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Assessment of popping ability of new tropical popcorn hybrids

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Abstract

Popcorn is an important snack food worldwide with significant nutritional benefits, including minerals and vitamins. However, adequate production of popcorn in Sub-Saharan Africa is hampered by lack of adapted varieties. This therefore calls for breeding investigations to develop new hybrids. The objectives of the study were to determine variability among hybrids for popping quality traits, gene action involved in conditioning of quality traits in popcorn hybrids and relationships among quality traits in popcorn. Random crosses were generated among inbred lines resulting in 119 experimental F_1hybrids with adequate seed. A commercial hybrid P618 grown under the same conditions was used as a standard check. The F_1 hybrids were grown at two locations. Two popping methods were used, the microwave and the hot air popping method. The data was analysed in SAS. Significant variability was observed among hybrids for popping quality traits ($p \leq 0.05$). The study identified 15 hybrids with superior popping quality. The hybrid 11POPH13 gave the highest flake volume (1 288 cm^3) and the highest popping fold (25.75). The check hybrid P618 had a flake volume of 1156 cm^3 and a popping fold of 23.1 and was ranked 16th for popping ability. Additive gene action was more prominent than non-additive action for all traits. A significant negative relationship was observed between flake volume and kernel size; while the number of unpopped kernels was positively correlated with kernel size ($p \leq 0.05$). Generally, genotype x method interaction effects on popping ability were negligible, indicating that there could be less complications in breeding new varieties.

Keywords: Combining ability, gene action, popcorn hybrids, popping quality.
Abbreviations: FV_flake volume, kn10g_number of kernels per 10 g, MC_grain moisture content, PF_popping fold, QS_quality score, G x E_genotype by environment interaction, GCA_general combining ability, SCA_specific combining ability.

Introduction

Popcorn (*Zea mays Everta*) is a popular snack consumed all over the world. It is a special type of flint maize which explodes when exposed to heat treatment and produce flakes. Despite increasing consumption of popcorn worldwide, adequate production in Sub-Saharan Africa is hampered by lack of varieties which are adapted to stress-prone environments which are prevalent in Africa. This, therefore, calls for breeding investigations to develop new adapted hybrids. There are not many programmes which emphasise popping ability in maize in Africa and many other developing countries. The breeding of popcorn is not given as much attention as dent maize. In South Africa, the only record of popcorn breeding efforts was in 1954 (Josephson et al., 1954) but this did not continue for various reasons. Currently, there are no popcorn breeding programmes in Southern Africa. Popcorn breeding progresses slower than that of dent maize; apart from grain yield, popcorn breeders need to consider additional quality traits which are unique to popcorn, such as popping expansion, freedom from hulls, and overall texture of flakes (Ziegler, 2001). To emphasize the slow breeding progress in popcorn, it is reported that in Brazil, by the end of 2006/2007 growing season, only 7 out of 278 maize cultivars available in the market were popcorn cultivars. The slow progress in popcorn breeding is in contrast with the high economic value of the crop (Sakın et al., 2005).

Popcorn is an economically important crop with possible multiplier effects like income generation for under-resourced communities, especially in developing countries. Developing countries such as India, Brazil and Turkey are gradually increasing popcorn production due to the economic value of the crop (Vieira et al., 2009; Vijayabharathi et al., 2009b; Oz and Kapar, 2011). Popcorn is recognized as a high value crop (Santacruz-Varela et al., 2004; Babu et al., 2006). In Brazil, the economic value of popcorn is reported to be three times that of dent maize (Moterle et al., 2012). In Africa, the economic importance of the crop has also been recognized (Iken and Amusa, 2010), but there are no local varieties hence the seed is imported which increases production costs. The price of popcorn in South Africa is also more than three times that of dent maize (personal observation). In October 2012, the average retail price of popcorn grain was R12 000 (approx. 1 200 US$ per ton, compared to R2200 (approx. 220 US$) per ton for dent maize. The relatively high prices of popcorn may be attributed to the fact that there are no locally adapted varieties of popcorn with desirable traits that can be produced locally despite growing consumption of popcorn in South Africa, especially in movie theatres across the country. Thus, if locally adapted varieties were developed, popcorn could provide cash income to resource-poor farmers in developing countries.

