HETEROSIS AND COMBINING ABILITY FOR MORPHOLOGICAL, YIELD AND QUALITY CHARACTERS IN COFFEE (C*offea arabica* L.) HYBRIDS

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APPROVAL SHEET

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As Thesis Research advisors, we here by certify that we have read and evaluated this thesis prepared, under our guidance, by **Ashenafi Ayano**, entitled "**Heterosis and Combining Ability for Morphological, Yield and Quality Characters in Coffee (C*offea arabica* L.) Hybrids**" we recommend that it can be submitted as fulfilling the thesis requirement.

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DEDICATION

I dedicated this thesis manuscript to my late Father **AYANO FOLLE** and late brother **ADMASU AYANO**.

STATEMENT OF THE AUTHOR

First, I declare that this thesis is my own work and that all sources of material used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements of M.Sc. degree at Jimma University, College of Agriculture and Veterinary Medicine and is deposited at the University Library to be made available to users under rules of the Library. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
BPH	Better Parent Heterosis
CBD	Coffee Berry Disease
CD	Canopy Diameter
Cm	Centi Meter
CWD	Coffee Wilt Disease
EIAR	Ethiopian Institute of Agricultural Research
GCA	General Combining Ability
ha	Hectare
IAR	Institute of Agricultural Research
IPGRI	International Plant Genetic Resource Institute
JARC	Jima Agricultural Research Center
Masl	Meter Above Sea Level
mm	Milli meter
MP	Mid Parent
MPH	Mid Parent Heterosis
NPB	Number of Primary Branch
OBP	Over Better Parent
OCH	Over Check Hybrid
OMP	Over Mid Parent
RCBD	Randomized Complete Block Design
SAS	Statistical Analysis System
SCA	Specific Combining Ability
SS	Sum of Square
TNSRC	Tepi National Spice Research Center

BIOGRAPHICAL SKETCH

The author was born on October 24, 1966 in Arsi Zone Bekoji Town. He attended his elementary and junior secondary school at Bekoji Junior Secondary School. He also completed his high school study at Bekoji Comprehensive Secondary School. Passing the Ethiopian School Leaving Certificate Examination (ESLCE), he joined the then Alemaya University of Agriculture, now Haramaya University in 1984 and graduated with Diploma in Plant Sciences in November 1985.

Right after his graduation, the author was recruited as a Technical Assistant by the then Institute of Agricultural Research (IAR), now the Ethiopian Institute of Agricultural Research (EIAR) and assigned at Jimma Agricultural Research Center (JARC) starting from January 1986.

He joined Jimma University College of Agriculture and Veterinary Medicine to study horticulture and graduated with B.Sc degree in horticulture in 2007. Starting from May, 2007 he was assigned as researcher in Crop Research Department to work on coffee research at Jimma Agricultural Research Center (JARC) where he is still serving. Finally, he rejoined the School of Graduate Studies of Jimma University February, 2010 to pursue his study of Master of Science in Horticulture (Coffee, tea and spices).

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF TABLES continued

LIST OF TABLE IN THE APPENDIX

ABSTRACT

Increasing coffee productivity is one of the highest national priorities of the rural development policy of Ethiopia; and thus, the choice of promising genotypes from diverse genetic base and subsequent utilization of hybrids is one of strategies of improving productivity. A half diallel analysis involving five parents, ten F1 hybrids and one check hybrid was studied for several quantitative and quality traits to generate information on heterosis and combining ability. The genotypes were evaluated in a randomized complete block design (RCBD) with three replications at Melko, Metu and Tepi research centers. The analysis of variance revealed highly significant difference among genotypes at ($p<0.01$) for almost all characters. This consistent significant difference for different traits suggests the presence of genotypic difference among parental lines and hybrids evaluated. There was consistently high overall mean of the hybrids compared to the parental mean value for yield and other morphological characters. In contrast, the mean value of hybrids was less than the mean value of parental lines for quality characters. Heterosis over mid parent (MP) and over better parent (BP) for yield ranged 12.8 to 57.8 and 12.1 to 41.8% respectively. Cross combinations P1XP2, P1XP3, P2XP4 and P3XP5 showed relatively high positive heterosis MP and BP for most important favorable characteristics. Hybrids P2XP4 and P1XP5 had comparable yield result with the commercially released check hybrid showing respective positive heterosis of 11.5% and 5.1 % over check hybrid. Even though the heterosis over check hybrid was not significant, these two hybrids do have better yield and can be used as candidate after repeated performance evaluation across locations for quality and resistance to CBD and CWD. The BP and MP heterosis for the majority of quality characters was negative. This result may give a clue for the dominance of unfavorable quality character over favorable characteristics. Yet this calls for further study of quality inheritance by crossing between known top quality parents with that of known poor quality parents. Both GCA and SCA mean squares were highly significant for yield indicating both additive and non-additive gene actions are important for the inheritance of this economic trait; however the higher the percentage relative contribution of SCA over GCA indicates the predominance of non-additive gene action. Both the additive and non-additive gene actions were involved in the control of the characters studied for fruit length, fruit width, fruit thickness, bean length, bean width, bean thickness and 100-bean weight similar to aforementioned trait. Parental line P4 found to be the best combiner for stem girth, length of first primary branch and internode length showing significant and positive GCA effects for these traits; this parent may contribute favorable additive genes to its progenies for the synthesis of vigorous hybrids. Parental lines P4 and P5 were found good general combiners for important economic trait yield showing highly significant GCA effects in across locations GCA effects. These parental lines may have good prospect for the inclusion in the breeding program for yield improvement in synthesis of new high yielding hybrid varieties. Parental line P3 showed highly significant and positive GCA effect for flavor and overall quality; higher positive value for body and physical quality character shape & make. This gives an indication for the possible contribution of this parent in crossing for quality breeding program. Nearly 90% of the crosses showed positive SCA effects for yield out of which five crosses: P3XP5, P1XP5, P2XP5, P2XP4 and P3XP4 showed positive and significant SCA values for yield indicating that these crosses were good combinations. Crosses with higher values of SCA effects also showed higher value of mean yield performance, indicating good correspondence between SCA effects and mean yield. Hence such cross combinations could effectively be exploited in hybrid coffee breeding program.

1. INTRODUCTION

Coffee (*Coffea arabica* L.) is the most important crop, and one of the most enjoyed beverages throughout the world. As a result several hundred millions of people in the world drink coffee. It is one of the leading commodities in the international trade, and currently generates revenue of about US$ 14 billion annually for the producing countries. More than 80 countries, including Ethiopia cultivate coffee, which is exported the product for more than 165 countries worldwide providing a livelihood for some 100 million people around the world (ICO, 2001). Until the early 1990s, coffee (*Coffea* spp., *Rubiaceae*) was the world's most important internationally traded commodity in terms of monetary value, after oil. Currently, however, coffee is ranked as only the 5th most important traded commodity after oil, aluminium, wheat and coal. Despite its decline in rank as a traded commodity, coffee continues to be an important source of foreign exchange earnings, and primary export of many developing countries. Cultivation, processing, trading, transportation and marketing of coffee provides employment for millions of people worldwide (ICO, 2005).

In Ethiopia, coffee is one of the major and leading export items. Ethiopia is currently producing an estimated 9.8 million bags that would rank the country as the third largest coffee producer in the world after Brazil and Vietnam, beating out Columbia (ICO, 2012). Apparently coffee is at the center of Ethiopian culture and economy, and contributing to about 35% of the country's foreign currency earnings. It accounts for 10% of the gross domestic product, and supports the livelihoods of around 25% of the population of Ethiopia (representing around 20 million people) in one way or another (Gole and Senebeta,2008)**.**

It has been certain that Ethiopia is both the center of origin and diversification of *C. arabica L.* (Fernie, 1966; Bayetta, 2001). The crop spreads widely from the river bank of Gambella plain (550 m.a.s.l) stretching to the central and Eastern highlands of the country, where it exists in the great range of types within species (Bayetta, 1986). Due to the fact that Ethiopia is the center of origin and diversity, there is immense genetic variability that offers great potential for improvement of the crop. The country is well known not only for being the home of arabica coffee, but also for its very fine quality coffee acclaimed for its unique aroma and flavor

characteristics. The coffee types that are distinguished for such unique characteristics include Sidamo, Yirgacheffe, Harer, Gimbi and Limu types (Workafes and Kassu, 2000).

Despite its great importance, the average national productivity is very low (500-600 kg ha^{-}) as compared to the average productivity of the world and other major coffee producing countries (Abera, 2007; Workafes and Kassu, 2000). This is attributed to shortage of improved varieties, diseases, insect pests, drought, and poor management (Admasu and Klaus, 2007; Abera, 2007). Among many reasons that limited coffee productivity improvement, shortage of pure line and hybrid varieties is the major one (Bayetta, 2001; Mesfin, 1988; Babur, 2009).

Intensive efforts have been made by Jima Agricultural Research Center (JARC) to boast coffee productivity in the country. Over the last 33 years (1977-2010), thirty seven coffee varieties out of which thirty four pure lines and three hybrids (Ababuna, Gawe and MelkoCH2) were released for the various major coffee growing agro-ecologies of the country (Bayetta *et al*., 1998; MOA, 2010). On the other hand, there is immense genetic potential of coffee in the country which gives chance for development of improved varieties. In spite of having such large genetic variability in Ethiopia, research work on genetics and breeding of coffee is not adequate. In arabica coffee actual breeding of the species was given attention after 1942 and most varieties grown commercially at present have evolved from simple systems of line selection with in genetically homozygous parent populations (Van der Vossen, 1987; Carvalho, 1988). In Ethiopia systematic coffee research work started much latter than other countries in 1967 (IAR, 1969) and actual coffee breeding program was started in 1978 (Mesfin, 1982).

Heterosis occurred widely in both self and cross-pollinated crop species (Allard, 1960; Welsh, 1981). In crosses among varieties of *C.arabica L*., however, heterosis for yield and other desirable characters was found to be lacking (Carvalho *et al*., 1969) or low (Van der vossen and Walyaro, 1981). A higher yield heterosis of up to 53% and 100% were reported in Tanzania (Fernie, 1970). Leory *et. al*., (2006) also indicated the superiority of hybrids 30-70% more than traditional coffee varieties.

On the other hand, in Ethiopia with the first attempt of crossing program made among five indigenous pure lines, heterosis up to 60% for yield (Mesfin and Bayetta, 1983) and 30% for components of yield (Mesfin, 1982) was reported over the better parent. Such appreciable results were obtained mainly due to presence of high genetic variability since Ethiopia is both the center of origin and diversity for *C.arabica L*.

Currently, the analysis of combining ability has become an important and integral part of all breeding programs. It helps to identify the best combining parent, to know the type of gene action and to choose appropriate breeding methods (Sprague and Tatum, 1942; Mathur and Mathur, 1983). Indeed diallel analysis for combining ability suggested by Griffing (1956) is one of the powerful tools to provide the above information. In arabica coffee, information in this regard is very scarce.

The phenomenon of heterosis has not been exploited extensively in coffee. The effort to exploit heterosis or hybrid vigor in coffee was started following the recommendations of Mesfin (1982). The development of promising hybrids requires the identification of genetically superior parental inbreds, with superior performance in artificial hybridization. Combining ability of the pure lines is the ultimate factor determining future usefulness of these lines for hybrids. Sprague and Tatum (1942) apparently were the first to propose combining ability concept. They described that combining ability is an effective tool which gives useful genetic information for the choice of parents in terms of their performance in series of crosses. Combining ability analysis provides information on the relative importance of additive and non-additive gene effects involved in the expression of the quantitative traits.

From the few crossing works done so far encouraging heterotic effects were obtained in crosses among indigenous coffee lines and this has stimulated the Ethiopian coffee breeders to continue the crossing program among diverse parents. In his terminal report Bayetta (2007) indicated from the various sets of pure line variety development program in Ethiopia it had been observed that it is rarely possible to improve yield above 1800-2000 kg ha^{-} through direct selection indicating the need to look heterotic hybrids to maximize yield as high as 2500-3000 kg ha^{-}.

Cognizant to this, the present study was conducted to investigate the extent of heterosis and combining ability of parents in crosses between lines from south western region of Ethiopia with the following objectives:

- To determine the magnitude of heterosis and identify single cross coffee arabica hybrids for yield, yield components and quality characteristics
- To estimate GCA of selected parents, and SCA of hybrids

2. LITERATURE REVIEW

2.1. Origin and Botany of *Coffea arabica* L.

The natural habitats of all *Coffea* species are the understory of African tropical forests. Many forms of C*offea canephora* can be found in the equatorial lowland forests from Guinea to Uganda, whereas natural populations of C*offea arabica* are restricted to the highland forests of southwestern Ethiopia at an altitudes of 1600-2800m (Berthaud and Charrier, 1988). Mesfin and Bayetta (1987) also reported that, Arabica coffee grows under very diverse agro-ecologies of Ethiopia covering ranges of altitudes from 500m in the Gambella plain to 2600m in Wollo, Northern Ethiopia.

Coffee is the major genus of the *Rubiacea* family, which includes over 500 genera and over 6000 species. The genus *Coffea* itself comprises 105 species, but only two of them (*Coffea arabica* and C*offea canephora*) are currently of real economic importance (ITC, 2002; Wrigly, 1988). *Coffea arabica* is the only tetraploid species (2n = 4x = 44) in the genus while other species are diploid (2n = 2x =22). Recent investigations established the *C. arabica* is amphidiploids formed by natural hybridization between two closely related diploid species, *Coffea canephora* and *Coffea euginoides* (Lashermes *et al*., 1999).

The architecture of the coffee tree is characteristic of a tree growing in tropical forests: a vertical (orthotroic) stem, with horizontal (plagiotropic) branches arising in pairs opposite to each other. The growth is by a typical form of monopodial branching where the branches (primaries) remain subsidiary to the main stem, which continues to grow indefinitely by extension of the apical bud (Wrigley, 1988). The coffee plant takes approximately three years to develop from seed germination to first flowering and fruit setting. A well-managed coffee tree can be productive for up to 80 years or more, but the economic life span of coffee plantation is rarely more than 30 years (Wintgens, 2004).

