
Juice purity (%)	0.405	1.038	0.000	0.000	6.060	5.826	0.747	1.145	1.219	1.460	0.376	0.616	0.8	1.6
Fibre content (%)	0.107	0.225	0.273	0.000	0.681	0.971	2.024	2.911	3.237	3.541	0.391	0.676	2.2	4.2
Sugar yield (t ha^{-1})	1.161	0.880	1.775	0.000	11.986	16.765	7.308	7.587	11.911	13.392	0.376	0.321	7.9	7.6
Brix yield (t ha^{-1})	2.613	3.704	1.642	0.571	26.871	37.097	7.033	5.818	10.786	8.559	0.425	0.462	8.1	7.0

σ^2_g, σ^2_{gl}, σ^2_e = genotypic, genotype × location interaction, environmental variances; GCV, PCV = genetic, phenotypic coefficients of variation, h^2 = broad sense heritability and GA% = expected genetic advance as percentage of the phenotypic mean of the trait

Table 3. Combined variance components and heritability for sugar yield and related traits in 14 sugarcane genotypes evaluated in Kibos, Mumias and Nzoia in plant and first ratoon crops (2007-2010).

Trait	σ^2_g	σ^2_{gl}	σ^2_{gy}	σ^2_{gly}	σ^2_e	GCV%	PCV%	h^2	GA%
Hand refractometer Brix(°)	0.076	0.000	0.054	0.584	0.486	1.323	2.147	0.380	1.4
Sucrose content (Pol % cane)	0.244	0.064	0.000	0.061	0.715	3.694	4.376	0.712	5.5
Juice purity (%)	0.407	0.000	0.000	0.769	6.842	0.733	1.099	0.445	0.9
Fibre content	0.076	0.108	0.000	0.000	0.861	1.696	2.463	0.474	2.1
Estimated sugar yield (tha^{-1})	0.595	0.665	0.000	2.599	14.209	5.690	10.534	0.292	5.4
Brix yield (tha^{-1})	1.827	0.000	0.000	9.481	31.361	6.393	10.733	0.366	6.7

σ^2_g, σ^2_{gl}, σ^2_{gy}, σ^2_{gly}, $\sigma^2 e$ = genotypic, genotype × location, genotype × crop-year, genotype × location × crop-year interaction, environmental variances; GCV, PCV = genetic, phenotypic coefficients of variation, h^2 = broad sense heritability and GA% = expected genetic advance as percentage of the phenotypic mean of the trait

higher in the ratoon than the plant crop. This was probably due to the higher genetic variance for the two traits in the ratoon crop. Error variance components for sugar yield and Brix yield were 19 and 10 fold the respective genotypic components. GCV values for all the cane quality characters were less than 10% in both crops. Most of the quality traits had moderate to high heritability (>0.5) but sugar yield had low heritability (0.321). Genetic parameters from the combined analysis are shown in Table 3. For all traits, error variances were higher than the genetic components. G×Y variances were negligible in all the traits except refractometer Brix. The magnitude of GCV relative to PCV ranged from 54% for sugar yield to 84.4% for sucrose content. Heritability was highest (0.712) for sucrose content and lowest (0.292) for sugar yield. Brix yield (6.7%), sucrose content (5.5%) and sugar yield (5.4%) had highest genetic gains.

Genetic and phenotypic correlations coefficients between sugar yield and its attributes

High genetic and phenotypic correlations were detected between hand refractometer brix and Pol% cane (r_g = 0.998, r_p = 0.966) and between Pol% cane and juice purity (r_g = 0.624, r_p = 0.523) (Table 4). Correlations between fibre content and juice quality traits were low.

Table 4. Genotypic (upper row) and phenotypic (lower row) correlations for cane quality traits over crops and locations (2007 – 2010)

Trait	Sucrose content (Pol% cane)	Juice purity (%)	Fibre content (%)
Hand refractometer Brix (°)	0.998*[g]	0.66*	0.295
	0.966*[p]	0.17*	0.015
Sucrose content (Pol % cane)		0.624*	Not estimable
		0.523*	
Juice purity (%)			0.11
			-0.132*

* = significant if |r|> at least twice its standard error (Holland, 2006); [g] = genotypic correlation, [P] = phenotypic correlation.