Popping quality is a critical factor for selection in popcorn. In addition to popping quality, yield is very important to justify value for cultivation and use. Therefore, there is need to quantify the relationship between popping quality traits and crucial agronomic traits. Popcorn quality depends on several factors and there are a number of indicators for the quality. Popcorn of high quality is free from pronounced hulls, has good kernel colour, popping expansion and flavour, and is fluffy and tender (Allred-Coyle, et al., 2000; Dickerson, 2003). Expansion volume is a quality trait of great importance to consumers, as unpopped kernels are sold by weight and popcorn flakes are sold by volume (Shimoni et al., 2002; Borras, 2006). The main indicators for popcorn expansion volume are the percentage or number of unpopped kernels and grain moisture content at the time of popping. Desirable popcorn varieties should have grain moisture content between 13 and 14.5 % at the time of popping (Ziegler, 2001) and a low number of non-popping kernels. Factors such as kernel size and shape have an impact on expansion volume (Karababa, 2006; Ertas et al., 2009). Popcorn kernels are classified commercially by size into small, medium and large kernelled varieties. Medium sized kernels are appealing to both home consumers and processors. Genetic variation in popcorn is also important because variety improvement depends on it through inheritance. In popcorn, yield has been found to have low heritability because it is highly influenced by environmental factors (Sleper and Poehlman, 2006). Popping expansion volume, on the other hand, has been reported to have high heritability estimates, ranging between 60% and 96% (Ziegler, 2001; Babu et al., 2006). Another challenge that could affect breeding for popcorn quality is the genotype x popping method interaction. There are three popping methods used to produce popcorn flakes, namely oil popping, microwave popping and hot air popping. These factors need to be considered in devising a viable popcorn breeding strategy. The objectives of the study were to determine variability among hybrids for popping quality traits, determine gene action involved in conditioning of quality traits in popcorn hybrids, determine relationships among quality traits in popcorn, and evaluate the effect of genotype by method interaction on quality traits on popping ability.

Results

Hybrid variation

There were significant differences between popcorn hybrids for both qualitative and quantitative traits. Hybrids which produced a large number of unpopped kernels were observed and the majority of them fell in the large kernel category (Fig 1). Some of the hybrids produced large hulls which are not desirable (Fig 1). The quality of popcorn flakes varied among hybrids. The flake colour when visually observed varied from white to yellow-brown (Fig 2). The colour of flakes produced by various hybrids was not uniform, and the shape also varied from butterfly to mushroom (Fig 2). There were hybrids which produced a mixture of butterfly and mushroom flakes. Large as well as small flakes were also observed. The analysis of variance shows differences among the 120 hybrids (Tables 1 and 2). Variation among hybrids was highly significant ($P \leq 0.01$) for all traits except grain moisture content ($P \leq 0.05$). There were significant differences among hybrids for flake volume, popping fold, and number of unpopped kernels, quality score and number of kernels per 10 g, which depicts kernel size. Flake volume across sites and across popping methods ranged from 734 cm^3 to 1288 cm^3. Popping fold ranged from 14.69 to 25.75. The number of unpopped kernels ranged from 19 to 121. Kernel size ranged from 49 to 90 kernels per 10 g. Grain moisture content ranged from 12% to 14%. Quality scores ranged from 1.2 to 3.1. The means and ranking for popping quality traits for the top 15 and bottom five hybrids are presented in Table 3. The hybrid POPH13 gave the highest flake volume (1 288 cm^3) and the highest popping fold (25.75). The check, hybrid P618 had the flake volume of 1 156 cm^3 and the popping fold of 23.1. The check was ranked 16th for popping ability. The top performing hybrid POPH13 yielded a flake volume that was 11% higher than the check hybrid. The frequency distribution of kernel size for hybrids (Fig 3) indicates that the majority of hybrids produced large kernels. Out of 120 hybrids, including the check, 63 had large kernels, 27 had medium kernels and 28 had small kernels. Two hybrids produced extra-large kernels, with the kernel count of less than 52 kernels per 10 g. The frequency distribution of flake volume for hybrids (Fig 4) indicates that 3 out of 120 hybrids produced a flake volume ranging from 701-800 cm^3, 11 hybrids 801-900 cm^3, 26 hybrids 901-1 000 cm^3, 37 hybrids 1 001-1100 cm^3, 35 hybrids 1101-1200 cm^3 and 8 hybrids 1201-1300 cm^3.