The root consists of stout central root, often multiple, tapering more or less abruptly, and rarely extending as a recognizable unit more than 30 to 45 cm (1 to 1 ½ ft) from the soil surface. The stem and leaf tissues all originate in the dome shaped shoot apex. The leaves, borne in opposite

of pairs on the sides of braches. In the axils of each leaves on the primary braches there are three to six buds born one above the other in a serial pattern, closely packed and covered with a gum like substance. As the buds grow, some becomes visible above the stipules. Each bud in the axial can develop in to a new branch, or an inflorescence with one or more flowers, or remains undifferentiated. When the flower buds are 4-5mm long, they remain dormant until stimulated in to flowering. The stigma of flowers is receptive for only not more than 48 hrs in any one blossoming. The fruit of coffee tree is a drupe that normally contains two seeds but occasionally more. It is commonly referred to a cherry or berry.

Flower buds of coffee are formed on the leaf axil of the plagiotropic branches, or very less frequently in the leaf axil of orthotropic young stems. In each leaf axil a series of 4-6 buds called by Wormer and Gituanja (1970) ‘‘serial buds’’ may be found and one serial bud gives rise to the inflorescence. Usually from 2-5 individual compound inflorescences develop in each leaf axil. The inflorescences have a short axis, two pairs of bracts at its base and 1-5 flowers. Each flower bud has a very short pedicel and the flowers that form the inflourescence are connected at the base of pedicels.

The flowers are white and fragrant varying in number from 1-20 per axil, on primary and secondary branches. The calyx is very rudimentary, small, inconspicuous and cup-shaped. The corolla is white and has five expanded lobes. The stamens are usually 5, epipetalous and are inserted in the corolla tube between the lobes with their short filaments. The anthers are bilocular opening length wise. The pollen grains are numerous, but smaller in size. The ovary is inferior and is made up of two united carpeles and one ovule per carpel. The style is long with two stigmatic branches. The ovule consists of a single integument and small nucellus which disappears as the ovule matures.

The flower buds generally opens on sunny days early in the morning and pollen shedding starts soon after wards; the stigma is receptive at the opening of the bud and remains receptive for 3-4 days depending upon the weather conditions (Carvalho et al., 1969). In Kenya, however, Walyaro and Van der vossen (1977) found the stigma to remain receptive for at least nine days and recommended the bagging after artificial pollination not to be removed until two weeks.

C. arabica L. is the only self-compatible (autogamous) species of the genus whereas all other species are self-incompatible (allogamous) of the gametophytic type (Krug and Carvalho, 1951; Carvalho and Monaco, 1962). The rate of out-crossing in arabica coffee was found to vary according to the region and mutant used as a marker. Different researchers demonstrated and reported different figures for the rate of out-crossing for *Coffea arabica* L. Clifford and Wilson (1985) indicated that the out crossing of *Coffea arabica* L is 7-10%. Using of different mutants Carvalho (1988) observed 7-11%, to be used as an indication of the rate of out-crossing in arabica coffee, which is generally accepted figure.

2.2. Distribution and Importance of Coffee

Today several hundred million people in the world drink coffee. It is one of the most traded commodities over the world. *Coffee arabica* L.is preferred over all other species because of its superior quality and continued to be the exclusive product of all coffee in the world, as it had been for more than 150 years until the end of the 19 century. It is cultivated in most parts of the tropics, accounting for 80 % of the world market and about 70% the global coffee production (Woldemariam *et al*, 2002).

In Ethiopia estimated area of land covered by coffee is about 600,000 hectares, whereas the estimated annual national production of clean coffee is about 350,000 tons (Alemayehu *et al*, 2007). Of the estimated 600,000 hectares of land cropped with coffee, about 50,000 hectares (8.3%) is considered as forest coffee, semi-forest coffee covers about 180,000 hectares (30%) and garden coffee accounts for 56.70%. The remaining 5% is categorized as modern coffee. In general, small holding accounts for about 95% of the total coffee production of the country (Demel, 1999; Workafes and Kassu, 2000).

2.3. Selfing and Crossing Techniques in Coffee

Selfing is the technique taking place to acquire seed which maintain its purity which is free from natural out-crossing. In coffee selfing normally takes about three days before anthesis. Flowers that are already opened and young developing flowers bud removed by hand. This is just to control the already out-crossed flower and late flowering one which may receive pollen from uncontrolled condition. After selecting out immature and opened flowers; uniform flower buds enclosed by waxed paper bag until complete shading of the flowers seven to ten days. Then after normally expected coffee fruit phenology selfed seed harvested.

Regarding crossing technique, similar to selfing two to three days before flower opening branches containing ready flowers selected and make ready for emasculation. Then emasculation will take place after selecting out and removing of already opened and immature flower buds (Bayetta, 1991). During emasculation the whole corolla, together with the attached stamens, above and middle of corolla tube are removed by hand without damaging the pistle. The portion of the branches with emasculated flowers enclosed in waxed paper bag. Flower bud collection from the pollen parent takes place side by side to the emasculation activity. Similar to the emasculated flower bud the pollen parent flower collection is by selecting well matured flower bud collected either by taking the flower bud by cutting with the branches or directly collecting unopened flower buds in to petridish and placed in the laboratory until the stigma of emasculated flower opened. The following morning, flowers (pollen) transported to the emasculated parent field. The paper bag enclosed the branch with the emasculated flowers opened at the upper end and the male flower gently shacked over against the stigma to effect pollination immediately after pollination the paper bag closed and the branch labeled using water proof label and marker.

The bag normally removed 10-15 days after pollination i.e. after complete shading of the flowers from the surrounding area. Frequent visit and check-up required to remove emerging new flower buds periodically arising. Then after normal maturing stage hybrid seed harvested from crossed branches specifically (Bayetta, 1991; Wassu, 2004).

2.4. Variety Development Process in Coffee

Arabica coffee breeding principles and methods applied in different coffee growing countries and the overall objectives, improved productivity and quality, are generally similar. Van der Vossen (1987) distinguished four basic methods – pure-line selection, pedigree selection, hybridization (intraspecific F1 hybrids), and interspecific hybridization followed by backcrossing and pedigree selection. However, the application of these methods may vary from country to country depending on the amount of genetic variability available, ecological conditions and prevailing production problems. In Ethiopia, pure-line selection and intra-specific hybridization are commonly used (Bayetta and Labouisse, 2006).

2.4.1. Pure line variety development and progeny testing

The conventional pure line variety development program includes the following three stages of field performance trails like: screening, local adaptation and verification trials. The Ethiopian coffee ecology is so diverse that varieties suited to one location do not equally perform in other locations. This problem led to development of cultivars for different ecology. The availability of genetic variations provides immense possibilities for improvement of the crop for any desirable traits of interest. On the other hand, the presence of high environmental diversity, distinct variation in coffee quality within and between regions or localities (CTA, 1999) and location specificity of our improved varieties (Mesfin and Bayetta, 1987) make the breeding program more complex.

Therefore, it would be difficult to easily obtain varieties that have wider adaptation and at the same time maintain the typical quality of each particular area. This challenge was an impetus for the development of a new breeding strategy that alleviates these problems, best fits to the Ethiopian conditions and enables to exploit all the available advantages of ecological and genetic diversities. In effect, a new improvement strategy known as '*local landrace development program*' has been initiated by JARC (Bayetta and Labouisse, 2006). Materials that exhibited superior performance for yield and other characters are selected for advanced replicated multi-location trials in different parts of the country to test their adaptability and

repeatability. The best selections are further verified in their respective areas of adaptation on a larger plot size under farmers condition. Selections that pass the final verification test are released as a new variety upon approval. In the pure line variety development program until now about 34 pure line varieties released for different agro ecologies of Ethiopia (Bayetta *et al*., 1998; MOA., 2010).

2.4.2. Exploitation of heterosis and hybrid coffee variety development

Heterosis is defined as improvement of F_1 over the mean of both parents (mid parent heterosis or relative heterosis) (Pickett, 1993; Surendran *et al*., 1994; Stubber, 1999); over the mean of the better or heterobeletiosis (Surendran *et al*., 1994; Briggs and Knowles, 1967; Jinks, 1983). Heterosis or hybrid vigor described in terms of superiority of F_1 hybrid performance over some measure of parental performance; which means that it differ depending on the basis of comparison used. It referred to increase in vigor, size, fruitfulness, speed of development, resistance to disease and pest, or to climate rigors of any kind, manifested by cross breed organisms as compared with corresponding inbred (Shull, 1952; Zirkel, 1952).

The genetic basis of heterosis is due interaction of alleles at a single locus (allelic interaction) or due to developed divergent function, i.e., A_1A_2 would have greater effect than the homozygous condition A_1A_1 or A_2A_2 (Hayes *et al*., 1955). The three main hypotheses to explain: (1) dominance hypothesis and (2) over dominance (3) epistasis. The dominance hypothesis assumes that hybrid vigor is the accumulation of favorable dominant gene in the F_1 hybrids where the corresponding unfavorable alleles are recessive and their effects are masked by the effect of dominant favorable genes (Singh, 1993). According to this theory heterosis in F_1 hybrid is the result of the masking of the harmful effects recessive alleles present in the other parent.

In the over dominance hypothesis the value of heterozygote is considered superior to either homozygote. Therefore, heterozygosity is essential for and is the cause of heterosis. And hybrid vigor increases in proportion to the amount of heterozygosity. According to this theory

homozygosity leads to weakness and it would be impossible to find inbred as vigorous F_1 hybrid. There is no doubt that in the case of some genes, heterozygotes are superior to the homozygotes (Singh, 1993).

The estimates of heterosis in the crosses were expressed either on the basis of the mid parents, better parent and standard/economic heterosis. It is calculated in term of percent increase (+) or decrease (-) of hybrid against its mid-parent better parent and check values.

Mid-parent heterosis (MPH) (%) = 100[(F1- MP)/MP] and
Better parent heterosis (BPH) (%) = 100[(F1-BP)/BP]
Standard/economic heterosis (%) = 100[(F1-CH)/CH]
Where F1, MP, BP and CH are hybrid mean, mean of two parents, better parent mean, and check hybrid for each cross, respectively.

Hybridization is a way in which desirable characters of two or more species, varieties or lines are combined together or transferred from one to the other (Simmonds, 1986). Hybridization program in indigenous coffee was started in 1977. Mesfin (1982) and Mesfin and Bayetta (1983) evaluated a set of 5 X 5 diallel crosses among the indigenous cultivars. They observed positive better parent heterosis as high as 60% for yield and 30% for yield components. Bayetta (1991) studied heterosis and combining ability in six parents differing in geographical origin and morphological characteristics at seedling stage. The F1's from the half diallel experiment exhibited positive overall mean better parent heterosis for the seven seedling characters studied ranging from 3- 18 % considering individual crosses. The amount of heterosis was as high as 69% and the highest heterosis was obtained from crosses involving parents from distinctly differing in geographical characters. And also from different set of crosses it was noted that better parent heterosis ranging from 60% to 120% for yield and the presence of high level of heterosis in crosses among elite indigenous coffee (*coffea arabica* L.) cultivars has been well determined (Mesfin and Bayetta (1983); Bayetta (2001).

Once the presence of heterosis in crosses among indigenous arabica coffee cultivars was noticed the next step was to investigate as to how to maximize the observed level of heterosis

and make best use of the available enormous genetic potential. Many early and recent investigations showed that maximum expression of heterosis observed through the genetic diversity among parents is the basic requirement. Studies also confirmed that strikingly high and significant variation between and within-region and between-region crosses in the level of heterosis clearly demonstrated the requirement of genetic divergence among parents with respect to geographical origin and/or morphological traits for maximum heterosis to occur, at least in certain hybrid characteristics (Bayetta *et al.,* 2007; Wassu, 2004). Moreover Bayetta *et al.,* (2007), study report suggested that morphological variation is more important than geographical origin to maximize heterosis.

Effort to combine these important agrotypes to improve the present yield, quality and resistance level by hybridization is one of the positive strategies to promote the coffee industry. To attain this goal, high yielder selections which represent the major coffee growing locations (Sidamo, Keffa and Illubabor); and major morphological classes (compact, intermediate, and open canopy) which have partial to high resistance reaction to CBD are selected as parents for crossing program. In this respect out of different sets of crosses made during last periods three hybrid varieties namely Ababuna, Melko CH2 and Gawe were released in Ethiopia (Bayetta *et al*., 1998; MOA., 2010) . On top of these there are pipeline hybrid varieties under study.

2.5. Combining Ability

Combining ability describes the breeding value of parental lines to produce hybrids. It may be defined as the performance of a parent in hybrid combination (Kehr, 1961). Combining ability is especially useful: (1) to study or compare the performance of lines in hybrid combinations and (2) to determine the nature of gene action involved in the control of inheritance of quantitative traits which in turn, helps to choose appropriate breeding methods (Mathure and Mathur, 1983). Sprague and Tatum (1942) used the term general combining ability (GCA) to designate the average contribution that the inbred makes to the hybrid performance in a series of hybrid combinations in comparison to the contribution of other inbred lines to hybrid performance in the same series of hybrid combinations and used the terms specific combining

ability (SCA) to define those cases in which certain combinations do relatively better or worse than expected on the basis of the average performance of the lines involved.

The importance of combining ability studies lies in the assessment of parental lines and their hybrids showing significant additive and non-additive effect with respect to certain traits. Genetically, general combining ability (GCA) is a consequence of additive gene action while specific combining ability (SCA) is a consequence of non-additive (dominance and epitasis) gene action (Welsh, 1981; Falconer, 1989). In a systematic breeding program, it is essential to identify superior parents for hybridization and crosses to expand the genetic variability for selection of superior genotypes (Inamullah *et al*., 2006).

Combining ability analysis is also important in that it indicates the ability of parents to transfer their desirable traits to their descendants/ progenies and compare the performance of lines in hybrid combinations. It also helps to identify the best hybrid combination and supplies data on the type of gene action, which control the different agronomic traits (Griffing, 1956; Gravios and McNew, 1993; Kambal and Webster, 1965).