The association between Pol% cane and fibre content could not be estimated.

DISCUSSION

Combined analysis of variance and genotype × environment interactions

The significant differences among the clones for all the traits indicate existence of genetic variation in the material. This suggests that opportunities for further improvement through selection do exist. Significant GL interactions for sucrose content (Pol% cane), fibre content, estimated sugar yield and brix yield indicated that the test environments discriminated the sugarcane clones differently. Similarly, significant GY effects for sucrose content indicated the inconsistent nature of this trait from one crop-year to another. However, no significant GL, GY and GLY interactions were detected for hand refractometer brix and juice purity suggesting that performance of clones in these traits was stable over the locations and crop-years. This suggests that the variance components for these traits could be estimated from one location and one crop-year data. Chang (1996) obtained similar results for juice purity in Taiwan.

Interactions of genotypes with environments (GEI) complicate the identification of superior genotypes by plant breeders during selection and cultivar recommendations. GEI have been reported to be a major problem in breeding programmes as they reduce progress from selection (Comstock and Moll, 1963; Mirzawan et al., 1993; Kimbeng et al., 2009). In de Sousa-Vierra and Milligan (2005) reported significant GL and GY interactions for Pol% cane. In a recent study, Shikanda et al. (2017) reported significant GL interactions for Brix in selected Kenyan clones. Similar results have been reported in other programmes (Tena et al., 2016; Singh et al., 2019). The results of our study suggest that more emphasis should be placed on testing clones in many locations than on testing ratoon crops within locations for reliable selection (Khan et al., 2004).

Variability, heritability and genetic advance

High GCV values suggest good prospects for improvement in the traits by selection. However, Burton (1952) suggested that the use of GCV together with heritability estimates gave a better understanding of heritable variation present in a population. The magnitude of heritability of a trait indicates the effectiveness of selection based on phenotypic observation of the trait (Hanson, 1963). Most quality characters had moderate heritability (>0.4) except sugar yield. Thus improvement of these traits through selection would be somewhat difficult but more effective than selecting for sugar yield *per se*. Butterfield and Nuss (2002) reported that effective selection of superior clones depended not only on heritability but also on genetic advance (GA). In this study, moderate GA values were associated with moderate heritability and GCV. The low heritability coupled with low GCV implies large influence of environmental and genotype × environment interaction effects on some traits and limited scope for their improvement. This explains the low expected genetic gain for cane quality traits. Singh (1993) observed that selection for traits with low heritability may be practically difficult. However, Cesnick and Vencovsky (1974) obtained moderate heritability for brix (0.52) and Pol% juice (0.54) and considered that breeding progress for these traits was still possible. The results of our study suggest that brix yield, sugar yield and sucrose content may respond positively to selection and offer opportunities for improvement in the breeding programme. The expected GA for sugar yield, sucrose content, brix yield and cane yield indicate considerable potential for improvement through breeding. Milligan et al. (1990b) and Singh et al. (2019) reported similar observations but with higher GA values.

Genotypic and phenotypic correlations among traits

The strong positive correlation between hand refractometer brix and sucrose content indicated that the former was a reliable indicator of sugar content in cane. Similar results were obtained by Kang et al. (1983), Milligan et al. (1990b) and Chang (1996). Sucrose content and purity of juice are tedious and costly to measure as they are determined in the laboratory while brix can easily be measured in the field with a hand refractometer and punch. Brix measures total soluble solids in cane juice and a high fraction of these solids contain sucrose thus brix is a useful correlated trait for selection. This study suggests that it is possible to identify varieties with high sucrose content and purity by selecting for high hand refractometer brix.

Conclusion

The study has demonstrated availability of genetic variability among the genotypes for the cane quality traits studied implying that genetic improvement through selection is possible. The presence of GL effects and absence of GY and GLY interactions suggests that sugarcane clones should be evaluated in more locations rather than years/seasons for effective selection. The high expected genetic gains for sucrose content, sugar yield and Brix yield indicates that selection and genetic improvement for these traits would be effective. Refractometer Brix is a reliable correlated trait when selecting for sucrose content.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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