Genotype x environment interaction effects

The results in Table 4 indicate that site main effects were highly significant for flake volume, popping fold, number of unpopped kernels, quality score and number of kernels per 10 g ($P \leq 0.05$). Site effects were not significant for grain moisture content. Site x entry interaction effects were only significant for number of unpopped kernels and quality score. Site x female x male interaction effects were significant for quality score and number of kernels per 10 g ($P \leq 0.05$). The effect of popping method was significant for flake volume, popping fold, quality score, number of unpopped kernels and number of kernels per 10 g, but was non-significant for grain moisture content ($P \leq 0.05$). The hybrid x method interaction was not significant. Consequently, method x female interaction effects, method x male effects, method x female x male interaction effects, site x method x female effects, site x method x male effects and site x method x female x male interaction effects were not significant for all traits.

Gene action

The male and female main effects represent general combining ability (GCA) effects which are attributed to popcorn inbred lines used as male and female in crosses. The male x female interaction is equivalent to specific combining ability (SCA) effects. Therefore, partitioning of site x entry interaction effects show how each of these genetic components interacted with the sites for popping quality. Mean squares for GCA and SCA for popping quality traits are shown in Table 4. GCA due to females was highly significant for all traits ($P \leq 0.01$). GCA due to males was significant for flake volume, popping fold, number of unpopped kernels and number of kernels per 10 g. GCA due to males was non-significant for moisture content and quality score. SCA was significant for flake volume, popping fold and number of kernels per 10 g ($P \leq 0.05$). SCA was non-significant for number of unpopped kernels, moisture content and quality score. Proportions for GCA and SCA as shown in Table 5 indicate that GCA (85.99%) is important than SCA (14.01%) in conditioning of flake volume and popping fold. A similar trend where GCA is greater than SCA was also observed for number of unpopped kernels, quality score, moisture content and number of kernels per 10 g. Significant

Table 1. Mean squares (MS) for popping quality traits of 120 popcorn hybrids across two sites.

		Flake Volume		Popping Fold		Unpopped Kernels	
Source	DF	MS	Pr > F	MS	Pr > F	MS	Pr> F
Site	1	981671.58	<0.0001	392.6048	<0.0001	74533.941	<0.0001
Rep	1	29244.41	0.2649	11.70883	0.2646	67211.799	<0.0001
Method	1	1417002.13	<0.0001	566.8779	<0.0001	198937.86	<0.0001
Entry	119	96158.08	<0.0001	38.46585	<0.0001	3186.7229	<0.0001
Site X method	1	35652.39	0.2183	14.24880	0.2185	4792.8031	0.0099
Entry X method	119	21728.85	0.6906	8.692815	0.6900	717.8388	0.4766
Site X entry	119	28983.23	0.0649	11.59366	0.0648	835.4975	0.1311
Site X entry X method	119	21078.4	0.7591	8.431487	0.7588	568.7896	0.9344
Error	477	23468.07		9.386190		714.761	
R^2		0.70		0.70		0.70	
CV (%)		14.60		14.60		52.80	
Min		734.0		14.69		19	
Max		1288.0		25.75		121.0	
Mean		1046.5		20.93		50.7	

DF, degrees of freedom; MS, mean square; Pr > F, probability greater than F.

Fig 1. Un-popped kernels and amount of hulls produced by some popcorn hybrids.

and large proportion of total GCA was observed for all traits (Table 5). Heritability estimates for popping quality traits are shown in Table 1. In general heritability was large for flake volume (76%), popping fold (74%), number of kernels per 10 g (71%) and number of unpopped kernels (71%) which is consistent with observation of large additive effects.

Relationships among popping quality traits

Relationships among popping quality traits are presented in Table 6. The results indicate a significant strong correlation (r=1) for flake volume with popping fold. There was a significant weak and negative correlation (r= -0.31) between flake volume and popping fold with number of unpopped kernels as well as kernel size (r= -0.27). There was significant and strong positive correlation (r=0.56) between kernel size and number of unpopped kernels. Grain moisture content showed a significant weak and positive correlation with kernel size (r= 0.09) and number of unpopped kernels (r= 0.11). Correlation was not significant for flake volume and popping fold with grain moisture content.