2.6. Diallel Analysis

A diallel cross is a set of all possible matings among several genotypes, which may be individuals, clones or homozygous lines. It estimates the genetic components of total variance of quantitative characters, general and specific combining abilities of inbred lines involved in the crosses (Narain, 1990). The diallel analysis was developed in order to generate information on the genetic mechanisms controlling the inheritance of various characters in the first filial generation.

Griffing (1956) proposed practical methods of diallel analysis depending on the material involved in the analysis. These are: method 1 includes parents (n), F1's [n (n-1)/2] and reciprocals; method 2 parents and F1's only; method 3 F1's and reciprocals and method 4 F1's only. Griffing (1956) has also described the method of analysis for combining ability as model I (fixed effect) and model II (random effect) from which one can choose the best fitting model

and method depending on the nature of the study and materials employed. In most cases, a random sample is unlikely, since breeders usually select parental lines to fit the specific breeding objective. In addition, he suggested that the parents need not be included unless the objective is to choose the best parent to use and reciprocal crosses need not be used unless maternal effects are suspected. Thus, among biometrical genetic methods available to obtain information concerning the inheritance of quantitative traits, diallel analysis developed by Griffing (1956) is one of the most commonly used one. It has proven informative in determining the inheritance of quantitative traits of interest to plant breeders (Hallauer and Miranda, 1988; Hill *et al*., 2001). For this study Model I method II diallel analysis was employed.

3. MATERIALS AND METHODS

3.1. Experimental Materials

Five pure lines that were selected from the national collection trials representing the different agro ecologies of southwestern Ethiopia and canopy classes were used as parents in half diallel crosses. The origin, altitude and description of parental lines are given in Table 1.

Table 1. Coffee pure lines, their origin and descriptions

	Line	Origin	Altitude (m)	Description
1	75227 (P1)	Gera	1900	Open canopy, Highly resistant to CBD and released pure line variety, high yielder
2	744 (P2)	Washi, Kefa	1700	Open canopy, Highly resistant to CBD, bold bean size and released, high yielder
3	74148 (P3)	Bishari, Illuababora	1600	Compact canopy, Highly resistant to CBD and high yielder, released pure line
4	F-34 (P4)	Mizan-Teferi	1430	Open canopy, moderate resistant to CBD, quality, not released (pipeline variety)
5	206/71 (P5)	Maji	1600	Compact canopy, moderate resistance to CBD, high yielder, small bean size, bronze leaf tipped, not released (pipeline variety)

Source: Extracted from data base of coffee breeding and genetics research division, JARC

Due to the perennial nature of coffee this study was conducted on the already established coffee hybrids produced and planted in half diallel fashion. The hybrids and parental lines were planted in July 2000; at Melko, Metu and Tepi Ten trees per plot, in three replications. The entries planted include the 10 F1 hybrids, the five parents and one standard check hybrid (Aba-Buna).

3.2. Description of the Study Sites

The study was conducted at Jima Agricultural Research Center (JARC), Metu Agricultural Research Sub-Center and Tepi National Spice Research Center (TNSRC). The study locations are among major coffee producing areas in south western Ethiopia. Summary of the study sites is shown in Table 2.

Table 2. Ecological description of study sites

Location	Latitude	Longitude	Altitude (masl)	Rainfall/ annum (mm)	Temperature (^{o}c)		Relative humidity (%)
					Min	Max	
Melko	7^{0}40'N	36^{0}47'E	1753	1572	11.6	26.3	67
Metu	8^{0}19"N	35^{0}35"E	1580	1829	12.7	28.9	-
Tepi	7^{0}11"N	35^{0}25"E	1220	1594	15.7	29.9	70

Source: Labouisse, 2006.

Generally, the study locations are situated in the wet humid sub-tropical region of southwestern Ethiopia. The bulk of the soil in the south-west coffee growing region in general is described as Eutric Nitosol and clay; deep and well drained, with PH of 5-6 medium to high in exchangeable cation (Paulos, 1994; Brhanu, 1978; Tesfu and Zebene, 2006).

3.3. Experimental Design, Management and Season

The study was conducted during the year 2011/12 with randomized complete block design in three replications. Dabholkar (1992) described that randomized block design is commonly used and applicable to this type of study. A total of sixteen entries planted with 10 trees per plot across three locations used in the study. The trees were planted each in 2m x 2m spacing. Other cultural practices such as weeding, herbicide application, pruning, etc. were applied as per recommendation of JARC (IAR, 1996; Endale *et al.,* 2008).

3.4. Data Collected

Data were collected on yield and yield components from the experimental plots of each location during November 2011 to June 2012. For execution of quality assessment, samples were collected from each experimental plot from November 2011 to January 2012. Accordingly, the quality assessment data in the JARC liquoring laboratory was done from April to June 2012. Details of data collection procedures are described as follows:

i) Field data collected

a) Leaf characteristics. For these parameters average of five one-year old leaves sampled and measured as recommended by IPGRI (1996)

- Leaf length (cm) - measured from petiole end to apex.
- Leaf width (cm)- measured at the widest part of the leaf.
- Leaf area (cm) this parameter was calculated as = (length * Width) * 0.88 (Walyaro, 1983)
- Leaf petiole (cm) - Measured from the base to the insertion with the blade.

b) Stem characteristics

- Total plant height (cm) – the length from the ground level to the tip of the tree measured using meter tape.
- Plant height up to first primary branch (cm)- the length from the ground level to the first primary branch of the tree measured using meter tape.
- Number of main stem node –number of nodes on main stem counted.
- Internode length (cm) –computed as (TH-HFPB)/(NN-1) where, TH=total height, HFPB=height up to first primary branch, NN=number of nodes on main stem.
- Stem diameter (girth) (cm) –main stem measured at 5 cm above the ground using caliper.

c) Branch characteristics

- Length of the 1st single primary branch (cm) –length of first longest primary branch measured from main stem to the tip of the branch.
- Canopy diameter (cm) –average length of tree canopy measured twice, East-West and North- South; from the broadest portion of the tree.
- Number of primary branches –number of primary branches counted per tree.

d) Fruit characteristics. Average of five normal matured fruits measured as recommended by IPGRI (1996)

- Fruit length (mm) – Average of five normal matured fruits measured at the longest part using digital caliper.
- Fruit width (mm) - Average of five normal matured fruits measured at widest part using digital caliper.
- Fruit thickness (mm) - Average of five normal matured fruits measured at the thickest part using digital caliper.

e) Seed/bean characteristics - Average of five normal matured beans measured as recommended by IPGRI (1996)

- Bean length (mm) – Average length of five normal matured beans measured at maximum longest part using digital caliper.
- Bean width (mm) - Average of five normal matured beans measured at the widest part using digital caliper.
- Bean thickness (mm) - Average of five normal matured beans measured at the thickest part using digital caliper.
- 100-bean weight at 11% moisture (gm) –calculated as: ("bean weight at 0% moisture content" X 100)/ (Bean No X 0.89). Oven was used for drying of beans to make 0% moisture and weight recorded using sensitive balance.

f) Yield (kg/ha): fresh cherries were harvested and weighed in grams per tree basis and converted to kg/ha.

ii) Quality assessment

Coffee sample preparation and organoleptic data collection procedures (from data collection to cup testing) is described as follows.

Ripe red coffee cherries were handpicked. Before pulping fully ripened and healthy berries were separated from foreign materials. A total of 144 samples were prepared from hybrids and

parents. Samples which were prepared from ten trees per plot per replication at peak harvest period were bulked. The samples were carefully prepared using wet processing method (pulping, fermentation, and drying) following the recommended processing method:

a) **Pulping**: Fully ripened beans of berries was separated from the skin and pulp by using a hand pulping machine that squeezes the berries between fixed and moving surfaces.

b) **Fermentation**: The beans then stored in a plastic bucket for 48 hrs for Melko and Metu and 24 hrs for Tepi till first washing (Behailu *et al*., 2007). Then, samples were stored for 24 hrs for final washing. Altogether until final washing the average length of time that was required is 64 hrs For Melko and metu, 48 hrs for Tepi (IAR/JARC, 1996).

c) **Drying:** Samples were placed on mesh wire under sun for drying. During drying, the moisture content of the bean was measured by moisture tester to maintain the moisture level at 10-12% for all samples uniformly. About 300-500gm of green coffee bean samples was prepared per entry per replication separately for each hybrid and/or selection for physical and organoleptic quality characteristics analysis. A sensorial quality analysis was carried out at Jimma Agricultural Research Center by well-trained cup tasters as per the standard.

d) Roasting and grinding: The roaster machine was first heated at about 160-200^{o}c. About 100 g of green coffee bean sample was prepared per entry per replication for roasting. Medium roast (7 minutes on average) was used. And it was blown to remove the loose silver skins before grinding. Then, medium sized ground coffee was prepared using electrical grinder with middle adjustment.

e) **Brewing:** Soon after grinding, coffee powder weighing 8g was placed in a cup with a capacity of 180 ml. Then, boiled water poured on to the ground coffee up to about half way in the cup. Soon after, volatile aromatic quality and intensity parameters were recorded by sniffing. Then, the contents of the cup were stirred to ensure an infusion of all coffee grounds. The cup was then filled to the brim with boiled water. The brew was made ready for panelists within 8 minutes.

f) **Cup tasting:** Cup tasting was carried out by well experienced 3-5 cuppers each session. Cupping was performed after once the beverage cooled to around 60 ^{0}C (Drinkable temperature). Three cups per sample were prepared for tasting session. Aroma (aromatic quality and intensity), acidity, body, bitterness and astringency were scored using scales ranging from 0 to 5 (Table 3). Typical flavor was assessed as an after taste aromatic quality. There was also an overall standard for liquor quality based on the above attributes that ranged from 0 to 5 (As per the coffee quality assessment format of JARC). Mean of each variable by the panel were used for statistical analysis.

Table 3. Quality parameters and their descriptive value

	Character		Description of each scale					
		Scale	0	1	2	3	4	5
1	Aromatic intensity	0-5	Nill	Very light	Light	Medium	Strong	Very strong
2	Aromatic quality	0-5	Nill	Very light	light	Medium	Strong	Very strong
3	Acidity	0-5	Nill	Very light	light	medium	Strong	Very strong
4	Astringency	0-5	Nill	Very light	light	medium	Strong	Very strong
5	Bitterness	0-5	Nill	Very light	light	medium	Strong	Very strong
6	Body	0-5	Nill	Very light	light	medium	Strong	Very strong
7	Flavor	0-5	Nill	Very light	light	medium	Strong	Very strong
8	Overall standard	0-5	Nill	Very light	light	medium	Strong	Very strong
		2-15	2	5	8	12	15	
9	Shape and make		small	mixed	average	good	Very good	
10	Over screen 14	%						

3.5. Statistical Analysis

3.5.1. Analysis of variance (ANOVA)

All the quantitative and organoleptic quality data collected were statistically analyzed based on randomized complete block design using XLSTAT, Computer program and SAS (SAS, 2002) version9.2 software. Least Significant Difference (LSD at $P < 0.05$) was employed to identify accessions that are significantly different from each other. Combining ability analysis was performed using SAS DiallAll05 program of SAS statistical software version 9.2 (Zhang *et al.,* 2005). ANOVA was run for the three locations separately combined over the three locations for those characters that showed homogeneity of error variances (Gomez and Gomez, 1984)

Thus the mathematical linear **model** for *ijk*th observation expressed as:

$Y_{ijkl} = \mu + v_{ij} + b_k + e_l + (bv)_{ijk} + (vbe)_{ijkl} + e_{ijkl}$

Where;

Y_{ijkl} = the response measurement for the ijkl^{th} observation

μ= is the population mean effect,

v_{ij} = is the effect of *ij*th genotype,

b_k = is the effect of *k*th block,

e_l = is the *l* th location

$(bv)_{ijk}$= is the interaction of *ij*th genotype with *k*th block,

$(vbe)_{ijkl}$= is the interaction of *ij*th genotype with *k*th block and *l* th location

e_{ijkl} = is the environmental effect peculiar to *ijkl* th observation.

Skeletons of ANOVA for individual and across locations are presented in Tables 4 and 5 respectively.

Table 4**:** Skeleton of ANOVA for individual location

Source	df	Ms	F-val
Replications	(r-1)	Mr	
Treatment	(t-1)	Mt	Mt/Me
Error	(r-1) (t-1)	M_e	

Table 5**:** Skeleton of ANOVA for combined over locations

Source	Df	Ms	Expected of mean squares
Replications	(r-1)	MSr	$\delta^2_r + ac\ 1/(r-1)\sum r^2_k$
Treatment	(t-1)	MSt	$\delta^2 t + rc\ 1(r-1)\sum^{k} r^2_i$
Location	(L-1)	MSL	
Entries X Location	(t-1) (L-1)	MStL	
Error	tr(L-1)	MS_e	δ^2_e

Heterosis and Combining ability analysis was also done to determine GCA and SCA effects. Moreover, % heterosis over the mid-parent, high parent and standard check hybrid Aba-buna (economic heterosis) was computed for yield, yield components and quality characters.

The linear mathematical **model** for half diallel model 1, method 2 Griffing (1956) analysis expressed as:

$$Y_{ij}=\mu+g_i+g_j+s_{ij}+1/bc\sum_{K}\sum_{l} e_{ijkl}$$

Where μ is population mean,

g_i and g_j are general combining effects of ith and jth parent, respectively,

sij=sji.

e_{ijk} is the environment at effect associated with ijk^{th} observation.

