Heterosis and Combining Ability Analysis for Coffee Quality in Diallel Crosses of Diverse Coffee (*Coffea arabica* L.) Parents in Origin

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Abstract: In view of the lack of study on heterosis and combining ability in coffee quality breeding programs of Ethiopia, the present study was conducted on six distinct *Coffea arabica* L. lines in origin and 12 hybrids made among them in half diallel fashion to evaluate coffee hybrids for Sidamo coffee quality, to estimate heterosis effects for different coffee quality parameters and to determine the gene actions involved in controlling the quality parameters. Coffee samples were prepared during the 2002/2003 cropping season from hybrids and parents planted at the Wonago Agricultural Research Sub-station (06^o 03' N and 38^o 03' E) in Sidamo following a randomized complete block design. The coffee samples were evaluated for Sidamo coffee quality at the National Coffee and Tea Liquoring and Inspection Center. The hybrids exhibited positive and significant heterosis that ranged from 14 to 33% relative to the commercial Sidamo coffee variety for most of the parameters studied. Two hybrids; 7440 x 75227 and 744 x 1681, evaluated as having highly acceptable Sidamo coffee quality were the best specific combinations and heterotic for all coffee quality parameters. Two Kaffa coffee parents namely, 7440 and 75227 were good combiners and produced hybrids better than the commercial Sidamo coffee variety for Sidamo coffee quality. Predominance of non-additive gene actions were detected for acidity, body, cup quality and overall Sidamo coffee quality and additive gene action was important for the expression of flavor. The results of this study suggested selection of parents on the basis of their quality performance regardless of their origin and crossing among them is an appropriate breeding method to improve target region coffee quality. This study was conducted using coffee parents obtained only from two coffee growing regions and the results might not be sufficient to reach at a general conclusion for all coffee types in Ethiopia. However, the present findings can be used as good evidence for the possibility of using coffee lines of diverse origin and their crosses to improve unique coffee quality of the target region.

Keywords: Additive Gene Action; *Coffea arabica*; Combining Ability; Heterosis; Non-additive Gene Action; Sidamo Coffee Quality

1. Introduction

Many factors contribute to determine the quality of coffee, mainly non-genetic (harvest and post harvest, pedo-climatic effect and physiology) and genetic variations. Regarding cup quality, the geographical origin of the plants within the genetic groups is the main factor of variability (Moschetto *et al.,* 1996). In terms of genetics, significant genetic variability for bean chemical composition and organoleptic characteristics exists at both the between and within species levels (Thierry *et al.,* 2006). As a consequence, genetic gains for quality are assumed to be achieved either by interspecific (between species of coffee parents) or within species hybridization strategies.

There is a persistent demand for quality coffee in the world. As a result, coffee quality is the most important factor that determines the desirability and market value of coffee. However, coffee producing countries as a whole have been emphasizing more on yield increase and less on quality, and only recently have, many coffee growing countries, started giving emphasis for quality coffee production (Srinivasan and Vishveshwara, 1978; Walayro, 1983, Moreno *et al*., 1995). Coffee price in the international market has always been fluctuating affected mainly by overproduction. In this situation, improvement of coffee quality could provide the coffee chain with a new impetus. Therefore, it is necessary to integrate coffee quality as a main target in the breeding programs as opposed to its previous status as a secondary selection criterion.

The quality requirements in coffee are both voluntary as well as mandatory. Sanitary and phytosanitary measures under the World Trade Organization (WTO) agreement are mandatory. Besides, the consumers in most of the developed countries are preferring specialty coffees identified with distinct cup qualities or distinct production methods. The market share for specialty coffees is increasing at a steady rate. Specialty coffees are good opportunity for the growers as they fetch premium prices. In addition, coffee quality differs to everyone depending on their upbringing as well as their society. For instance, the Germans and Swedes prefer lighter and more acidic coffee than the Italians and Saudi Arabian Sheiks who like the most expensive of coffees, known as Bun Harrari or Khawa Harrari, which comes from the Eastern highlands of Ethiopia (Thierry *et al.,* 2006).

Ethiopia has diverse and favorable environments in five major coffee growing regions (Onwueme and Sinha, 1991) for the production of Arabica coffee and coffee types with unique flavor and taste, variable specialty distinguished as Sidamo; Yirgachefe; Hararghe, Gimbi and Limu types (Workafes and Kassu, 2000). These specialty coffees will have good opportunity in the international market to fetch premium prices as far as their conspicuous unique aroma and flavor are maintained and/or improved.

In Ethiopia coffee hybridization program was started in 1978 by crossing coffee lines from similar origin (Mesfin, 1982; Mesfin and Bayetta, 1983) and from different origins (Bayetta *et al*., 2007; Wassu *et al*., 2007) with the objective of increasing clean coffee yield. However, coffee quality genetic studies have not been conducted on crosses of coffee parents having different or similar origin acclaimed for different coffee qualities. This remain as one of the bottlenecks in selection of coffee parents for coffee crossing programs to produce heterotic coffee

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hybrids suited for different coffee growing regions without blending their fine coffee quality. This implies that genetic study, evaluation and comparison of coffee qualities of hybrids obtained from diverse coffee parents in origin are necessary. Therefore, the present study was conducted with the objectives i) to evaluate coffee hybrids generated from parents diverse in origin for Sidamo coffee quality, ii) to estimate the magnitude of heterosis effects of hybrids for different coffee quality parameters and iii) to determine the gene actions involved in controlling coffee quality parameters.