Discussion

There were significant differences among hybrids for all traits except grain moisture content. Variability of hybrids that was observed in this study presents an opportunity to select for superior hybrids for popping ability. Significant variability among popcorn hybrids for quality traits were reported in previous studies (Daros et al., 2004; Sakın et al., 2005; Moterle et al., 2012). The non-significant variation of hybrids for grain moisture content indicates that there were non-significant differences in moisture content for the samples of popcorn grain that were popped. Therefore, moisture differences could not be used to explain the variation observed among hybrids for flake volume. The check hybrid was ranked 16th in terms of popping ability. There were therefore 15 experimental hybrids identified, which performed better than the check hybrid grown and popped under the same conditions. In addition to high popping expansion volume, popcorn flakes that are tender, uniformly coloured, freedom from tough hulls and objectionable flavours are desirable to consumers (Ziegler et al., 1984). As stated earlier, in this study, quality scores used ranged from 1 to 5, with the score of 1 being the best quality and 5 being the worst. According to the results of this study, quality scores ranged from 1.2 to 3.1. The check, hybrid P618 had a quality score of 1.6. Hybrids which performed well in terms of quality were identified. Six hybrids out of the top 15 had a quality score of 1.6 and below. Additive gene action was found to be more prominent in the conditioning of all quality traits. The proportions for GCA and SCA show that GCA (85.98%) is more important than SCA in the conditioning of flake volume and popping fold. A similar trend where GCA was greater than SCA was also observed for the number of unpopped kernels, quality score, moisture content and the number of kernels per 10 g. Since GCA is an indicator for additive gene action, results show that additive gene action is more important for the conditioning of popping quality traits. This suggests a good opportunity to select for popping quality traits. Previous studies have reported additive gene action for popping expansion volume (Pajic´ and Babic´, 1991; Pereira and Amaral Júnior do, 2001; Miranda et al., 2008) and popping fold (Li et al., 2007). There is no reference of previous studies on gene action for the number of unpopped kernels, number of kernels per 10 g and quality score, therefore our study forms the baseline. Successes in selection of popcorn varieties has been reported in the

Table 2. Mean squares for moisture content, quality score and kernel size of 120 popcorn hybrids across two sites.

		Moisture Content		Quality Score		Kernels per 10g	
Source	DF	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	37.748	0.0223	37.080	<0.0001	5916.040	<0.0001
Rep	1	9.931	0.2392	0.013	0.8375	21.309	0.4822
Entry	119	7.176	0.4776	0.612	<0.0001	337.868	<0.0001
Site X entry	119	7.354	0.4165	0.412	0.0333	79.771	<0.0001
Error		7.132		0.310		43.012	
R^2		0.51		0.68		0.85	
CV (%)		20.67		27.77		9.58	
Min		12.14		1.2		49.0	
Max		27.30		3.1		90.0	
Mean		12.90		2.0		68.0	

DF, degrees of freedom; MS, mean square; Pr > F, probability greater than F.

Fig 2. Variation in popcorn flakes showing flake shape, flake size and flake colour.

literature (Daros et al., 2004; Viana, 2009; Amaral Júnior do et al., 2010; Arnhold et al., 2010), which is in agreement with observation of large additive effects in the current study. All traits, except moisture content, were found to have high heritability scores. This indicates that inheritance of quality traits is due to additive gene action. Similar results were reported in previous studies (Lu et al., 2003; Babu et al., 2006; Li et al., 2007b). The results of this study indicate a significant strong correlation (r=1) for flake volume with popping fold. The study shows that hybrids with high flake volumes are the ones with high popping fold. These traits are directly correlated. Positive correlation between these traits was also reported by Li et al. (2007). There was a significant weak and negative correlation between flake volume and popping fold with the number of unpopped kernels as well as kernel size. The greater the number of unpopped kernels left after popping, the smaller the flake volume. According to Singh et al. (1997), unpopped kernels are not desirable because they do not contribute to expansion volume and they are considered defective. A negative relationship was observed between flake volume and popping fold with the number of kernels per 10 g. This means that small kernels do not pop well and hence fail to contribute significantly to flake volume and popping fold. Large and medium sized kernels are therefore preferred to achieve high expansion volumes. There was significant and strong positive correlation between the number of kernels per 10 g and the number of unpopped kernels. The relationship further indicates that the smaller the kernel size, the larger the number of unpopped kernels. Grain moisture content showed a significant weak and positive correlation with number of kernels per 10 g (r= 0.09) and number of unpopped kernels (r= 0.11). These results indicate that the grain moisture content of the large kernels was lower than that of the small kernels. The results indicate that site effects were highly significant for all traits ($P \leq 0.01$). Popping quality traits were therefore affected by different sites. The results concur with previous studies (Broccoli and Burak, 2004). The effect of popping method was significant for flake volume, popping fold and number of unpopped kernels. The results are in agreement with previous studies (Broccoli and Burak, 2004). However, the genotype x method interaction was not significant, indicating that popping ability would not be affected by the popping method (Table 2), which has positive implication for both breeding progress and processing at the household level. There was not any significant genotype x site interaction effects for quantitative traits (Table 2), suggesting that the hybrids were generally stable for popping ability. Nevertheless, a significant G x E was observed for the quality score and kernel size, indicating that quality performance would be affected by the location the popcorns were grown. Site x female x male interaction effects were significant for quality score and the number of kernels per 10 g. The females and males interacted with the environment for these traits. Method x female interaction effects, method x male effects, method x female x male effects, site x method x female effects, site x method x male effects and site x method x female x male interaction effects were not significant for all traits. This, therefore, suggests that genotype x environment interaction effects were generally minimal for popping quality traits indicating that the quality of popcorns would not depend on the environmental conditions.