3.5.2. Estimation of heterosis

Heterosis, expressed as percent increase or decrease in the performance of F_1 hybrid over the mid-parent (average or relative heterosis), better parent (heterobeltiosis) and standard heterosis was computed for each character using the following formula described in Falconer (1989):

$$\text{Relative heterosis} = \frac{\overline{F}_1 - \overline{MP}}{\overline{MP}} \times 100$$

$$\text{Heterobeltiosis} = \frac{\overline{F_1} - \overline{BP}}{\overline{BP}} \times 100$$

$$\text{Standard heterosis} = \frac{\overline{F_1} - \overline{CP}}{\overline{CP}} \times 100$$

Where,

$\overline{F_1}$ = Mean performance of F_1 hybrid

$\overline{P_1}$ = Mean performance of parent one

$\overline{P_2}$ = Mean performance of parent two

$\overline{BP}$ = Mean performance of better parent

$\overline{CP}$ = Mean performance of check hybrid

$\overline{MP}$ = Mean mid-parental value i.e. $(P_1+P_2)/2$

The significance of heterosis was tested with‘t’ test as given below:

For relative heterosis

$$t = \frac{\overline{F_1} - \overline{MP}}{\sqrt{3\,Me/2r}}$$

For heterobeltiosis

$$t = \frac{\overline{F_1} - \overline{BP}}{\sqrt{2Me/r}}$$

For standard heterosis

$$t = \frac{\overline{F_1} - \overline{CP}}{\sqrt{2Me/r}}$$

Where,

$\overline{F_1}$ = Mean of F_1 hybrid

$\overline{BP}$ = Mean of better parent

$\overline{CP}$ = Mean of check hybrid

$\overline{MP}$ = Mean of mid-parental value

Me = Error mean square from ANOVA table and

r = number of replications

3.5.3. Combining ability analysis

Combining ability analyses was computed by Griffing's approach through Model 1 and Method 2 Griffing (1956). The analysis of variance for combining ability is given in Table 6 and 7.

Table 6: Skeleton of individual location combining ability analysis

Source	d.f.	S.S.	M.S.	Expected mean square
General combining ability (GCA)	*(p-1)*	S_g	M_g	$\sigma_e^2 + (p+2)\{1/(p-1)\}\sum_{i=1}^{p} g_i^2$
Specific combining ability (SCA)	*p(p-1)/2*	S_s	M_s	$\sigma_e^2 + 2/\,p(p-1)\sum_{i=1}^{p}\sum_{j=1}^{p} s_{ij}^2$
Error	*m*	S_e	M_e	σ_e^2

The sum of squares was calculated as follows:

$$S_g = \frac{1}{p+2}\left(\sum_{i=1}^{p}(x_{i.} + x_{ii})^2 - \frac{4}{p}x_{..}^2\right)$$

$$S_s = \sum_{i}^{p}\sum_{j}^{p} x_{ij}^2 - \frac{1}{p+2}\sum_{i=1}^{p}(x_{i.} + x_{ii})^2 + \frac{2}{(p+1)(p+2)}x_{..}^2$$

Where,

g_i = general combining ability of i^{th} parent

s_{ij} = specific combining ability for the cross between the i^{th} and j^{th} parent such that $s_{ij} = s_{ji}$

p = number of parents

S_g = sum of square due to general combining ability

S_s = sum of squares due to specific combining ability

$x_{i.}$ = array totals of i^{th} parent

x_{ii} = mean values of i^{th} parent

$x_{..}$ = grand total of 'p' parental lines and p (p-1)/2 progenies

x_{ij} = mean value of ij^{th} cross

m = error degrees of freedom obtained in RBD analysis.

The mean sum of squares for general and specific combining ability was obtained by dividing their sum of squares by respective degree of freedom. The error mean square (M_e) for

combining ability analysis was obtained by dividing error mean square (M_e) with number of replications.

The following 'F' ratios were used to test significance of the variance due to general and specific combining ability effects.

(i) To test for differences among GCA effects

$$F = \frac{M_g}{M_e}$$, for (p-1) and 'm' degree of freedom

(ii) To test for differences among SCA effects

$$F = \frac{M_s}{M_e}$$, for p (p-1) and 'm' degree of freedom

Table 7: Skeleton of ANOVA of combining ability for combined over locations

Source of variation	df	Ms	F Probability
Environment	E-1	MSe	
Rep (environment)	R(E-1)	MSr	
Crosses	N-1	MScr	
Crosses X Environment	(N-1) (E-1)	MScr x e	
GCA	(P-1)	MSgca	
SCA	(N-P)	MSsca	
GCA x L	(P-1)	MSgcaxl	
SCA x L	(N-P)	MSscaxl	

Relative importance of GCA and SCA was calculated as per the following formula:
Relative contribution of GCA=(GCA ss/GCA ss+SCA ss)x100
Relative contribution of SCA=(SCA ss/SCA ss+GCA ss)x100

Estimates of general (gi) and specific combining ability effects (sij)

These effects were estimated as follows:

$$\mu = \frac{2}{p(p+1)} x..$$

$$g_i = \frac{1}{(p+2)}\left(\sum(x_{i.} + x_{ii}) - \frac{2}{p} x..\right)$$

$$S_{ij} = x_{ij} - \frac{1}{(p+2)}(x_{i.} + x_{ii} + x_{j.} + x_{jj}) + \frac{2}{(p+1)(p+2)} x..$$

Where,

g_i = general combining ability effect of i^{th} parent and

S_{ij} = specific combining ability effect of cross between i^{th} and j^{th} parents

p, $x_{i.}$, x_{ii} and x.. have the same meaning as explained earlier, $x_{j.}$ refers to the array total of the j^{th} array and x_{ij} stands for mean value of the j^{th} parent.

Variance of effects and differences between effects of two parents or crosses was estimated as follows:

(i) The variance of any parent of F_1 mean value

$$Var.(\hat{x}_{ij}) = \sigma_e^2 = M'_e$$

(ii) The variance of the difference between any two mean values

$$Var.(x_{ij} - x_{kl}) = 2\hat{\sigma}_e^2 = 2M'_e$$

(iii) $$Var.(\hat{g}_i) = \frac{p-1}{p(p+2)} M'_e$$

(iv) $$Var.(\hat{s}_{ij}) = \frac{p^2 + p + 2}{(p+1)(p+2)} M'_e \ (i \neq j)$$

(v) $$Var.(\hat{g}_i - \hat{g}_j) = \frac{2}{p+2} M'_e \ (i \neq j)$$

(vi) $$Var.(\hat{s}_{ij} - \hat{s}_{jk}) = \frac{2(p+1)}{p+2} M'_e \ (i \neq j,k; \ j \neq k)$$

$$Var.(\hat{s}_{ij} - \hat{s}_{kl}) = \frac{2p}{p+2} M'_e \ (i \neq j,k,l; \ j \neq k,l; k \neq l) \quad \text{(vii)}$$

4. RESULTS AND DISCUSSION

4.1. Analysis of Variances

ANOVA were computed for yield components of yield (agronomic traits) and quality characteristics (Table 8 and 9)

4.1.1. Analysis of variance for individual location

Individual location ANOVA for some of yield components (agronomic traits) and quality characteristics are presented in Table 8.

At Melko, Metu and Tepi mean squares for number of primary branch (NPB), number of node (NN) and canopy diameter (CD) were highly significant for all genotypes studied. The highly significant difference observed among the genotypes, clearly indicates the presence of variability among the parental lines and hybrids.

Similarly in all locations genotypes revealed highly significant difference at ($P< 0.01$) for both quality traits aromatic quality (AQ) and acidity.

Table 8: Mean squares of genotypes for some growth and quality parameters at different study locations

Traits	Locations and Source of variation								
	Melko			Metu			Tepi		
	Genotype (15)†	Block (2)	Error (30)	Genotype (15)	Block (2)	Error (30)	Genotype (15)	Block (2)	Error (30)
Growth parameters									
NPB	80.13**	51.58 NS	22.16	65.80**	3.00 NS	16.27	26.24**	16.40 NS	3.48
NN	17.60 **	15.44 NS	5.82	13.38**	3.15 NS	2.90	7.65**	4.15 NS	0.75
CD	1108.31**	1581.75**	106.04	380.24**	1063.58**	44.16	1475.25**	2085.44**	140.77
Quality parameters									
AQ	0.26**	0.01ns	0.04	0.198**	0.13**	0.018	0.076**	0.036ns	0.027
AC	0.21**	0.02ns	0.01	0.172**	0.009ns	0.097	0.226**	0.100**	0.014

† - Numbers in parenthesis shows degree of freedom; * ,** significant at 0.05 and 0.01 probability level. Ns=non-significant

NPB=number of primary branch, NN=number of node on main stem, CD=canopy diameter, AQ=aromatic quality, AC=acidity

4.1.2. Analysis of variance for across location

Over location data were combined after checking homogeneity of variance test over location error variance (Appendix 1). Across locations analysis of variance was conducted for five growth characters; four leaf characters; eight yield, fruit, bean characters and eight quality parameters. For most characters the combined analysis of variance revealed the presence of highly significant difference among study locations and among genotypes (Table 9). Significant genotype by environment interaction also observed for some of the traits and discussed below.

Growth characters

Out of five growth characters only the mean square for length of first primary branch (LFPB) showed significant genotype x environment interaction all the rest characters showed non-significant interaction. This result was in line with the result reported by Yonas (2005) for LFPB only. Highly significant difference were observed ($P<0.01$) among genotypes for most studied traits. The significance of the genotypic mean square for most traits (agronomic and yield related traits) against their corresponding interaction mean square indicated the existence of true genetic difference among genotypes (Dabholkar, 1992; Crossa, 1990). It was also observed that for all traits there was significant difference among study locations.

Leaf characters

Among the four leaf characters; leaf length (LL), leaf width (LW), leaf area (LA), leaf petiole length (LPL) only LA showed significant G x E interaction at ($P<0.01$). On the other hand there was significant difference among genotypes and locations for all leaf characters under study.

Yield, fruit and bean characters

The genotype by environment interaction for yield was non-significant, while the genotype and location was significant at ($P<0.01$). Similarly, interaction for fruit length was non-significant. For the rest of fruit and bean characters: fruit width (FW), fruit thickness (FT), bean length (BL), bean width (BW), bean thickness (BT) and hundred bean weight (HBW) analysis of variance for genotype x environment interaction was significant. Analysis of variance results for genotype and location was also highly significant at ($P<0.01$) for all fruit and bean characters recorded and analyzed, indicating the variation among genotypes and study locations.

Quality parameters

The trend of genotype x environment interaction seems to be different for quality characters from that of yield, growth and leaf characters. All quality characters exhibited significant genotype x environment interaction suggesting the interaction of both genotype and environment influence for quality characters. Genotype x Environment interaction was significant ($p<0.01$) for aromatic intensity (AI), bitterness (BIT), body (BOD), flavor (FLA), overall standard (OVS) and significant ($P<0.05$) for astringency (AST) and shape & make (SH&MK). This result was in line with the result observed by Getu (2009) in that he observed highly significant interaction for all organoleptic quality attributes except astringency and bitterness. Similarly, Agwanda *et al* (2003) indicated the presence of strong Genotype x Environment that challenges development of wide adapting cultivars. Whereas Walyaro (1983) reported lower Genotype x Environment interaction. On the other hand Van der Vossen (1985) observed non-significant Genotype x Environment interaction. These results indicate the need for fine tuning of G x E interaction for coffee organoleptic quality characters by conducting similar observations. In addition, the analysis of variance showed significant difference among genotypes for all traits indicating reasonable difference among genotypes under study.

Table 9: Mean squares of genotype, location, and interaction for growth parameter, leaf character, yield, fruit, bean and quality characters

Source	Genotype	Loc	Genotype *Loc	Block	Error
DF	15	2	30	2	94
Growth parameters					
PH	1644.79**	20170.90**	196.75NS	2248.40**	118.37
HFPB	54.24**	442.80**	7.41 NS	1.05 NS	6.18
SG	1.64**	3.34**	0.08 NS	0.05 NS	0.06
LFPB	992.14**	1614.77**	82.00*	123.27 NS	49.07
IL	1.56 **	9.96**	0.11 NS	2.19**	0.10
Leaf characters					
LL	8.63**	56.90**	0.81 NS	0.55 NS	0.58
LW	4.07**	8.70**	0.19 NS	0.06 NS	0.14
LA	1265.04**	4424.25**	100.25*	46.27 NS	56.75
LPL	0.05**	0.23**	0.01 NS	0.002 NS	0.01
yield, fruit and bean characters					
YL	104.76**	57.89**	8.51 NS	3.87 NS	6.82
FL	4.26**	14.85**	0.40 NS	16.92**	0.71
FW	1.65**	2.46**	0.22*	0.48*	0.13
FT	2.37**	1.44**	0.24*	0.21 NS	0.13
BL	3.05**	6.90**	0.36**	0.02 NS	0.08
BW	0.20**	0.70**	0.03*	0.01 NS	0.02
BT	0.19**	0.47**	0.03**	0.01 NS	0.02
HBW	20.96**	43.15**	3.49**	0.65 NS	0.91
Quality parameters					
AI	0.123**	0.438**	0.097**	0.142**	0.001
AST	0.045**	0.001ns	0.011*	0.009ns	0.006
BIT	0.051**	0.074**	0.018**	0.005ns	0.003
BOD	0.077**	1.921**	0.195**	0.083**	0.001
FLA	0.343**	1.359**	0.097**	0.003ns	0.001
OVS	0.323**	0.843**	0.107**	0.003ns	0.0006
SH&MK	5.733**	0.674ns	2.363*	7.001**	0.026
OS14	4.102**	6.049**	1.900**	1.507*	0.001

* ,** significant at 0.05 and 0.01 probability level. Ns=non- significant PH=plant height, HFPB=height up to first primary branch, SG=stem girth, LFPB=length of first primary branch, IL=internode length, LL=leaf length, LW=leaf width, LA=leaf area, LPL=leaf petiole length YL=yield, FL=fruit length, FW=fruit width, FT=fruit thickness, BL=bean length, BW=bean width, BT=bean thickness, HBW=hundred bean weight AI=aromatic intensity, AST=astringency, BIT=bitterness, BOD=body, FLA=flavor, OVS=over all standard, SH&MK=shape and make, OS14=over screen 14

4.2. Performance of Parents and F_1 Progenies

4.2.1. Performance of parents and their crosses across three environments

Based on the homogeneity test, those traits which have shown homogenous error variance with non-significant interaction were yield (YL), fruit length (FL), plant height (PH), height up to first primary branch (HFPB), stem girth (SG), internode length (IL), leaf length (LL), leaf width (LW) and leaf petiole length (LPL). These groups were compared with the mean value and LSD results of over location analysis because of the non-significant interaction result observed across location. The reason is no change in relative performance of genotypes in over location and no need to discuss individual location mean. Though the interaction results are non-significant there is highly significantly different among genotypes for all traits mentioned above (Table 10).