2. Materials and Methods

The materials comprised of six distinct lines, three from southwestern Ethiopia (Kaffa type) namely, 744 (P1), 7440 (P2) and 75227 (P3) and two from southeastern Ethiopia (Sidamo type), 1377 (P4) and 1681 (P5) and their 10 hybrids made among them in the half-diallel fashion (Griffing's method 2 Model 1) for genetic analysis. A third Sidamo coffee type; 2970 (P6), with its two hybrids obtained by crossing it with the two Sidamo coffee parents from adjacent Sidamo x Sidamo crosses experimental block was included to compare the coffee hybrids for Sidamo coffee quality. The Kaffa parental lines were selected for their high or medium yielding ability and coffee berry disease resistance and the ones from Sidamo were selected for possessing typical flavor of Sidamo, high yielding and distinct differences from the former parents in origin.

Seeds of the six selfed parental lines and their 12 hybrids were sown in polythene tubes filled with a finely prepared mixture of top-soil, well rotted coffee husk and sand (6:2:1 ratio) in November 1996. Seven months old seedlings were planted in the field in August 1997 at the Wonago Agricultural Research Sub-station (06^{o} 03' N and 38^{o} 03' E) that represents the Sidamo coffee growing locations laid down in a randomized complete block design (RCBD) in four replications, five trees per plot with 2 m x 2 m spacing. All agronomic management practices were uniformly applied to the plots following the recommendation from the Jima Agricultural Research Center. The experimental plots were maintained under temporary shade trees known as *Sesbania sesban* planted with 4 m x 4 m spacing.

Red fresh cherries were selectively harvested during the 2002/2003 cropping season from each plot and wet processed following the standard processing procedures. These wet processed coffee samples were provided to the National Coffee and Tea Liquoring and Inspection Center in February 2003 for blind test to determine the performances of the coffee genotypes for Sidamo coffee quality. Group of professional and experienced cuppers evaluated the coffee samples for the Sidamo coffee beans for shape and make, color and odor that accounted for 15% each for the former two and 10% for the latter which summed up to 40% and determined the raw coffee quality value. The raw coffee beans quality parameters were analyzed following internationally accepted procedure. Cup quality (organoleptic quality measurement) which included acidity, body and flavor each accounted for 20% and summed to 60%. Organoleptic analysis relies overall on sensory evaluation of beverage prepared from roasted coffee beans and grinded by rosters using sample roasting machine and standard grinder, respectively, which were prepared in a set of cups, mixed with freshly boiled water and tasted by group of cuppers when the liquid has cooled to a palatable temperature. Raw and cup quality values of the coffee samples were summed and determined the overall Sidamo coffee quality and acceptability in the international coffee market. In addition, screen and moisture analyses were conducted from green beans samples at the laboratory to determine bean size and moisture contents, respectively. The average values of samples for each genotype for each coffee quality parameter were reported to the Jima Agricultural Research Center which was considered for statistical analysis.

Data analysis was conducted using MSTAT-C of Michigan University statistical soft ware (MSTAT Development Team, 1986). The data from the F_1 crosses and parents were subjected to analysis of variance for RCBD. Further genetic analysis was performed for the coffee quality parameters in which statistically significant differences existed among genotypes. To study the performance of hybrid for each cross combination (P1 x P2), the mid parent value (MP), absolute mid parent heterosis (MPH) and relative mid-parent heterosis (MPH%), better parent heterosis (BPH%) and standard heterosis (SH%) were calculated as follows: MP = (P1+P2)/2; MPH = HY-MP; MPH(%) = (MPH/MP) x 100; BPH = HY-BP; BPH(%) = (BPH/BP) x 100, SH = HY-SV and SH(%) = (SH/SV) x 100 where MP is mean of the two parents of the hybrid, BP and SV are better parent and commercial Sidamo coffee variety values, respectively, and HY is hybrid value. The significance of heterosis was tested by comparing mean differences between F_1, MP, BP and SV means to LSD values derived from genotypes (F_1 and parent) analysis of variance. The genetic analysis was performed according to the Griffing's method 2 Model 1 (Griffing, 1956).

3. Results

3.1. Variation and Performances of Parents and Hybrids

Highly significant differences among genotypes (coffee parents and hybrids) were detected for acidity (ACD) and cup value (CUV) and significant ($P < 0.05$) differences for moisture content (MC), body (BOD), flavor (FLV%) and overall coffee quality (OVQ). However, only significant ($P < 0.05$) differences of the parents were observed for MC and ACD among the parameters studied (Table 1).

The mean coffee bean sizes of genotypes were nearly equivalent and statistically non-significant differences were observed. The mean coffee bean sizes calculated as 96 and 97% of the beans screen size No. 14 for all groups of coffee parents and hybrids. Genotypes bean samples mean moisture contents ranged from 8.9 to 10.2%. Kaffa x Kaffa and Sidamo x Sidamo coffee hybrids had the highest beans mean moisture content of 9.9% followed by Kaffa coffee parents beans mean moisture content of 9.7%. The Kaffa x Sidamo coffee hybrids and Sidamo coffee parents registered the lowest beans mean moisture contents of 9.4 and 9.3%, respectively.