Materials and Methods

Germplasm

Eighty-seven (87) popcorn inbred lines were generated using pedigree selection in the breeding program. The lines were derived from backcross progenies of flint x popcorn crosses, landrace populations from CIMMYT-Mexico, and from direct F2 population. The S5 to S7 generation lines were used to make crosses in the study. Random bi-parental crosses were generated among 87 popcorn inbred lines from the breeding program. Since there was no prior information regarding their flowering dates, the crosses which were made depended on the synchronisation of silk emergence and pollen shedding. This resulted in only 119 experimental F_1

Table 3. Means and rankings for popping quality traits for the top 15 and bottom 5 hybrids.

ENTRY	NAME	PEDIGREE	Flake Volume			Popping fold	Number of kernels		Grain Moisture content	Quality
			Relative to P618 (%)	Mean (cm^3)	Rank		Unpopped	Per 10g	(%)	(Score)
13	11POPH13	11MAK 2-11X51	111.35	1287.5	1	25.8	29.1	65.8	13.1	2.2
81	11POPH81	11MAK 2-55X29	108.10	1250.0	2	25.0	47.4	67.1	12.7	1.7
82	11POPH82	11MAK 2-59X49	106.48	1231.3	3	24.6	32.5	65.3	12.9	1.6
24	11POPH24	11MAK 2-20X77	105.40	1218.8	4	24.4	34.1	55.8	13.1	1.3
37	11POPH37	11MAK 2-35X32	105.40	1218.8	6	24.4	47.4	65.3	12.9	2.2
33	11POPH33	11MAK 2-33X5	105.40	1218.8	5	24.4	46.8	64.0	12.6	1.6
21	11POPH21	11MAK 2-18X8	104.86	1212.5	7	24.3	44.8	65.8	12.8	1.5
19	11POPH19	11MAK 2-13X72	103.91	1201.6	8	24.0	35.9	65.4	12.8	1.5
110	11POPH110	11MAK 2-83X48	102.70	1187.5	9	23.8	20.9	60.6	12.9	1.8
43	11POPH43	11MAK 2-38X10	102.43	1184.4	10	23.7	45.5	65.0	13.2	2.2
14	11POPH14	11MAK 2-11X64	101.62	1175.0	11	23.5	51.9	68.6	13.0	1.2
17	11POPH17	11MAK 2-12X62	101.35	1171.9	12	23.4	52.4	66.4	13.0	2.0
117	11POPH117	11MAK 2-71X47	101.35	1171.9	13	23.4	38.7	63.4	12.9	2.0
22	11POPH22	11MAK 2-18X49	101.08	1168.8	14	23.4	55.3	65.4	13.0	1.8
116	11POPH116	11MAK 2-11X36	101.08	1168.8	15	23.4	64.0	72.4	12.9	1.9
120	P618	P618	100.00	1156.3	16	23.1	53.9	64.0	13.0	1.6
Bottom Five Hybrids										
23	11POPH23	11MAK 2-19X55	70.54	815.6	116	16.3	24.8	52.1	12.7	1.7
87	11POPH87	11MAK 2-60X50	70.00	809.4	117	16.2	44.9	68.5	12.6	2.7
20	11POPH20	11MAK 2-14X81	65.40	756.3	118	15.1	29.8	50.0	12.8	2.2
108	11POPH108	11MAK 2-81X50	64.86	750.0	119	15.0	29.3	69.0	12.7	2.3
68	11POPH68	11MAK 2-50X22	63.51	734.4	120	14.7	18.8	49.1	12.9	2.3
LSD				160.02		3.20	31.83	11.83	3.70	0.93