Yield is the major and important trait which showed non-significant interaction among the three study locations. The genotype difference observed was highly significant. Very interesting difference between hybrids mean and parental lines mean for average yield kg ha^{-1} was observed. The hybrid mean value observed was 1739 and that of parental lines mean was 1231 kg ha^{-1} for four years average yield. This high difference clearly indicates that the possible comparative advantage that can be achieved by crossing of two different parents. Crosses that exhibited very high yield were P2XP4, P1XP5 and check hybrid Ababuna with average yield results of 2102, 1982 and 1885 kg ha^{-1} clean coffee respectively. The former two hybrids showed greater value than the commercial released hybrid Ababuna even though they are not statistically significantly different. This result indicates the possible chance of acquiring additional commercial hybrid varieties.

Fruit length also showed significant difference for genotypes but there is no as such clear difference in mean value of hybrids from that of parental mean. Even the highest value observed for parental line P2 and its cross P1XP2 exhibiting 17.66 and 17.33 mm length respectively. Parental line P2 has large bean size yet all of its crosses have shown less mean value than this parent (Table 10). This result may give some clue in that fruit length may not be improved by crossing or long bean length may not be dominant over short.

The only cross that exceeded in height over check was cross P2XP4 exhibiting plant height of 217.4 cm. Generally all the hybrids exhibited better vigor than parental mean value. This result was similar with the result observed by Bertrand *et al.,* (1997) in that they observed F1 hybrids are more vigorous and more productive than the best varieties in Central America. The average mean value of hybrids for PH, HFPB, SG and IL was 208.5, 27.76, 5.02 and 5.42 respectively. This result was significantly exceeded respective parental mean value of 186.71, 26.57, 4.485 and 5.0.

Similarly, average value of hybrids; exceeded average value of parents for LL, LW and LPL. Hybrids that showed significantly longer leaf were P2XP4, P1XP4 and check hybrid with the average value of 14.3, 13.8 and 13.7 cm. The highest results of leaf width observed from P2 and its cross P2XP4 with the average value of 6.2 and 6.3 cm respectively, indicating the broad leaved nature of P2. The average value of crosses with one of their parents is P2 showed greater value than the check hybrid Ababuna. The trend was the same for P2 for leaf petiole length (Table 10).

It was noted that for each individual characters the average value of hybrids exceeded the average value of parents indicating the apparent advantage of the hybrids over their parents and the possibility to make further progress through hybridization among selected indigenous lines. This result is in support of the recommendation made by Bayetta (1991), Mesfin and Bayetta (1983).

Table 10: Mean performance of parents and their crosses across three environments for Yield and some growth & leaf parameters

Entries	Yield (kg/ha)	Fruit Length (mm)	Leaf Length (cm)	Leaf Width (cm)	Leaf Petiole Length (cm)	Plant Height (cm)	Height up to first primary branch (cm)	Girth (cm)	Internodes length (cm)
P1XP2	1593	17.33	13.3	5.7	1	207.4	29.6	4.79	5.5
P1XP3	1359	15.75	12.6	4.9	0.9	205	28.1	4.775	5.1
P1XP4	1744	16.03	13.8	6	1	215.9	31.9	5.435	6.1
P1XP5	1982	15.66	12.2	4.9	1	209.2	28.7	5.118	5.5
P2XP3	1483	16.02	12.7	5.4	0.9	199.2	26.3	4.503	5.1
P2XP4	2102	16.59	14.3	6.3	1.1	217.4	27.8	5.412	5.9
P2XP5	1852	16.65	12.6	5.3	1.1	205.8	27.9	5.151	5.2
P3XP4	1791	15.78	12.8	5.2	0.9	209.2	23	4.898	5.6
P3XP5	1796	15.48	11.2	4.2	0.9	212.6	26.9	4.824	4.9
P4XP5	1684	15.93	12.4	5.1	1	203.3	27.4	5.294	5.3
Hybrids Mean	**1739**	**16.12**	**12.79**	**5.3**	**0.98**	**208.5**	**27.76**	**5.02**	**5.42**
P1	1111	15.98	12.2	5	0.9	183.8	29.4	4.441	5.1
P2	127	17.66	13.4	6.2	1.1	180.6	29	4.471	5.3
P3	788	14.89	10.9	4	0.8	172.2	23.9	3.75	4.4
P4	1483	15.75	12.7	5.4	0.9	190.2	25.2	5.011	5.1
P5	1502	15.81	11.1	4.3	1	207	25.4	4.751	5.1
Parents Mean	**1231**	**16.02**	**12.06**	**4.98**	**0.94**	**186.76**	**26.58**	**4.4848**	**5**
Ababuna	1885	16.33	13.7	5.6	1.1	215.8	31.3	5.036	5.9
Mean	**1589**	**16.1**	**12.6**	**5.2**	**1**	**202.2**	**27.6**	**4.854**	**5.3**
F test	**	**	**	**	**	**	**	**	**
LSD (5%)	244	0.79	0.71	0.345	0.07	10.2	2.3	0.236	0.3
CV(%)	16.43	5.25	6.016	7.06	8.016	5.4	9	5.207	5.9

** Significant at 0.01 probability level

4.2.2. Performance of parents and progenies with significant GXE interaction

Out of thirty traits recorded in this study two of the growth characters: length of first primary branch (LFPB), leaf area (LA); six of the fruit and bean characters: fruit width(FW), fruit thickness(FT), bean length(BL), bean width(BW), bean thickness(BT), hundred bean weight(HBW); and eight of the quality characters: aromatic intensity(AI), astringency(AST), bitter ness(BIT), body(BOD), flavor(FLA), over all standard(OVS), shape &make(SH&Mk), over screen 14(OS14) showed significant GXE interaction based on combined analysis (Table 11 to 13). To compare individual location mean values for each trait one LSD value which were acquired from the combined analysis was used. This is because of the presence of homogenous error variance.

Branch and Leaf characters

The mean performance of length of first primary branch and leaf area presented on Table 11 and discussed as follows.

For the trait length of first primary branch (LFPB) the highest results was observed by crosses P1XP2, P2XP4, P2XP5, P4XP5 at Tepi, crosses P2XP4 and P4XP5 at Metu and cross P2XP4 at Melko. In all the three locations cross P2XP4 consistently has the longest first primary branch indicating this hybrid is very open canopy in its nature.

For the leaf area the highest value observed for the cross P2XP4 at Tepi which is very significantly different from others followed by cross P1XP4 at Tepi and P2 at Metu. The largest leaf area size of cross P2XP4 is due to the large leaf nature of both parental lines P2 and P4.

Table 11: Mean performances of coffee genotypes at three locations for branch and leaf characters that showed significant GXE interactions

Entries	Length of first primary branch (cm)				Leaf Area (cm^2)			
	Melko	Metu	Tepi	mean	Melko	Metu	Tepi	mean
P1XP2	88	96.7	117.7	**100.8**	59.1	71.6	71.9	**67.5**
P1XP3	83.3	96.7	100	**93.3**	43.8	67.5	51.6	**54.3**
P1XP4	102.7	110	111	**107.9**	55.9	80.3	83.9	**73.4**
P1XP5	96	109.3	107	**104.1**	45.6	60.2	53.9	**53.2**
P2XP3	79.3	98.7	100.3	**92.8**	52.3	67.1	63.7	**61.0**
P2XP4	114.3	110.7	115.7	**113.6**	59.9	82.3	96.7	**79.6**
P2XP5	97.3	110	114.7	**107.3**	49.5	68.3	60	**59.3**
P3XP4	90.3	96.7	100.7	**95.9**	46.5	65.3	65.6	**59.1**
P3XP5	87.7	94.3	94.7	**92.2**	34.6	50.5	40	**41.7**
P4XP5	101.3	111	112.7	**108.3**	44.8	63	60.7	**56.2**
Hybrids Mean	**94.02**	**103.41**	**107.45**	**101.6**	**49.2**	**67.61**	**64.8**	**60.5**
P1	80.7	99.3	100	**93.3**	43.9	56.4	60.8	**53.7**
P2	88.7	96	99.3	**94.7**	58.6	87.8	74.4	**73.6**
P3	67.3	73.3	64	**68.2**	31.5	46.7	36.3	**38.2**
P4	101.7	98	94.7	**98.1**	55.4	65.6	59.7	**60.2**
P5	83.3	91.3	93.3	**89.3**	37.6	47.9	41.6	**42.4**
Parents Mean	**84.34**	**91.58**	**90.26**	**88.7**	**45.4**	**60.88**	**54.56**	**53.6**
Ababuna	90.7	96	104.7	**97.1**	48.2	75.7	81	**68.3**
Mean				**97.3**				**58.9**
F test				*				*
LSD (5%)				6.6				7.05
CV(%)				7.2				12.8

*significant at 0.05 probability level

Fruit and bean characters

As it is mentioned above, all of the bean characters and two of the fruit characters have shown homogenous error variance and each location mean value discussed with one LSD value. As it is illustrated in the Table 12 the highest fruit width (FW) was observed at Metu for the parental line P2 with average value of 13.05 mm width. The FW of this parent is consistently higher in all study sites indicating the boldness of this parent and none of its cross showed comparable size; this probably indicate the largest fruit size may not be transferred to the off spring. Similar trend was observed for fruit thickness (FT) in that the same parental line exceeded all other crosses and parents exhibiting 15.1 mm thickness at Metu.

For the traits bean length(BL), bean width(BW), bean thickness (BT) and hundred bean weight (HBW) even though an interaction of GXE is significant and environment contributed for the difference, the size of parental line P2 was high for most of these traits. Still parental line P2 showed the higher BL at Tepi and Melko with the mean value of 11.42 and 11.37 mm length respectively. Except cross P2XP3 all other crosses with one of their parents is P2 have shown relatively the highest mean value. The relative lower value of cross P2XP3 may be due to the small bean sized nature of P3. With Regard to the bean width the widest cross appeared to be the check hybrid Ababuna followed by cross P2XP5 and parental line P2 with the average value of 7.49, 7.37 and 7.35 mm width respectively at Melko. For the trait BT cross P2XP4 at Melko, parent P2 at Tepi and cross P2XP5 at Melko were the highest with respective value of 4.46, 4.37 and 4.35 mm.

Coste (1968) suggested 100 bean weight is in an average range of 18-22 gm for arabica coffee. The result observed in this study was almost in this range, of course it was observed that some upper and lower results for some crosses and parental lines. Hundred bean weight (HBW) was computed at 11% moisture bases and the highest record was 22.97 gm for P2 followed by cross P2XP4 with value 21.37 gm and cross P2XP5 with value of 21.27 gm at Melko. Likewise cross P2XP4 at Tepi with the average value of 21.13 gm showed better results.

Quality characters

Mean performance of organoleptic characters presented on Table 13 and discussed as follows.

Liquor quality is undoubtedly the most important factor that determines the suitability of coffee for human consumption (Agwanda, 1999). Among quality characters having error variance homogenous and GXE interaction significant were aromatic intensity (AI), astringency(AST), bitterness(BIT), body(BOD), flavor(FLA), over all standard(OVS) shape & make(SH&MK) and over screen 14(OS14).

Six hybrids and two parents at Melko, three hybrids and one parent at Metu, nine hybrids and two parents at Tepi showed higher value than the respective mean value. Best aromatic intensity value was recorded for the parental line P3 at Metu followed for parental line P5 at Melko with respective value of 4.0 and 3.9.

Astringency (AST) and bitterness (BIT) are undesirable characteristics in coffee quality. For this reason lower value appeared to be best. In the study similar trend was observed in that for both characters less average value attained at Metu than the rest two locations. Seven of the sixteen entries gave zero value for AST at Metu and Tepi, only four of the sixteen genotypes were zero at Melko. As it is mentioned at Metu only three of the treatments shown slight bitterness all the rest has zero bitterness values.

Body (BOD) is one of the critical estimators of the coffee quality in which the mouth fullness of the coffee is manifested with the high value of this characteristic (Agwanda, 1999). High average value of body observed was at Melko followed by Metu and Tepi with 3.47, 3.39 and 3.09 values respectively. The higher value was observed for the hybrid P2XP5, parental lines P3 and P5 with similar high value 3.8.

Agwanda (1999) in his study concluded that flavor rating is the best selection criterion for the genetic improvement of liquor quality in arabica coffee. In this study also flavor considered as very important quality trait which is distinguished by sensory analysis. Location wise the highest average result was observed at Metu followed by Melko and Tepi with the average of 3.25, 3.15 and 2.92 respectively. Surprisingly the best genotype was parental line P3 in all locations. This parental line shown very interesting result at Metu followed by Melko and Tepi with the value of 4.0, 3.8 and 3.5 respectively though statistically different from one location to the other. No other hybrid or parental line performed such best and consistent result across location.

Over all standard (OVS) is also the cumulative effect of different quality parameters that is evaluated by cuppers. Quite similar result was observed with that of flavor. Still parental line P3 manifested its superiority with regard to quality character over all locations with similar trend.

The other physical quality characters which were analyzed across location were shape &make (SH&MK) and over screen 14 (OS14). Parental line P3 shown very good shape and make value in all locations.

For almost all quality characteristics hybrids involving P3 as one of their parental line didn't performed similar to the parent, probably indicating non-transferable behavior of the trait or not dominant characteristics of the trait. The references on the inheritance for coffee quality traits was very scarce and difficult to compare with others work. On the review paper of Bertrand et al., (2006) it was indicated no clear differences for bean chemical contents and cup quality in sensory evaluations comparing F_1 hybrids with traditional cultivars under various edapho-climatic conditions and at different elevations that they tested. The review do not clearly mentioned the F1's with parental lines.