The overall mean coffee quality values of the hybrids considerably exceeded the parents, particularly overall mean Sidamo coffee quality value of Kaffa x Kaffa coffee hybrids exceeds all groups of genotypes overall mean values (Table 2). Both the Kaffa and Sidamo coffee parents had equal mean Sidamo raw coffee quality value of 33% and the Kaffa x Kaffa, and Kaffa x Sidamo hybrids had equal mean Sidamo raw coffee quality value of 37%. The mean Sidamo raw coffee quality value for the Sidamo x Sidamo hybrids was 36%. All groups of hybrids (Kaffa x Kaffa, Sidamo x Sidamo and Kaffa x Sidamo) mean Sidamo raw coffee quality values ranked as better than usual Sidamo coffees raw quality values. The Sidamo coffee parents, Sidamo x Sidamo and Kaffa x Sidamo hybrids performed mean Sidamo coffee cup quality value of 31% while the Kaffa x Kaffa hybrids and the Kaffa coffee parents had 36 and 32%, respectively.

Table 1. Mean squares due to quality parameters of *Coffea arabica* L. parents and hybrids.

	Parents plus hybrids			CV	Parents alone		
Quality parameter	Genotype (14)	Error (42)	SE	(%)	Genotype (5)	Error (15)	SE
Moisture content (%)	0.57 *	0.22	0.47	4.88	0.73 *	0.19	0.15
SB > Scr. 14	4.02	2.22	1.49	1.54	8.57	2.37	0.51
Shape and make (%)	5.71	3.19	1.79	13.59	7.27	4.97	0.59
Color (%)	5.28	4.28	2.07	16.09	1.57	4.57	0.55
RV (%)	19.02	11.66	3.14	9.49	13.40	17.95	1.08
Acidity (%)	25.95 **	7.26	2.69	21.85	31.67 *	6.67	0.96
Body (%)	7.70 *	2.94	1.71	17.93	10.00	3.75	0.59
Flavor (%)	3.66 *	1.82	1.35	13.74	5.07	2.52	0.45
CUV (%)	87.20 **	25.39	5.04	15.94	107.07	31.27	1.84
OVQ (%)	83.79 *	29.61	5.44	8.01	75.17	50.32	1.86

**, ** = Significant at P < 0.05 and P < 0.01, respectively; Number in parenthesis are degrees of freedom; SB > Screen No. 14 = Percentage of beans size > Screen No. 14; RV = Raw coffee quality value; CUV = Cup coffee quality value; OVQ = Overall coffee quality value; SE = Standard Error; CV = Coefficient of variation*

The Kaffa coffee parent; P1 and Kaffa x Sidamo hybrid; P1 x P5 registered the highest Sidamo raw coffee quality values among the parents and genotypes, respectively. The mean Sidamo coffee cup quality values registered for the Kaffa coffee parent (38%) and the P2 x P3 or Kaffa x Kaffa (42%) hybrid were the highest among the coffee parents and the genotypes., respectively. The Sidamo x Sidamo coffee hybrid; P4 x P5 (21%) and Kaffa coffee parent; P1 (23%) registered the lowest Sidamo coffee cup quality values. The two hybrids; P2 x P3 (Kaffa x Kaffa) and P1 x P5 (Kaffa x Sidamo) registered highly acceptable overall Sidamo coffee quality values (≥ 75%). One Kaffa coffee parent (P1) and one Sidamo x Sidamo hybrid (P4 x P5) performed < 60% of the overall Sidamo coffee quality values which was internationally unacceptable (Table 2).

3.2. Estimate of Heterosis for Coffee Quality Parameters

Heterosis relative to mid and better parent was computed and the results are presented in Table 3. The coffee hybrids exhibited mid and better parent heterosis for all the coffee quality parameters except for odor. The mid parent heterosis for shape and make ranged from -7.69 to 34.33%, while for color and raw coffee quality ranged from -1.41 to 27.27% and from -2.39 to 20.62%, respectively. Mid parent heterosis for body, flavor, acidity and cup value ranged from -33.33 to 23.09%, -20 to 23.08%, -42.86 to 63.64% and -32.68 to 32.08%, respectively, while for the overall coffee quality, it ranged from -13.13 to 22.28%. Five hybrids for Sidamo raw coffee quality, four for overall Sidamo coffee quality and for shape and make, three for color, two for acidity and one hybrid for body, flavor and Sidamo coffee cup quality exhibited positive and significantly (P < 0.01 and/or P < 0.05) different mid parent heterosis. On the other hand, two hybrids for acidity, flavor, Sidamo coffee cup quality, overall Sidamo coffee quality and one hybrid for body registered negative and significantly (P < 0.01 and/or P < 0.05) different mid parent heterosis.

Better parent heterosis for shape and make, color and Sidamo raw coffee quality ranged from -14.29 to 25%, -2.78 to 25% and -4.67 to 14.17%, respectively. Better parent heterosis for body, flavor, acidity and Sidamo coffee cup quality ranged from -33.33 to 14.29%, -20 to 14.29%, -50 to 50% and -36 to 16.67%, respectively, while it ranged from 15.69 to 17.19% for the overall Sidamo coffee quality (Table 3). Three hybrids for overall Sidamo coffee quality; two for shape and make and acidity; and one hybrid for color, Sidamo raw coffee quality and flavor exhibited positive and significantly (P < 0.01/P < 0.05) better parent heterosis. On the other hand, five hybrids for flavor, three for acidity, two for Sidamo coffee cup quality and one hybrid for body showed negative and significantly (P < 0.01/P < 0.05) better parent heterosis. Positive and significantly better parent heterosis was registered for the Kaffa x Kaffa hybrids while negative and significantly better parent heterosis were recorded for Kaffa x Sidamo and Sidamo x Sidamo hybrids (Table 3).