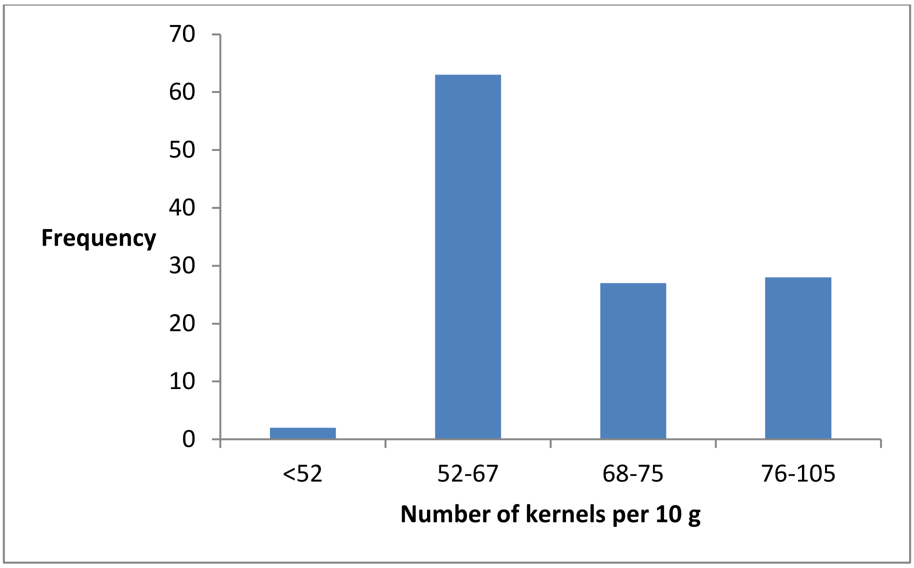

Fig 3. Frequency distribution of kernel size for 120 popcorn hybrids.

hybrids with adequate seed for the study. A widely grown hybrid P618 was adopted as the standard control (check) in all experiments.

Field experimental design and management

The experimental hybrids and a commercial check P618 were evaluated at Cedara, South Africa (Altitude 1066 m, Latitude 29.54°S; Longitude 30.26°E) and at the University of KwaZulu-Natal experimental farm (Ukulinga) (Altitude 812 m, Latitude 29.66°S; Longitude 30.40°E) during summer of 2011/2012. The trial was laid out as a randomised complete block design with two replications at each site. The trials were planted on 22 November 2011 at Ukulinga and 1 December 2011 at Cedara. The hybrids were managed using standard production practices recommended for maize in South Africa. The basal fertilizer 2:3:4 (6.7% N, 10%P, 13% K, and 0.5% Zn) was applied at the rate of 150 kg ha^{-1} at planting. Topdressing was done at 6 weeks after planting by applying LAN (28% N) at the rate of 150 kg ha^{-1}. Standard cultural practices were followed, including hand weeding, use of herbicides and insecticides. Trials at both sites were rain fed, with occasional supplementary irrigation at Ukulinga. The F_2 grain which was harvested from the trials was taken to the laboratory for popping tests.

Popping experiments

Popping experiments were performed on 119 experimental hybrids and the standard check hybrid P618 at the University of KwaZulu-Natal, Pietermaritzburg Campus in June 2012. Two popping methods were used, the microwave method and the hot air popping method. Samples were popped in two replicates for each method and each site (giving a total of 8 replicates for each genotype).

Microwave popping

Samples with a volume of 25 cm^3 each were measured in duplicate and placed in brown paper bags. Microwave popping was performed using a 900W Defy DMO 351 microwave oven, with 28 litre capacity and power of 230V. The samples were popped for three minutes as recommended in the previous study (Shandu, 2012).