Table 12: Mean performance of entries in each of the test locations for fruit and bean characters that showed significant GXE interactions

Entries	Fruit width (mm)			Fruit thickness (mm)			Bean length (mm)			Bean width (mm)			Bean thickness (mm)			Hundred bean weight at 11% moisture (gm)		
	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	12.18	12.34	12.37	14.17	14.14	14.31	10.78	9.85	11.12	7.22	6.94	6.85	4.22	3.96	4.17	21.1	18.4	20.07
P1XP3	11.51	11.3	11.39	13.29	13.19	13.2	9.29	8.74	9.53	7.03	6.71	6.81	4.25	3.9	4.02	19.37	17.03	15.63
P1XP4	11.61	11.98	11.48	13.69	13.86	13.57	10.07	9.02	10.21	6.84	6.73	6.92	4.04	3.99	4.18	20	16.47	19.7
P1XP5	11.68	11.86	11.28	13.2	13.36	13.06	9.5	9.88	10.22	7.14	6.92	6.87	4.08	3.94	4.11	19.6	18.9	18.4
P2XP3	11.5	11.8	11.2	13.27	13.89	13.25	9.48	9.23	10.09	6.99	6.78	7	4.13	4.01	4.13	19.07	17.17	17.03
P2XP4	11.81	12.59	11.85	13.77	14.74	14.24	10.54	9.23	10.91	7.11	7.13	7.03	4.46	3.89	4.29	21.37	17.87	21.13
P2XP5	11.93	11.98	11.64	13.53	13.53	13.56	10.66	10.08	10.58	7.37	7.13	7.06	4.35	3.9	4.09	21.27	18.97	19.73
P3XP4	11.44	11.35	10.87	13.33	13.5	13.25	9.58	8.97	10.04	6.93	6.9	6.83	4.16	3.95	4.15	19.37	18.63	16.67
P3XP5	11.41	12.07	10.74	12.89	13.52	12.5	9.34	10.05	9.64	6.9	6.98	6.78	3.98	4.02	3.89	17.5	17.43	16.23
P4XP5	11.53	11.88	11	13.2	13.33	13	9.48	9.47	9.9	6.95	6.66	6.9	3.96	3.92	4.1	18.07	15.77	17.77
Hybrids Mean	**11.66**	**11.92**	**11.38**	**13.43**	**13.71**	**13.39**	**9.87**	**9.45**	**10.22**	**7.05**	**6.89**	**6.91**	**4.16**	**3.95**	**4.11**	**19.67**	**17.66**	**18.24**
P1	12.21	11.93	11.97	13.65	13.31	13.32	9.65	9.26	9.72	7.05	6.77	7	3.98	3.96	3.97	17.93	17.33	16.77
P2	12.18	13.05	12.4	14.15	15.1	14.15	11.37	10.73	11.42	7.35	6.89	7.01	4.4	4.18	4.37	22.97	18.07	19.63
P3	11.39	10.78	10.51	13.03	12.75	12.12	8.7	8.76	8.79	6.95	6.58	6.76	3.83	3.88	3.78	15.4	14.9	14.63
P4	11.39	11.58	11.04	13.38	13.46	12.93	9.48	8.5	10.33	6.94	6.58	6.88	4.06	3.88	4.04	17.3	14.9	17.47
P5	11.55	11.47	11.23	12.7	12.87	12.63	9.65	9.28	9.46	6.93	6.59	6.87	3.74	3.66	3.72	16	17.2	15.67
Parents Mean	**11.74**	**11.76**	**11.43**	**13.38**	**13.50**	**13.03**	**9.77**	**9.31**	**9.94**	**7.04**	**6.68**	**6.90**	**4.00**	**3.91**	**3.98**	**17.92**	**16.48**	**16.83**
Ababuna	11.52	12.25	12.02	12.85	13.68	13.85	9.98	9.42	10.58	7.49	7.04	7.31	3.98	3.61	4.08	18.73	16.17	18.8
Mean	**11.67**			**13.44**			**9.8**			**6.95**			**4.03**			**18.03**		
F test	*			*			**			*			**			**		
LSD (5%)	0.33			0.34			0.27			0.14			0.12			0.89		
CV(%)	3.06			2.71			2.93			2.08			3.17			5.3		

* ,** significant at 0.05 and 0.01 probability level

Table 13: Mean performance of entries in each of the test locations for quality characters that showed significant GXE interactions and homogenous error variance based on combined analysis

Entries	Aromatic Intensity			Astringency			Bitterness			Body			Flavor			Over all standard			Shape &Make			Over screen 14 (%)		
	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	3.8	3.1	3.6	0.17	0.17	0.17	0.13	0.0	0.0	3.5	3.3	2.9	3.2	3.2	2.8	3.3	3.2	2.9	12.0	14.0	13.0	99.0	97.0	98.7
P1XP3	3.5	3.4	3.8	0.0	0.0	0.25	0.0	0.0	0.25	3.1	3.4	3.6	3.2	3.3	2.9	3.2	3.5	3.1	12.0	12.0	13.0	98.0	98.3	98.0
P1XP4	3.5	3.7	3.8	0.08	0.3	0.0	0.42	0.0	0.42	3.4	3.4	3.1	2.8	3.1	3.1	3.0	3.3	3.3	12.0	13.0	13.0	99.3	97.3	99.0
P1XP5	3.8	3.5	3.5	0.33	0.0	0.17	0.5	0.0	0.08	3.5	3.4	3.0	2.8	3.2	3.0	3.0	3.2	3.2	12.0	12.0	14.0	98.7	97.7	99.0
P2XP3	3.6	3.5	3.3	0.0	0.0	0.08	0.58	0.0	0.0	3.7	3.4	2.9	3.0	3.0	3.0	3.2	3.1	3.0	12.0	12.0	12.0	97.3	98.3	96.0
P2XP4	3.7	3.5	3.8	0.08	0.0	0.0	0.33	0.0	0.25	3.6	3.5	3.0	3.2	3.4	2.7	3.1	3.5	3.0	13.0	12.0	12.0	99.0	97.7	98.7
P2XP5	3.7	3.8	3.8	0.17	0.50	0.17	0.0	0.0	0.5	3.8	3.7	2.6	3.4	3.6	2.6	3.5	3.7	2.8	13.0	12.0	14.0	99.0	98.0	99.0
P3XP4	3.5	3.5	3.8	0.25	0.25	0.0	0.0	0.0	0.25	3.3	3.3	3.4	3.3	3.4	2.9	3.3	3.4	2.9	14.0	14.0	14.0	99.0	97.7	98.3
P3XP5	3.5	3.2	3.6	0.25	0.0	0.08	0.0	0.17	0.0	3.5	3.4	2.9	3.0	2.9	2.9	3.2	2.9	3.0	14.0	12.0	12.0	98.7	98.3	98.3
P4XP5	3.5	3.4	3.6	0.0	0.0	0.0	0.0	0.0	0.08	3.0	3.4	3.4	3.0	3.3	3.0	3.0	3.4	3.0	13.0	12.0	12.0	98.3	98.0	98.3
P1	3.4	3.3	3.6	0.33	0.50	0.0	0.17	0.0	0.08	3.6	3.4	3.0	2.8	3.1	2.7	3.0	3.3	2.9	12.0	13.0	10.7	98.3	97.3	98.0
P2	3.4	3.1	3.4	0.13	0.08	0.08	0.17	0.0	0.0	3.3	3.5	2.9	3.2	3.1	2.8	3.3	3.3	3.0	13.0	13.0	12.0	98.7	98.3	99.0
P3	3.7	4.0	3.4	0.08	0.0	0.08	0.0	0.0	0.0	3.8	3.7	3.3	3.8	4.0	3.5	3.8	4.1	3.7	15.0	15.0	14.0	98.0	98.0	98.0
P4	3.4	3.3	3.8	0.0	0.25	0.33	0.0	0.0	0.08	3.1	3.1	3.4	3.0	2.9	3.0	3.2	3.1	3.1	14.0	12.0	14.0	98.3	97.7	97.7
P5	3.9	3.3	3.5	0.33	0.25	0.0	0.0	0.08	0.0	3.8	3.2	3.0	3.5	3.1	3.0	3.6	3.0	3.1	10.0	12.0	12.0	94.7	97.3	98.0
Ababuna	3.6	3.6	3.6	0.08	0.25	0.0	0.0	0.17	0.25	3.5	3.3	3.0	3.3	3.3	2.8	3.3	3.3	2.9	12.0	12.0	14.0	97.3	94.7	97.3
Mean	**3.5**			**0.1**			**0.1**			**3.3**			**3.1**			**3.2**			**12.7**			**98.0**		
F test	**			*			**			*			**			**			**			**		
LSD (5%)	0.19			0.07			0.05			0.23			0.17			0.17			1.19			0.78		
CV(%)	5.8			9.62			7.4			7.5			5.9			5.6			10.0			0.9		

* ,** significant at 0.05 and 0.01 probability level

4.2.3. Mean performance of entries for individual locations

Growth characters

Mean performance of entries for growth characters is given in Table 14. At Melko the highest NPB was observed for cross P3XP5 and parental line P5 with average number of 73.7 and 70.7 primary branches. With similar trend at Metu, cross P3XP5 and parental line P5 still showed the highest branch number even though they are not statistically different from crosses P1XP2, P1XP5, P2XP3, P2XP5, P4XP5 and parental line P3. At Tepi with similar trend cross P3XP5 showed the highest followed by cross P2XP3 resulting 65 and 62 primary branches respectively. In all locations cross P3XP5 consistently showed the highest number of primary branch.

Number of node (NN) is directly proportional to number of primary branches in that primary branches emerged from primary nodes. Because of this the trend of data was very similar for all crosses and parental lines. Genotypes that showed the highest number of primary branches had also the higher number of nodes.

The canopy diameter (CD) manifests the spacing coverage of a given genotype. In general the mean value of all treatments at Tepi is higher than the two sites due to the high vegetative growth rate at this site. The average diameter of all hybrids and parents is 180.1, 156.2 and 147.4 cm at Tepi, Melko and Metu respectively. At Melko the highest canopy diameter value was observed for cross P1XP4 with the value of 188.3 cm. showing non- significant results with cross P2XP4 and parental line P4. At Metu the largest canopy was observed from cross P1XP4 (162.3) and the lowest F1 was shown by P1XP3 (138.7 cm). Among parents the highest canopy diameter (158 cm) was shown by P5 and the lowest canopy of 120 cm by P3. At Tepi still the highest canopy diameter observed for cross P1XP4 (217 cm) and the lowest P2XP3 with (156 cm). The highest canopy was observed for pure line P4(198 cm) and P3 was the lowest. In all the three locations pure line P3 showed the lowest canopy diameter indicating the compact nature of the line and indicating its compatible nature for closer plant spacing. On the other hand cross P1XP4 consistently showed larger canopy diameter in all the three locations demonstrating its requirement of large plant spacing for this cross.

Table 14**:** Mean performance of entries for some of growth parameters in each of testing locations

Entries	Number of Primary Branch (No)			Number of Node (No)			Canopy Diameter (cm)		
	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	55.3	62	57	30.7	33.7	31.7	147.3	150.7	169.7
P1XP3	62	60	60.3	34.3	33.7	33.3	146.3	138.7	168.7
P1XP4	59.3	56	56.7	31	30	31.3	188.3	162.3	217
P1XP5	62.7	62	59.3	33	34	33	159.3	157	183.7
P2XP3	62.3	63	62	33.7	34.7	33.7	135.3	140.7	156
P2XP4	62.7	59.7	59.7	32.7	32.7	32.3	186	157.7	214.7
P2XP5	64.3	62.7	62	34.7	33.3	34.3	167.7	149	193.3
P3XP4	63.3	61	61.7	32.7	35	34.3	158.7	149	183
P3XP5	73.7	68	65	38.3	36.7	36	150.3	142.3	173.3
P4XP5	63.7	63.7	60.3	33.7	34.7	33.3	170.7	160	196.7
P1	58	54.7	55.3	30	30.3	30.7	141.3	135.7	163
P2	52	50.7	54.7	29.3	29.3	30.3	157	136	181
P3	65	61.3	55.3	36	33.7	30.7	111.3	120	128.3
P4	62.3	56.3	56	34.3	32	31	171.7	149.3	198
P5	70.7	67.7	60.3	36.7	35.7	33.3	145.7	158	168
Ababuna	63.7	55.3	58.7	33	31	32.3	162	152.3	186.7
Mean	**62.7**	**60.3**	**59**	**33.4**	**33.2**	**32.6**	**156.2**	**147.4**	**180.1**
F test	**	**	**	**	**	**	**	**	**
LSD (5%)	7.8	6.7	3.1	4	2.8	1.4	17.2	11.1	19.8
CV(%)	7.5	6.7	3.2	7.2	5.1	2.6	6.6	4.5	6.6

** highly significant at 0.01 probability levels

Quality characters

As depicted in Table 15 aromatic quality (AQ) and acidity (AC) discussed in individual locations.

Aromatic quality is the trait that cuppers observed by sniffing of coffee after the boiled water poured in to ground coffee. At Melko the best aromatic quality observed from P3 followed by P5 with non-significant values of 4.2 and 4.0, respectively. Similarly at Metu parental line P3 was significantly different from other treatments with value of 4.1. At Tepi also significant difference among genotypes was observed for this trait. In this location cross combination P1XP4 showed the higher result with value of 3.8 for aromatic quality.

Acidity is one of the pertinent organoleptic quality attributes of coffee brews parameters for coffee (Agwanda, 1999). In all locations statistically different results was observed. At Melko, the highest result detected from parental lines P3, P5 and cross P2XP5 with respective value of 3.8, 3.7 and 3.6. Similarly at Metu P3 was the best with value of 3.9 followed by cross P2XP4 and P2XP5 even though statistically different from P3. Consistent result was observed for P3 at Tepi followed by cross P1XP4 exhibiting 3.8 and 3.4 values. Generally, the overall mean of acidity at Tepi was lower than Melko and Metu. This result is in agreement with the result observed by Getu (2009). He argued that variation of some organoleptic characters like acidity and aromatic intensity are more attributed to location. Similarly, Hawaii Cvaletto *et al.,* (1991) reported distinct effect of elevation on acidity; with acidity positively correlated to elevation. Similarly, Brollo *et al.,* (2008) stated that acidity influenced by several factors including variety, origin, processing roasting degree and brewing method.