Table 2. Mean performance of coffee (*Coffea arabica* L.) parents and their 12 hybrids grown at Wonago for 11 coffee quality parameters.

Accessions*	MC (%)	SB > Scr.14 (%)	SM (15%)	CL (15%)	RV (40%)	ACD (20%)	BOD (20%)	FLV (20%)	CUV (60%)	OVQ (100%)	Remark
744 (P1)	9.9	99	14	12	36	8	7	8	23	59	4
7440 (P2)	9.1	95	12	12	34	15	10	10	35	69	3
75227 (P3)	10.0	95	10	10	31	15	12	12	38	69	3
Mean of Kaffa coffee	9.7	96	12	11	33	13	9	10	32	65	
1377 (P4)	9.9	97	14	12	35	13	10	10	33	68	3
1681 (P5)	9.0	98	12	12	34	10	10	10	30	64	3
2970 (P6)	9.0	92	12	8	30	10	10	10	30	60	3
Mean of Sidamo coffee	9.3	96	13	11	33	11	10	10	31	64	
744 x 7440 (P1 x P2)	9.8	98	12	12	34	15	10	10	35	69	3
744 x 75227 (P1 x P3)	10.2	97	15	14	39	13	10	10	33	72	2
7440 x 75227(P2 x P3)	9.6	95	14	13	37	15	13	13	42	79	1
Mean of K x K hybrids	9.9	97	14	13	37	14	11	11	36	73	
1377 x 1681 (P4 x P5)	9.7	97	14	12	36	7	10	8	21	57	4
1377 x 2970 (P4 x P6)	10.0	95	12	12	34	15	10	10	35	69	3
1681 x 2970 (P5 x P6)	10.0	98	15	12	37	15	10	10	35	72	2
Mean of S x S hybrids	9.9	97	14	12	36	12	10	9	31	67	
744 x 1377 (P1 x P4)	9.2	98	13	12	35	13	10	10	33	68	3
744 x 1681 (P1 x P5)	10.1	98	15	15	40	15	10	10	35	75	1
7440 x 1377 (P2 x P4)	9.9	98	15	13	38	8	7	8	23	61	2
7440 x 1681 (P2 x P5)	9.2	96	12	12	34	10	10	10	31	64	3
75227 x 1377 (P3 x P4)	9.2	97	14	13	37	13	10	10	33	70	2
75227 x 1681 (P3 x P5)	8.9	96	15	14	39	12	10	10	32	71	2
Mean of K x S hybrids	9.4	97	14	13	37	12	9	10	31	68	

** MC = Moisture content; SB > Scr.14 = Percentage of beans' size > Screen no.14; SM = Coffee beans shape and make; CL = Coffee beans' color; RV = Raw coffee beans' quality value; ACD = Acidity; BOD = Body; FLV = Flavor; CUV = Cup quality value; OVQ = Overall coffee quality value; K x K, S x S and K x S = Hybrids obtained from Kaffa x Kaffa, Sidamo x Sidamo and Kaffa x Sidamo coffee parents, respectively; Note that 1, 2, 3 and 4 under remark indicate raw coffee quality better than the usual Sidamo coffee and highly acceptable cup quality; raw coffee quality better than the usual Sidamo coffee and acceptable cup quality; acceptable cup quality; and raw coffee quality better than the usual Sidamo coffee but cup quality not acceptable, respectively.*

Table 3. Percentage of mid and better parent heterosis for eight coffee quality parameters of 12 coffee hybrids of diverse parents in origin grown at Wonago as evaluated for Sidamo coffee quality.