Hot air popping

Samples of 25 cm^3 each were measured in duplicate and placed in a hot air popping machine. The Samsung hot air popcorn maker model SPC 900 was used for popping. Popcorn grain samples were popped for two minutes as recommended by the manufacturer.

Data collection and measurement

Grain moisture content of each sample was measured using the Dole® moisture tester. Kernel size was determined by measuring 10-g samples, and then counting the number of kernels per 10 g. The kernels were classified into small, medium and large. Popcorn kernels were classified by size in the following manner: 52-67 large, 68-75 medium, 76-105 small (Song et al., 1991; Singh et al., 1997; Allred-Coyle et al., 2000). Flake volume was measured using a 2 000 cm^3 measuring cylinder tapped once to settle popcorn flakes. The number of unpopped kernels was counted and recorded for each sample. Popping fold was calculated by dividing the flake volume by the original volume (25 cm$^{3)}$ of unpopped kernels. The quality score of popcorn flakes after popping was measured visually in a scale of 1-5 in terms of whiteness and uniformity of flake colour, flake size, uniformity of flake shape (mushroom or butterfly), tenderness and amount of hulls. The score of 1 was best quality and 5 the worst.

Data analysis

Data was analysed using Proc GLM procedure in SAS statistical package. Analysis of variance (ANOVA) was done to determine differences among inbred lines in terms of quality traits and to quantify GCA and SCA effects on the conditioning of quality traits. Means were compared by Duncan multiple range test (DMRT). The data was analysed as a factorial experiment because hybrids (entries) were partitioned into male, female and male x female interaction effects to determine gene action for popping ability. Variance component analysis was performed using REML tool in GenStat. Heritability estimates were done according to the equation V_G/V_P, where V_G = genetic variance and V_P = phenotypic variance. Frequency distribution for each trait was plotted.

Table 4. Mean squares (MS) for the genetic analysis of popcorn hybrids for popping ability.

		Flake Volume		Popping Fold		Unpopped Kernels		Grain Moisture Content (%)		Quality Score		Number of kernels per 10g	
Source of variation	DF	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	643430	<0.0001	257.29	<0.0001	51882	<0.0001	19.74	0.0996	30.12	<0.0001	4705.97	<0.0001
Rep	1	26087	0.2928	10.45	0.2925	66832	<0.0001	10.15	0.2371	0.01	0.8566	22.23	0.4754
Method	1	1222372	<.0001	489.07	<0.0001	160663	<0.0001	8.46	0.223	0.60	0.001	214.34	<0.0001
Female	47	81720	<.0001	32.69	<0.0001	1317	0.0009	11.39	0.0174	0.59	0.0015	259.25	<0.0001
Male	44	70226	<.0001	28.09	<0.0001	3113	<0.0001	7.80	0.3717	0.28	0.6071	79.94	0.0179
Female X male	20	56470	0.0007	22.59	0.0007	685	0.5130	9.04	0.1451	0.44	0.0552	67.70	0.0187
Site X female	46	35224	0.0222	14.09	0.0221	744	0.4046	11.37	0.0186	0.45	0.051	70.79	0.0126
Site X male	43	22241	0.5725	8.90	0.5723	829	0.2331	8.38	0.2910	0.31	0.4654	78.29	0.0215
Site X female X male	20	11461	0.9711	4.58	0.9711	655	0.5673						
Method X female	47	20554	0.7092	8.22	0.7086	788	0.3045						
Method X male	44	22380	0.5631	8.95	0.5629	687	0.5460						
Method X female X male	20	11626	0.9687	4.65	0.9687	552	0.7490						
Site X method X female	46	18089	0.8637	7.24	0.8632	513	0.9175						
Site X method X male	43	26241	0.2893	10.50	0.2891	638	0.6694						
Site X method X female X male	20	22259	0.5276	8.90	0.5275	433.99	0.9089						
Error		23518		9.41		715.69							
Heritability estimate		0.76		0.74		0.71		-0.03		0.61		0.91	
R^2		0.7		0.7		0.7		0.5		0.7		0.8	
CV (%)		14.7		14.7		52.8		0.7		27.9		9.6	
Mean		1046.0		20.9		50.6		12.9		2.0		69.0	

MS, mean square; DF, degrees of freedom; Pr>F, probability greater than F.