Generally the consistent quality results of P3 is not manifested in to its F1 progeny which implies that this genes controlled might be recessive and this requires further inheritance study supported by generation mean analysis and molecular markers.

Table 15: Mean performance of coffee genotypes for some of quality characters at each of the three testing locations

	Aromatic Quality			Acidity		
Entries	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	3.6	3.2	3.4	3.3	3.2	2.7
P1XP3	3.3	3.5	3.6	3.1	3.3	3.1
P1XP4	3.5	3.4	3.8	3.0	3.5	3.4
P1XP5	3.7	3.6	3.6	2.9	3.4	3.2
P2XP3	3.3	3.2	3.5	3.2	3.3	2.9
P2XP4	3.4	3.6	3.5	3.4	3.7	2.9
P2XP5	3.3	3.3	3.5	3.6	3.7	2.8
P3XP4	3.3	3.5	3.3	3.3	3.5	3.0
P3XP5	3.4	3.0	3.5	3.2	2.9	2.9
P4XP5	3.4	3.4	3.6	3.1	3.3	3.0
P1	3.3	3.5	3.1	3.0	3.3	2.8
P2	3.1	3.1	3.5	3.3	3.3	3.2
P3	4.2	4.1	3.4	3.8	3.9	3.8
P4	3.4	3.3	3.6	3.1	3.3	3.3
P5	4.0	3.3	3.5	3.7	3.3	3.0
Ababuna	3.8	3.6	3.3	3.4	3.2	2.8
Mean	**3.5**	**3.4**	**3.5**	**3.3**	**3 .4**	**3.0**
F test	**	**	**	**	**	**
LSD (5%)	0.08	0.22	0.28	0.2	0.16	0.2
CV(%)	5.4	3.9	4.8	3.6	2.9	3.9

** highly significant at 0.01 probability levels

4.3. Heterosis

4.3.1. Estimates of heterosis at each locations for some growth and quality characters

Melko

Results of estimates of percentage heterosis over mid-parent (MP), over better-parent (BP) and over check hybrid (CH) for traits such as number of primary branch (NPB), number of node (NN), canopy diameter (CD), aromatic quality (AQ) and acidity is depicted in Table 16.

Growth characters

No hybrid showed significant heterosis over mid-parent and better parent for number of primary branch and number of node. Only cross P3XP5 showed significant heterosis over check hybrid (CH) Ababuna for these traits at Melko. Regarding canopy diameter, cross combinations P1XP3, P1XP4, P1XP5, P2XP4, P2XP5, P3XP4 and P3XP5 showed positive and significant MP heterosis. No cross showed BP heterosis for number of primary branch, number of node and canopy diameter. On the other hand, only cross combination P1XP4 and P2XP4 exhibited significant heterosis over CH for canopy diameter.

Quality characters

Percent heterosis for aromatic quality ranges from -17.9 to 11% for MP value. Crosses: P1XP2, P2XP4 and P1XP4 showed highly significant MP heterosis with values of 11%, 3.2% and 2.5%, respectively. Almost all crosses showed negative value of BP heterosis indicating better aromatic quality of parental lines than their hybrids. Similarly, negative values resulted for all CH heterosis showing better aromatic quality of check hybrid Ababuna than all crosses at Melko.

Crosses P2XP4, P1XP2 and P2XP5 showed highly significant heterosis values with respective values of 8.1, 5.3 and 4.3 percent acidity over MP. Similar to aromatic quality almost all hybrids exhibited negative to zero value over BP and over CH heterosis for acidity indicating better performance of parental line and check hybrid Ababuna than hybrids included in the study.

Metu

Results of percentage heterosis MP, BP and CH for traits number of primary branch, number of node, canopy diameter, aromatic quality and acidity is depicted in Table 17.

Growth characters

The highest and significant MP heterosis was observed for crosses P1XP2, P2XP3 and P2XP4 with percentage values of 17.7, 12.5 and 11.5, respectively for number of primary branch. Only cross P1XP2 showed significant heterosis BP with 13.4% value for this trait and significant heterosis CH was observed for number of primary branch for cross combinations P2XP3, P2XP5, P3XP5 & P4XP5. The trend was the same for number of node except for cross P1XP5 and P4XP5.

Significant and high percent MP heterosis was observed for majority of crosses for canopy diameter. The values ranged from 1.4 to 13.9; cross P1XP4, P1XP2 and P3XP4 being crosses with higher respective heterosis values of 13.9, 10.9 and 10.6%. The highest and significant BP heterosis was observed for the cross P1XP2 with percent BP heterosis of 10.8 followed by cross P1XP4 with percent BP heterosis of 8.7 for canopy diameter.

Quality characters

The highest and significant MP heterosis for aromatic quality was observed for cross P2XP4 followed by P1XP5, P4XP5 and P2XP5 with respective values of 12.5, 6.3, 2.7 and 1.9%. The same crosses except P2XP5 showed better BP heterosis with positive and significant value. Similar to results observed at Melko no crosses in the study showed better CH hetersis for aromatic quality suggesting better aromatic quality of check hybrid Ababuna.

The highest and significant MP heterosis for acidity was recorded for crosses P2XP5, P2XP4 and P1XP4 with respective value of 12.9, 12.2 and 5.8%. Similar crosses showed highest and significant BP heterosis for the trait acidity.

Table 16: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for some growth and quality characters of coffee hybrids at Melko

Crosses	Heterosis percentage														
	Number of primary branch			Number of Nodes			Canopy Diameter			Aromatic quality			Acidity		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	0.6	-4.6	-0.13	3.4	0.6	-0.07	-1.2	-6.2	-9.1	11.0**	7.5**	-0.05	5.3**	1.2	-0.03
P1XP3	0.8	-4.6	-0.03	4.0	0.8	0.04	15.8**	3.5	-9.7	-13.1	-22.2	-0.13	-9.0	-18.5	-0.09
P1XP4	-3.3	-8.2	-0.07	-3.6	-3.3	-0.06	20.3**	9.7	16.2**	2.4**	1.2*	-0.08	-2.6	-3.9	-0.12
P1XP5	-2.6	-11.3	-0.02	-1.0	-2.6	0.00	11*	9.3	-1.7	1.1	-7.3	-0.03	-13.0	-21.3	-0.15
P2XP3	6.6	-4.1	-0.02	3.1	6.6	0.02	0.9	-13.8	-16.5	-9.2	-21.0	-0.13	-8.8	-15.3	-0.06
P2XP4	7.4	-3.1	-0.02	2.6	7.4	-0.01	13.2**	8.3	14.8**	3.2**	-1.2	-0.11	8.1**	5.2	0.00
P2XP5	4.9	-9.0	0.01	5.1	4.9	0.05	10.8*	6.8	3.5	-7.4	-17.5	-0.13	4.3**	-2.2	0.06
P3XP4	-2.3	-2.6	-0.01	-7.1	-2.3	-0.01	23.5**	-7.6	-2	-15.0	-23.2	-0.13	-4.2	-13.2	-0.03
P3XP5	8.6	4.2	0.16*	5.5	8.6	0.16*	17**	3.2	-7.2	-17.9	-20.1	-0.11	-15.5	-16.4	-0.06
P4XP5	-5.9	-9.9	0.00	-5.2	-5.9	0.02	7.6	-0.6	5.4	-7.8	-14.5	-0.11	-7.8	-15.6	-0.09

*,** significant at 0.05 and 0.01 probability levels, respectively

Table 17: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for some growth and quality characters of coffee hybrids at Metu

Crosses	Heterosis percentage														
	Number of primary branch			Number of Nodes			Canopy Diameter			Aromatic quality			Acidity		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	17.7**	13.4*	0.12	12.9**	11.0*	0.09	10.9**	10.8*	-1.1	-3.2	-8.3	-0.11	-1.2	-1.2	0.00
P1XP3	3.4	-2.2	0.08	5.2	0.0	0.09	8.5*	2.2	-8.9	-8.3	-15.3	-0.03	-7.1	-15.1	0.03**
P1XP4	0.9	-0.6	0.01	-3.7	-6.3	-0.03	13.9**	8.7*	6.6	0.1	-3.4	-0.06	5.8**	5.2**	0.09**
P1XP5	1.4	-8.4	0.12	3.0	-4.7	0.10*	6.9*	-0.6	3.1	6.3**	3.7**	0.00	5.2**	5.2**	0.06**
P2XP3	12.5*	2.7	0.14*	10.1*	3.0	0.12*	9.9*	3.4	-7.6	-11.6	-22.3	-0.11	-9.3	-17.1	0.03**
P2XP4	11.5*	5.9	0.08	6.5	2.1	0.05	10.5**	5.6	3.5	12.5**	10.5**	0.00	12.2**	11.6**	0.16**
P2XP5	5.9	-7.4	0.13*	2.6	-6.5	0.07	1.4	-5.7	-2.2	1.9**	-1.2	-0.08	12.9**	12.9**	0.16**
P3XP4	3.7	-0.5	0.10	6.6	4.0	0.13**	10.6**	-0.2	-2.2	-6.2	-16.2	-0.03	-4.0	-11.7	0.09**
P3XP5	5.4	0.5	0.23**	5.8	2.8	0.18**	2.4	-9.9	-6.6	-18.5	-26.4	-0.17	-19.7	-26.5	-0.09
P4XP5	2.7	-5.9	0.15*	2.5	-2.8	0.12*	4.1	1.3	5.1	2.7**	1.5**	-0.06	0.6	0.0	0.03**

*,** significant at 0.05 and 0.01 probability levels, respectively

Tepi

Heterosis over mid parent, better parent and over check hybrid for traits number of primary branch, number of node, canopy diameter, aromatic quality and Acidity at Tepi were calculated and depicted on Table 18.

Growth characters

Estimates of MP heterosis for number of primary branch ranged from 1.8-12.7%. Crosses P2XP3, P3XP5 and P3XP4 showed high and significant MP heterosis values with 12.7, 12.4 and 10.8%, respectively. With similar trends crosses P2XP3 and P3XP4 showed greater than 10% BP heterosis. Negligible heterosis was found for CH heterosis for number of primary branch.

The trend of number of node for MP, BP and CH heterosis was the same with that of number of primary branch, since these two traits are highly correlated in coffee since the primary branch emerged from the main stem nodes.

Higher and significant MP heterosis was observed for seven crosses out of ten for canopy diameter. Crosses P1XP4, P3XP5 and P1XP3 were the highest heterosis value with 20.2, 17.0 and 15.8%, respectively, indicating the vigor increase of hybrids over mid parent value.

Quality characters

For the trait aromatic quality: four crosses out of ten showed positive and significant MP heterosis. Crosses P1XP4, P1XP3 and P1XP5 showed high MP heterosis value with 11.6, 10.7 and 9.6%, respectively. These three crosses similarly showed positive and significant BP heterosis for this trait.

At Tepi for acidity crosses P1XP4 and P1XP5 exhibited high and significant MP heterosis value of 11.8 and 10.1%. All the rest of the crosses showed negative value indicating the comparative low value of crosses from their respective parental lines for this trait. Similar results were obtained for BP heterosis except crosses P1XP4 and P1XP5 all the rest exhibited negative heterosis.

Table 18: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for some growth and quality characters of coffee hybrids at Tepi

Crosses	Heterosis percentage														
	Number of primary branch			Number of nodes			Canopy diameter			Aromatic quality			Acidity		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
1X2	3.6	3.0	-0.03	3.8	3.3	-0.02	-1.4	-6.3	-9.1	3.2*	-2.3	0.03*	-9.7	-14.5	-0.04
1X3	9.0**	9.0**	0.03	8.7**	8.7**	0.03	15.8*	-6.8	-9.6	10.7**	5.9**	0.09**	-6.1	-17.6	0.11**
1X4	1.8	1.2	-0.03	1.6	1.1	-0.03	20.2**	9.6	16.2**	11.6**	3.3**	0.15**	11.8**	4.0*	0.21**
1X5	2.6	-1.7	0.01	3.1	-1.0	0.02	11.0*	9.3	-1.6	9.6**	3.8*	0.09**	10.1**	7.0**	0.14**
2X3	12.7**	12.0**	0.06*	10.4**	9.8**	0.04	0.9	-13.8	-16.4	2.3	1.2	0.06**	-16.8	-23.2	0.04*
2X4	7.8**	6.5*	0.02	5.4*	4.3	0.00	13.3**	8.4	15.0**	-0.1	-2.5	0.06**	-10.8	-12.5	0.04*
2X5	7.8**	2.8	0.06*	7.9**	3.0	0.06**	10.8*	6.8	3.5	1.2	1.2	0.06**	-9.6	-12.0	0.00
3X4	10.8**	10.1**	0.05	11.4**	10.8**	0.06**	12.2*	-7.6	-2	-6.1	-9.4	0.00	-15.9	-21.1	0.07**
3X5	12.4**	7.7**	0.11**	12.5**	8.0**	0.11**	17.0**	3.2	-7.2	3.8	2.6	0.06**	-13.5	-22.1	0.04*
4X5	3.7	0.0	0.03	3.6	0.0	0.03	7.5	-0.7	5.4	2.4	0.0	0.09**	-3.3	-7.6	0.07**

*,** significant at 0.05 and 0.01 probability levels, respectively

4.3.2. Estimates of percent heterosis across locations

Growth characters

Percentage heterosis of the F1's relative to the mid parent, better parent and standard heterosis (over check hybrid) for five growth parameters is presented in Table 19. Most of the F1's exhibited positive mid parent heterosis ranging from 2.4 to17.3, -6.3 to16.7, 7.5 to16.6, 7.2 to 17.8 and 3.4 to 20.3 for plant height (PH), height up to first primary branch (HUFPB), stem girth (SG), length of first primary branch (LFPB) and internode length (IL), respectively. On the other hand, the magnitude of heterosis relative to better parents ranged from -1.8 to 14.3% for plant height, -9.2 to 8.3% for height up to first primary branch, -2.2 to 8.5% for stem girth, -2.3 to 15.7% for length of first primary branch, and -3.8 to 20.1% for inter node length.