Parameter	Heterosis†	P1 x P2	P1 x P3	P1 x P4	P1 x P5	P2 x P3	P2 x P4	P2 x P5	P3 x P4	P3 x P5	P4 x P5	P4 x P6	P5 x P6
Coffee beans shape and	MPH (%)	-7.69	23.29**	-7.14	15.38	25.37**	15.38	0.00	15.07	34.33**	7.69	-7.69	25.00**
	BPH (%)	-14.29	7.14	-7.14	7.14	16.67	7.14	0.00	0.00	25.00**	0.00	-14.29	25.00**
make (15%)	LSD (0.05) = 2.59, and LSD (0.01) = 2.99												
Coffee beans color (15%)	MPH (%)	1.41	27.27*	-1.41	26.76*	16.42	8.33	0.00	13.43	25.37*	0.00	20.00	20.00
	BPH (%)	2.86	20.00	-2.78	25.00*	8.33	8.33	0.00	5.56	16.67	0.00	0.00	0.00
	LSD (0.05) = 3.00, and LSD (0.01) = 3.46												
Raw coffee quality value	MPH (%)	-2.39	17.59**	-1.89	14.83*	14.43*	10.14	0.00	11.68	20.62**	4.35	4.62	15.63*
	BPH (%)	-4.67	9.35	-2.80	12.15	8.82	8.57	0.00	4.76	14.71*	2.86	-2.86	8.82
(40%)	LSD (0.05) = 4.95, and LSD (0.01) = 5.72												
Acidity (20%)	MPH (%)	28.57	14.29	23.08	63.64**	0.00	-41.18**	-20.00	-5.88	-6.67	-42.86**	28.57	50.00**
	BPH (%)	0.00	-11.11	0.00	50.00**	0.00	-44.44**	-33.33**	-11.11	-22.22	-50.00**	12.50	50.00**
	LSD (0.05) = 3.90, and LSD (0.01) = 4.51												
Body (20%)	MPH (%)	20.00	9.09	20.00	20.00	23.08*	-33.33*	0.00	-7.69	-7.69	0.00	0.00	0.00
	BPH (%)	0.00	-14.29	0.00	0.00	14.29	-33.33*	0.00	-14.29	-14.29	0.00	0.00	0.00
	LSD (0.05) = 2.48, and LSD (0.01) = 2.87												
Flavor (20%)	MPH (%)	11.11	1.69	11.11	11.11	23.08*	-20.00*	0.00	-7.69	-7.69	-20.00*	0.00	0.00
	BPH (%)	0.00	-14.29*	0.00	0.00	14.29*	-20.00*	0.00	-14.29*	-14.29*	-20.00*	0.00	0.00
	LSD (0.05) = 1.95, and LSD (0.01) = 2.26												
Coffee cup quality value	MPH (%)	20.69	8.70	18.34	32.08*	13.64	-32.68**	-3.59	-6.98	-7.32	-32.63**	10.53	16.67
	BPH (%)	0.00	-13.04	0.00	16.67	8.70	-34.29**	-10.48	-13.04	-17.39	-36.00**	5.00	16.67
(60%)	LSD (0.05) = 7.30, and LSD (0.01) = 8.44												
Overall coffee quality (100%)	MPH (%)	8.09	13.32*	7.37	22.28**	14.01**	-10.95*	-3.76	2.19	6.27	-13.13*	7.81	16.13**
	BPH (%)	0.00	4.83	0.00	17.19**	14.01**	-11.59*	-7.25	1.45	2.42	-15.69**	1.47	12.50*
	LSD (0.05) = 7.88, and LSD (0.01) = 9.11												

‡*, ** = *Significant at P < 0.05 and P < 0.01, respectively; MPH = Mid parent heterosis; BPH = Better parent heterosis; P1 = 744; P2 = 7440; P3 = 75227; P4 = 1377; P5 = 1681 and P6 = 2970. The significance of the percent heterosis was tested by comparing the differences between* F_1, *MP and BP means to the LSD values derived from genotypes (*F_1 *and parent) analysis of variance.*

Table 4. Percentage standard heterosis for seven coffee quality parameters of 12 coffee hybrids of diverse parents in origin grown at Wonago as evaluated for Sidamo coffee quality.

Hybrid‡	Color (15%)	Raw value (40%)	Acidity (20%)	Body (20%)	Flavor (20%)	Cup value (60%)	Overall quality (100%)	Remark
744 x 7440 (P1 x P2)	0	-3	13	0	0	5	1	Cup: acceptable
744 x 75227 (P1 x P3)	17	11	0	0	0	0	6	Raw: better than usual Sidamo coffee, Cup: acceptable
7440 x 75227(P2 x P3)	8	6	13	33**	33*	25**	16**	Raw: better than usual Sidamo coffee, Cup: highly acceptable
Mean of K x K hybrids	8.33	4.76	8.33	11.11	11.11	10.00	7.35	
1377 x 1681 (P4 x P5)	0	3	-50**	0	-20*	-36**	-16**	Raw: better than usual Sidamo coffee, Cup: not acceptable
1377 x 2970 (P4 x P6)	0	-3	13	0	0	5	1	Cup: acceptable
1681 x 2970 (P5 x P6)	0	6	13	0	0	5	6	Raw: better than usual Sidamo coffee, Cup: acceptable
Mean of S x S hybrids	0	2.86	-8.00	0	-6.67	-8.33	-3	
744 x 1377 (P1 x P4)	-3	-1	0	0	0	0	0	Cup: acceptable
744 x 1681 (P1 x P5)	25*	14*	13	0	0	5	10	Raw: better than usual Sidamo coffee, Cup: highly acceptable
7440 x 1377 (P2 x P4)	8	9	-38**	-33**	-20*	-31**	-10	Raw: better than usual Sidamo coffee, Cup: acceptable
7440 x 1681 (P2 x P5)	0	-3	-25	0	0	-6	-6	Cup: acceptable
75227 x 1377 (P3 x P4)	6	5	0	0	0	0	3	Raw: better than usual Sidamo coffee, Cup: acceptable
75227 x 1681 (P3 x P5)	17	11	-13	0	0	-5	4	Raw: better than usual Sidamo coffee, Cup: acceptable
Mean of K x S hybrids	8.80	5.87	-10.42	-5.56	-3.33	-6.17	0.16	
Mean of hybrids	2.31	4.60	-3.36	1.85	1.11	-1.50	1.50	
LSD (0.05)	3.00	4.95	3.90	2.48	1.95	7.30	7.88	
LSD (0.01%)	3.46	5.72	4.51	2.87	2.26	8.44	9.11	

‡*, ** = *Significant at P < 0.05 and P < 0.01, respectively; K x K, S x S and K x S = Hybrids obtained from Kaffa x Kaffa, Sidamo x Sidamo and Kaffa x Sidamo coffee parents, respectively.*