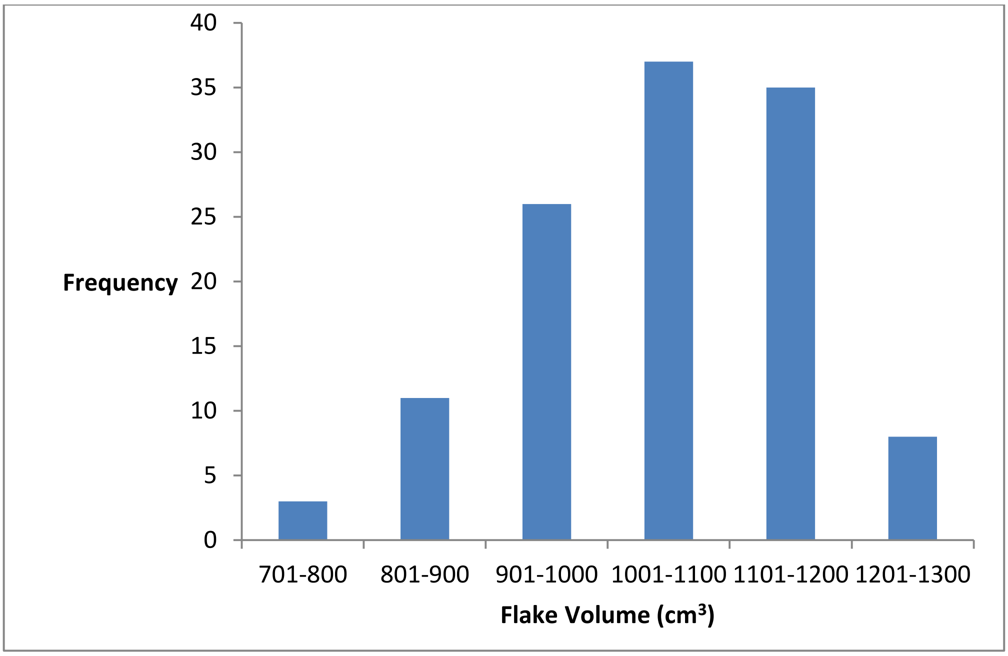

Fig 4. Frequency distribution of flake volume for 120 popcorn hybrids.

Table 5. Proportion (%) of GCA and SCA for popping quality traits.

	GCA			SCA
Variable	Female	Male	Total	
Flake Volume (cm^3)	47.65	38.34	85.99	14.01
Popping Fold	47.65	38.34	85.99	14.01
Unpopped Kernels (No.)	29.13	64.42	93.55	6.45
Grain Moisture Content (%)	37.71	47.51	85.21	14.79
Quality Score[§]	47.16	43.53	90.69	9.31
Kernels per 10g (No.)	43.65	49.42	93.07	6.93

[§] (Quality Score, 1 = best, 5 worst)

Table 6. Phenotypic correlations among popping quality traits.

Variable	Grain Moisture content (%)	Flake volume (cm^3)	Popping fold	Unpopped kernels (No.)	Kernels per 10 g (No.)
Grain moisture content (%)	1.00				
Flake volume (cm^3)	-0.05	1.00			
Popping fold	-0.05	1.00 **	1.00		
Unpopped kernels (No.)	0.11 *	-0.31 **	-0.31 **	1.00	
Kernels per 10g (No.)	0.09 *	-0.27 **	-0.27 **	0.56 **	1.00

**,* = r value significant at $P \leq 0.01$ and $P \leq 0.05$, respectively.

Conclusion

Overall, the study found significant variability among hybrids for popping quality traits, which presents an opportunity for selection of hybrids with good popping ability. The top 15 hybrids would be recommended for further testing. Additive gene action was more predominant over the non-additive action for all popping quality traits. This creates an opportunity to effectively improve these traits through selection. Popping quality traits were found to be highly heritable in line with previous studies (Lu et al., 2003; Babu et al., 2006). A significant positive relationship was observed between the number of kernels per 10 g and the number of unpopped kernels. Although both site and popping method main effects were significant for popping ability, results do not support significant role of G x E. The effect of popping method was significant for flake volume, popping fold and the number of unpopped kernels. The method x hybrid interaction effects were not significant, implying that popping quality would not depend on the popping method. Entry x site x method, entry x site, and entry x method interaction were not significant for all quantitative traits. The results contrast with previous findings which reported significant method x genotype interaction.

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