Standard heterosis relative to the Sidamo coffee variety (1377) was calculated to observe the advantage of the hybrids over the commercial variety and the results are presented in Table 4. Six and eight hybrids exhibited heterosis of -3 to 25% and -3 to 14%, respectively, relative to the commercial Sidamo coffee variety (1377) for color and Sidamo raw coffee quality, respectively. Only the Kaffa x Sidamo hybrid registered positive and significantly (P < 0.05) different standard heterosis for color (25%) and for Sidamo raw coffee quality (14%). Two hybrids, (Kaffa x Kaffa and Kaffa x Sidamo), registered significantly (P < 0.05) different positive and negative standard heterosis of 33 and -33%, respectively, for body. Similarly, the Kaffa x Kaffa hybrid registered a positive and significantly (P < 0.01) different standard heterosis of 33% while the P2 x P4 (Kaffa x Sidamo) and P4 x P5 (Sidamo x Sidamo) hybrids registered negative and significantly (P < 0.05) different standard heterosis of -20% for flavor. Five and eight hybrids exhibited positive standard heterosis for Sidamo coffee cup quality and the overall Sidamo coffee quality which ranged from -36 to 25% and -16 to 16%, respectively. Only the Kaffa x Kaffa hybrid exhibited a positive and a highly significant standard heterosis of 25 and 16% for Sidamo coffee cup quality and the overall Sidamo coffee quality, respectively.

3.3. Combining Ability for Coffee Quality Parameters

Variations due to both the general (GCA) and specific (SCA) combining ability effects were significant (P < 0.01/P < 0.05) for acidity, body and cup value whereas only the effects of GCA and SCA were significant (P < 0.01/P < 0.05) for flavor and the overall Sidamo coffee quality, respectively. The calculated variance component ratios for all organoleptic parameters (acidity, flavor and body), cup value and overall value were less than unity (Table 5).

In this study, the two Kaffa coffee parents; P2 (7440) and P3 (75227) possessed positive GCA effects for acidity, body, flavor and cup value whereas one Sidamo coffee parent; P5 (1681) had negative GCA effects for all these coffee quality parameters. One Kaffa, P1 (744) and one Sidamo, P4 (1377) coffee parents had positive GCA effects only for cup value and acidity, respectively, and negative GCA effects for all other coffee quality parameters (Table 6).

Table 5. General (GCA) and specific (SCA) combining ability mean squares for five coffee organoleptic quality parameters in a 5 x 5 diallel cross of coffee (*Coffea arabica* L.).

Organoleptic parameter	Mean square			Component due to		Variance ratio of GCA to SCA
	GCA (4)	SCA (10)	Error (28)	GCA	SCA	
Acidity (20%)	24.17*	26.67**	7.26	2.42	19.41	0.13
Body (20%)	9.88*	6.83*	2.94	0.99	3.89	0.26
Flavor (20%)	5.94*	2.75ns	1.82	0.59	0.93	0.63
Cup value (60%)	88.96*	86.5**	25.39	9.08	61.11	0.15
Overall value (100%)	60.04ns	90.08**	29.61	4.35	60.47	0.07

**, ** = Significant at P < 0.05 and P < 0.01, respectively; ns = Not significant at P > 0.05; Number in parenthesis = Degrees of freedom.*

Table 6. Estimate of general combining ability (GCA) effect for five coffee organoleptic quality parameters of five coffee (*Coffea arabica* L.) parents.

Parent	Acidity (20 %)	Body (20%)	Flavor (20%)	Cup value (60%)
744 (P1)	-0.10ns	-0.50*	-0.42ns	0.99**
7440 (P2)	0.62**	0.14ns	0.11ns	0.96**
75227 (P3)	1.33**	1.10**	0.87**	3.15**
1377 (P4)	0.33ns	-5.70**	-0.42ns	-1.23**
1681 (P5)	-1.52**	-0.10ns	-0.13ns	-1.90**
SE (gi)	0.20	0.22	0.23	0.20

**, ** = Significant at P < 0.05 and P < 0.01, respectively; ns = Not significant at P > 0.05; SE (gi) = Standard error for general combining ability*

Four coffee hybrids (P1 x P2, P2 x P3, P1 x P4 and P1 x P5) had positive SCA effects for acidity, body, cup value and overall Sidamo coffee quality whereas P2 x P4 and P4 x P5 registered negative SCA effects for all these coffee quality parameters (Table 7). Other coffee hybrids; P1 x P3 and P3 x P5 for overall coffee quality; P2 x P5 for body and P3 x P4 for acidity and overall Sidamo coffee quality had positive SCA effects.

Hybrids with highest SCA effects were arisen from any possible combinations of parents having negative and positive GCA effects as observed in P1 x P5 (4.29) for acidity and P1 x P4 (1.59) for body generated from parents both having negative GCA effects while in P1 x P5 (6.29) for cup value had parents with negative and positive GCA effects. Although, parents with good GCA effects not always produced good specific combinations as observed in P2 x P4 (-4.29) for acidity and P1 x P3 (-0.43) for cup value, all the highest mean values in all parameters were registered for hybrids that were generated from parents both having highest GCA effects.

In addition, in all the parameters, the highest performances were registered for the parents that possess the highest GCA effects with the exception of one parent (P1) which registered a positive GCA effect but registered the lowest mean cup value among the coffee parents.

Table 7. Estimate of specific combining ability (SCA) effect for five coffee organoleptic quality parameters of 10 coffee (*Coffea arabica* L.) hybrids.

Hybrid	Acidity (20 %)	Body (20%)	Cup value (60%)	Overall value (100%)
744 x 7440 (Kaffa x Kaffa)	2.14	0.87	3.43	0.84
744 x 75227 (Kaffa x Kaffa)	-0.24	-0.08	-0.43	1.46
744 x 1377 (Kaffa x Sidamo)	1.43	1.59	3.95	1.27
744 x 1681 (Kaffa x Sidamo)	4.29	1.11	6.29	8.75
7440 x 75227 (Kaffa x Kaffa)	0.71	0.87	2.62	5.46
7440 x 1377 (Kaffa x Sidamo)	-4.29	-2.46	-8.33	-5.73
7440 x 1681 (Kaffa x Sidamo)	-1.43	0.40	-0.67	-2.25
75227 x 1377 (Kaffa x Sidamo)	0.01	-0.08	-0.19	0.56
75227 x 1681 (Kaffa x Sidamo)	-0.48	-0.56	-2.86	1.70
1377 x 1681 (Sidamo x Sidamo)	-3.81	-2.22	-7.14	-7.49
SE (Sij)	3.84	1.72	6.81	6.78

SE (Sij) = Standard error for specific combining ability.

4. Discussion

Bean size, from a commercial point of view is an important factor since price is related to the coffee grade where small beans of the same variety can bring lower prices (Thierry *et al*., 2006). Roasting of uneven sized beans affect the visual appearance of the roasted beans since the smallest tend to burn and the largest tend to be under-roasted. More importantly, roasting of uneven sized beans affect the cup quality (Barel and Jacquet, 1994). According to the national standard, if coffee sample size has ≥ 80% of a size of screen No.14, it qualifies for the international market (Endale, 2007). In this study, all the genotypes registered ≥ 92% sample coffee beans a size of screen > No.14 indicating all genotypes produced internationally acceptable bean size. Nearly all of the sample beans of the entry 744 met a size of screen > No.14 indicating this parent had uniform and bold beans. Moreover, hybrids involving in this parent produced nearly similar beans' size to that of the parent coffee. This apparently indicates that this parent can be used in crossing if the objective of breeding is to increase bean size.

Moisture is an important attribute and indicator of quality. High moisture content of the beans is a loss of material and leads to physical and sensorial defects. If the beans are too wet (above 12.5% moisture), they will mould easily during storage and if the beans are too dry (below 8% moisture), they will loose flavor. The moisture content influences the way coffee roasts and loss of weight during roasting. Coffee beans with low moisture content tend to roast faster than those with high moisture content. In general, moisture influences the way coffee roasts, loss of weight during roasting and leads to physical and sensorial defects (ICO, 2002). In the present study, the beans of none of the genotypes evaluated registered moisture contents below or above the established limit. This showed that coffee samples were prepared carefully and the cup quality test was done with appropriate moisture content of samples.

All highest mean raw coffee quality values ranked as better than the usual Sidamo coffee were registered for the hybrids. Moreover, the highest mean overall Sidamo coffee quality values ranked as highly acceptable for coffee hybrids while the coffee parents failed to perform the same. This result showed the advantage of selection of coffee lines and followed by crossing among them to improve coffee quality than only selection of best performing coffee lines. In addition, one Kaffa coffee parent produced better than the usual Sidamo raw coffee quality and two Kaffa coffee parents registered higher overall Sidamo coffee quality than the Sidamo coffee parents. This result showed the advantage of including coffee lines other than the target region in crossing program or to use as a variety to improve the target specialty coffee quality.

It was observed that the highest mean cup quality values were registered for the Kaffa coffee parents and their crosses. Besides, individual Kaffa coffee parents and their hybrids registered the highest Sidamo coffee cup quality values. In addition, the mean cup quality value of the Kaffa x Sidamo hybrids was observed to be equivalent to the Sidamo coffee parents and Sidamo x Sidamo coffee hybrids. Five out of six Kaffa x Sidamo coffee hybrids showed the Sidamo coffee cup quality performances that were either better or equivalent to Sidamo coffee genotypes. These results showed the possibility of improving Sidamo coffee cup quality value by using coffee parents other than Sidamo origin as far as they have inherent best cup quality values. It also revealed that crossing of Sidamo coffee parents with Kaffa coffee lines did not negatively blend the Sidamo coffee cup quality.

All positive and significant heterosis relative to the mid parent and better parent were registered for either Kaffa x Kaffa or Kaffa x Sidamo except one Sidamo x Sidamo coffee hybrid. More importantly, the two hybrids that exhibited positive and significant heterosis relative to the commercial Sidamo coffee variety for six important coffee quality parameters were Kaffa x Kaffa and Kaffa x Sidamo coffee hybrids. This suggested that the Kaffa coffee parents possessed favorable genes that complement each other or with the Sidamo coffee parents better than the Sidamo coffee parents did. This implies the possibility of improving Sidamo coffee quality parameters through crossing of Kaffa parents among them or with the Sidamo coffee parents than selection of Sidamo coffee lines and crosses made among them. This study results were in contrast with studies conducted in Brazil that showed no clear differences for cup quality in sensory evaluations comparing F_1 hybrids with traditional cultivars while the result for acidity was in agreement with the results where F_1 hybrids appeared to be inferior to the traditional cultivars for acidity (Bertrand *et al.,* 2006).

Both additive and non-additive gene actions were important for the expression of acidity, body and coffee cup quality parameters as these are evident from the mean squares being significant for both GCA and SCA. However, the variance ratios of GCA to SCA being less than unity for these parameters suggested the predominance of non-additive gene actions. More importantly, significant ($P < 0.01$) mean square only for SCA was detected for the overall coffee quality indicating the importance of non-additive gene actions to determine the international marketability of Sidamo coffee. These results suggested the importance of coffee hybrids production either by crossing parents having similar or diverse origin to improve most important Sidamo coffee quality parameters. On the other hand, only the importance of additive gene action was detected in controlling coffee flavor suggesting selection of best performing coffee lines to improve Sidamo coffee for this coffee quality parameter. The results of this study are in contrast with Walayro (1983) who reported the predominance of additive gene action for cup quality parameters.

The high GCA effects of the two Kaffa coffee parents (P2 and P3) for acidity, body and cup values suggested the usefulness of these parents to include in coffee breeding program to improve the Sidamo coffee quality parameters. In addition, if it is necessary to improve only coffee beans cup quality and acidity, it is important to use P1 (Kaffa coffee parent) and P4 (Sidamo coffee parent), respectively, since they possessed positive GCA effects for the corresponding parameters. However, it might not be necessary to include P5 (Sidamo coffee parent) in coffee crossing program to improve any one of coffee quality parameters since it had negative GCA effects for all coffee quality parameters.

In this study, two Kaffa x Kaffa (P1 x P2 and P2 x P3) and two Kaffa x Sidamo (P1 x P4 and P1 x P5) coffee hybrids had good specific combinations for acidity, body, cup and overall coffee quality which was evident from their positive SCA effects for these coffee quality parameters. It was also observed that the hybrids with highest SCA effects arisen from any possible combinations of parents having negative and positive GCA effects and parents with good GCA effects did not always produce good specific combinations. But the highest performances were registered for the parents that had highest GCA effects and for hybrids obtained by crossing these parents. This result suggested the importance of selection of coffee parents with highest performances and then crossing of these parents to improve coffee quality.

5. Conclusion

In this study, superiorities of coffee hybrids for all Sidamo coffee quality parameters were registered. The results suggested selection of coffee parents and then crossing among them regardless of their origin is an appropriate breeding method than selection of Sidamo coffee lines to improve Sidamo coffee qualities. Moreover, Kaffa coffee parents and their crosses made among them or with Sidamo coffee parents performed better Sidamo coffee qualities as compared to the Sidamo coffee parents and their crosses. This suggested that the Kaffa coffee lines and their crosses either among them or with the Sidamo coffee parents did not negatively blend Sidamo coffee quality. This encouraged the use of Kaffa coffee parents and their crosses to improve Sidamo coffee qualities.

The predominance of non-additive gene actions for the expression of acidity, body and Sidamo coffee cup quality were evident from the variance component ratios of GCA to SCA being less than unity. In addition, the importance of non-additive gene actions for the overall Sidamo coffee quality was detected from the highly significant ($P < 0.01$) mean square only for SCA. These results suggested the importance of coffee hybrid production by crossing parents having similar or diverse origin to improve the Sidamo coffee quality parameters. Only the importance of additive gene action in controlling coffee flavor was detected which suggested selection of best performing coffee lines is an appropriate breeding method to improve this coffee quality parameter.

The two Kaffa coffee parents (P2 and P3) for acidity, body, and cup value, P1 (Kaffa coffee parent) and P4 (Sidamo coffee parent) for cup quality and acidity, respectively, possessed positive GCA effects suggesting their usefulness to include in coffee breeding program to improve the respective coffee quality parameters. However, it might not be necessary to include P5 (Sidamo coffee parent) in coffee crossing program to improve any one of the coffee quality parameters since it had negative GCA effects for all of the coffee quality parameters.

In this study, the majority of Kaffa x Kaffa or Kaffa x Sidamo coffee hybrids were heterotic, had good specific combinations and exhibited highest percentage and exploitable heterosis for almost all important Sidamo coffee quality parameters. The parents which produced these hybrids had positive or negative GCA effects, i.e. often coffee parents with good GCA effects did not necessarily produce good specific combinations. However, the coffee parents having the highest values for coffee quality parameters had also highest GCA effects for the same parameters. In addition, superior hybrid for

Sidamo coffee quality parameters was produced from both parents that had highest GCA effects and highest mean performances. This might suggested the importance of selection of coffee parents on the basis of their coffee quality performances and GCA effects then crossing among them than selection depending on their origin *per se* (in this case only selection of Sidamo coffee lines) to improve Sidamo coffee quality.

This study depended on coffee parents and their crosses having two distinctly different origins that were acclaimed for two unique Ethiopian coffee qualities grown at a single Sidamo coffee growing location and evaluated for Sidamo coffee quality. Thus, the results might not be sufficient to give general conclusion for all coffee types in Ethiopia that are known for their unique coffee qualities, rather it can be used as good evidence for the possibility of using coffee lines and their crosses having diverse origin to improve the known unique coffee quality of the target region. Therefore, instead of only selecting coffee lines and crossing among themselves from each coffee growing region to improve the corresponding known coffee quality parameters, it is important to conduct studies using coffee lines and their crosses regardless of their origin in all of the coffee growing regions.

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