It was observed that seven out of 10 hybrids showed highly significant and positive heterosis over mid-parent (MP) for plant height. However, crosses P2XP4, P3XP4 and P1XP4 were crosses with high heterosis. From this result one can see the contribution of one vigorous parent P4 in all the three top crosses. Similarly six crosses out of ten showed significant to highly significant positive heterosis over better parent value, cross P2XP4 and P1XP4 being the top heterosis producing entries in similar way to over mid-parent heterosis.

All crosses showed positive MP heterosis for stem girth, out of which nine of them showed significant to highly significant positive mid-parent value. Out of nine crosses the highest heterosis over mid-parent value exhibited by crosses P1XP3, P1XP4, and P2XP4 with heterosis percentage of 16.6, 15 and 14.2 percent over mid-parent respectively. This study result is in line with study made by Mesfin (1982). Only one cross (P1XP4) showed significant heterosis over better parent, even though nine of them showed positive heterosis. And no one cross showed significant heterosis over check hybrid for stem girth.

On the other hand, all crosses showed highly significant positive MP heterosis for length of first primary branch indicating the requirement of large planting spacing for hybrids than parents. Cross P2XP4 consistently exhibited highly significant positive MP, BP and CH heterosis with

respective value of 17.8, 15.7 and 16.9 percent heterosis. This indicates the entire vigor of cross P2XP4 which is due to the cumulative vigorous nature of parental lines P2 and P4.

The hybrids P1XP2, P1XP3, P2XP4 and P3XP5 showed relatively high positive heterosis over MP and BP for most important favorable characteristics. This probably indicates a concentration of favorable dominant genes in either one of the parents producing these hybrids. This result is in line with Bayetta. *et al.,* (1993) in that for most of growth characters observed mid-parent and better parent heterosis. On the other hand cross P4XP5 exhibited low or negative heterosis for most of the growth parameters, this might show poor combination or probably dominance was either lacking or present but interacted in unfavorable direction.

Leaf characters

Percentage heterosis of the F1's relative to the mid parent and better parent for four leaf characters is given in Table 20. Almost for all hybrids the mid parent heterosis was positive which ranged from 2.3 to 10.8 for leaf length; 2.9 to 15.4 for leaf width; 3.5 to 28.8 for leaf area and -2.3 to 10.6 for leaf petiole length. In contrary, for most of the hybrids heterosis over better parents shown negative value, especially for hybrids with one of the parents is P2. This is probably due to the large leaved nature of the parent P2, its hybrid do not exceeded the parent value. Similarly, majority of crosses exhibited negative heterosis over check hybrid for all leaf characters indicating the relative vigor of check hybrid over the majority of hybrids in the study.

While observing individual hybrids significant and positive OMP heterosis for leaf length was found for three crosses out of ten with heterosis percentage of 10.8, 9.7 and 8.9 for crosses P1XP4, P2XP4 and P1XP3, respectively. No cross showed significant results of OBP and OCH for this trait.

For leaf width only cross P1XP4 showed highly significant positive heterosis with 15.4% value over mid-parent. This particular cross still showed significant positive high heterosis OMP and OBP with 28.8% and 21.8%, respectively, for leaf area. Frequent and high heterosis exhibited from the cross P1XP4 for every leaf characteristics showing vigorous leaf nature of this cross.

Table 19: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for growth characters of coffee hybrids across locations

Crosses	Heterosis percentage														
	Plant Height			Height up to first primary branch			Girth			Length of first primary branch			Internodes length		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	13.9**	12.9**	-3.9	1.1	0.4	-5.7	7.5	7.1	-4.9	7.2**	6.5	3.8	6.6	4.8	-5.4
P1XP3	15.2**	11.5*	-5.0	5.4	-4.5	-10.3	16.6**	7.5	-5.2	15.5**	0	-3.9	7.9	0.7	-12.2
P1XP4	15.4**	13.5**	0.1	16.7*	8.3	1.8	15**	8.5*	7.9	12.7**	10	11.1	20.3**	20.1**	4.8
P1XP5	7.1	1.1	-3.0	4.5	-2.6	-8.5	11.3**	7.7	1.6	14**	11.5	7.2	7.2	6.8	-6.8
P2XP3	12.9**	10.3*	-7.7	-0.4	-9.2	-16.0	9.5*	0.7	-10.6	13.9**	-2	-4.5	4.8	-3.8	-13.1
P2XP4	17.3**	14.3**	0.8	2.5	-4.2	-11.3	14.2**	8	7.5	17.8**	15.7**	16.9**	13.3**	11.3*	0.5
P2XP5	6.2	-0.6	-4.6	2.5	-3.8	-11.0	11.7**	8.4	2.3	16.7**	13.4*	10.5	1.3	-0.7	-10.4
P3XP4	15.5**	10*	-3.0	-6.3	-8.8	-26.6	11.8**	-2.2	-2.7	15.3**	-2.3	-1.3	16.7**	9*	-5.1
P3XP5	12.1**	2.7	-1.5	9	5.7	-14.2	13.5**	1.5	-4.2	17.1**	3.2	-5.0	3.4	-3.2	-16.1
P4XP5	2.4	-1.8	-5.8	8.3	7.9	-12.4	8.5*	5.7	5.1	15.6**	10.4	11.6*	3.6	3.4	-10.0

*,** significant at 0.05 and 0.01 probability levels, respectively

Table 20: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for leaf characters of coffee hybrids across locations

Crosses	Heterosis percentage											
	Leaf length			Leaf width			Leaf area			Leaf petiole length		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	3.5	-1.3	-2.9	2.9	-7.2	1.8	6.1	-8.3	-1.2	2.2	-4.1	-9.1
P1XP3	8.9*	3	-8.0	9.3	-21	-12.5	18.3	1.2	-20.5	3.8	-2.4	-18.2
P1XP4	10.8*	8.6	0.7	15.4**	10.9*	7.1	28.8**	21.8*	7.5	10.6	10.6	-9.1
P1XP5	5.3	0.5	-10.9	5.4	-1.3	-12.5	10.8	-0.9	-22.1	0	-4.3	-9.1
P2XP3	4.4	-5.5	-7.3	7.2	-12	-3.6	9.2	-17	-10.7	-2.3	-13	-18.2
P2XP4	9.7*	6.7	4.4	8.2	1.3	12.5*	19*	8.2	16.5	5.5	-1	0.0
P2XP5	2.5	-6.5	-8.0	1.1	-14	-5.4	2.2	-20	-13.3	6.3	4.1	0.0
P3XP4	8.8	1	-6.6	10.8	-3.9	-7.1	20.1	-1.9	-13.5	6.2	0	-18.2
P3XP5	2.3	1.4	-18.2	1.1	-3.3	-25.0	3.5	-1.6	-38.9	1.2	-8.6	-18.2
P4XP5	4.2	-2.4	-9.5	4.9	-5.4	-8.9	9.4	-6.8	-17.7	-1.1	-5.4	-9.1

*,** significant at 0.05 and 0.01 probability levels, respectively

Yield, fruit and bean characters

Percentage heterosis of the F1's relative to the mid parent and better parent for eight yield, fruit and bean characters is indicated in Table 21. Interesting value was observed for yield over mid parent and over better parent heterosis. The range of heterosis was 12.8 to 57.8 and 12.1 to 41.8% for over mid parent and over better parent heterosis, respectively. Nine of the crosses showed significant to highly significant MP heterosis the highest being cross P3XP4 followed by crosses P3XP5 and P2XP4. However, only two crosses P2XP4 and P1XP5 showed significant positive BP heterosis although all crosses had shown positive heterosis. Such observed high heterosis value is in line with the result reported by (Mesfin 1982; Mesfin and Bayetta 1983). In addition with the research work done in Central America in similar condition Bertrand *et al* (2006) obtained 30% (heterosis) over the best parent for yield. The same author in another finding discussed that, based on controlled trials in full sunlight planting condition, estimated that heterosis ranged from 22 to 47% by comparing hybrids with their maternal lines (Bertrand *et al.* 2005*).* In another trials in Latin America and Africa by Walyaro (1983) and Cilas *et al*. (1998), confirmed that hybrids produced between 10 and 200% more than lines. With regard to heterosis over the check hybrid (Ababuna) only two crosses P2XP4 and P1XP5 in the study showed positive values with 11.5% and 5.1 %, respectively. Even though the

heterosis over check hybrid was not significant, these two hybrids do have comparable yield result with the commercially released hybrid and can be candidates for release after thoroughly observing to these hybrids for other favorable traits like disease resistance and quality.

On the other hand, majority of fruit and bean characteristics showed negative heterosis over mid-parent and better-parent values. This may generally suggesting dominance of the small sized fruit and bean character over large sized parents. Results obtained from cross made between P2 and P3 can be a very good example. These two parents have contrasting fruit and bean size in that P2 is big sized and P3 is smaller sized fruit and bean. The exhibited heterosis percentage from the cross of these two parents is either consistently negative or negligible. Similarly, majority of hybrids with one of their parents P2 showed negative heterosis, indicating the fruit and bean size of the offspring is reduced and probably suggesting smaller bean has dominant character over the big sized parent. All hybrids for bean width showed negative heterosis over check hybrid Ababuna suggesting high bean width value of the check. On the other hand, all hybrids in the study showed positive heterosis for bean thickness over check hybrid indicating thin bean nature of check than all hybrids even though they are not statistically significant.

Similar to yield for the trait hundred bean weight all crosses showed positive MP value, six of them showing significant positive high value. Out of these cross P3XP4 and P1XP5 showed high heterosis percentage of 15.6 and 12.8, respectively.

Quality characters

Percentage heterosis of the F1's relative to the mid parent and better parent for seven quality parameters is given in Table 22. Majority of values revealed negative MP and BP heterosis. This result may give a clue for the dominance of unfavorable quality character over favorable quality characteristics. This fact can be supported by considering crosses made with P3. This parent, showed consistently very good quality characteristics across the three locations. Nevertheless, the results of quality parameters obtained from each crosses where one of their parents is P3 shown negative heterosis. This means the quality characteristics that this parent possesses does not transmitted to the off springs dominantly. Yet this calls for further study of

quality inheritance by doing crosses between known top quality parents with that of known poor quality parent. In contrary to other crosses; cross P2XP4 and P2XP5 showed significant and positive heterosis values frequently for majority of organoleptic characters. For instance these two crosses showed highly significant positive MP heterosis for aromatic intensity with 7.7 and 8.6% value, respectively.

For body also crosses P2XP4 and P2XP5 showed positive and significant MP heterosis with respective value of 4.8 and 2.6%. The trend was the same for flavor and over-all standard.

With regard to heterosis over check hybrid majority of hybrids shown negative to zero heterosis value for aromatic intensity. The heterosis values over check hybrid for body, flavor and overall standard is negligible for majority of hybrids suggesting non-significant value differences among check hybrid and crosses included in this study.

Table 21: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for yield, fruit and bean characteristics of coffee hybrids across locations

Crosses	Heterosis percentage																							
	Yield			Fruit length			Fruit width			Fruit thickness			Bean length			Bean width			Bean thickness			Hundred bean Wt at 11% moisture		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	33.8*	25.4	-15.5	3	-1.9	6.1	0.1	-2	3.1	1.9	-1.8	5.6*	2.2	-5.3	5.9*	-0.2	-1.2	-3.8	-0.6	-4.7	5.9*	5.7	-1.8	10.9*
P1XP3	43.2*	22.3	-27.9	2.1	-1.4	-3.6	-0.6	-5.3	-4.4	1.5	-1.5	-1.7	0.4	-3.8	-8.1	0	-1.3	-5.9	4	2.2	4.4	7.3	0	-3.1
P1XP4	34.4*	17.6	-7.5	1	0.3	-1.8	0	-2.9	-2.0	2.7	2.1	1.9	2.9	2.3	-2.2	-0.6	-1.6	-6.2	2.2	1.9	4.6	10.5*	7.9	4.6
P1XP5	51.7**	32*	5.1	-1.4	-2	-4.1	-1	-3.6	-2.7	1	-1.6	-1.9	3.8	3.4	-1.2	1.6	0.5	-4.1	5.3*	1.8	3.9	12.8**	9.4*	6.0
P2XP3	44.1*	16.8	-21.3	-1.6	-9.3	-1.9	-1.9	-8.3	-3.6	-0.6	-6.9	0.1	-3.6	-14.1	-3.9	0	-2.3	-4.9	0.4	-5.3	5.1	0.9	-12.2	-0.8
P2XP4	52.7**	41.8**	11.5	-0.7	-6.1	1.6	1.2	-3.7	1.3	2.8	-1.5	5.9**	-0.8	-8.5	2.4	2.1	0	-2.6	1.4	-2.4	8.2**	9.4*	-0.5	12.4**
P2XP5	33.6*	23.3	-1.8	-0.5	-5.7	2.0	-1.1	-5.5	-0.7	-0.4	-6.4	0.6	1.2	-6.6	4.5	3.6*	1.5	-1.2	2.6	-4.7	5.9*	9.5*	-1.2	11.7**
P3XP4	57.8**	20.8	-5.0	3	0.2	-3.4	0.9	-1	-6.0	3.2	0.8	-0.7	4.8*	1	-4.6	1.5	1.2	-5.4	4.4*	2.3	5.1	15.6**	10.1*	1.8
P3XP5	56.8**	19.5	-4.7	0.8	-2.1	-5.2	2.3	-0.1	-4.4	2.3	1.9	-3.6	6.3*	2.3	-3.1	1.6	1.3	-5.5	5.1*	3.4*	1.8	9.1*	4.7	-4.7
P4XP5	12.8	12.1	-10.7	1	0.8	-2.4	0.8	0.5	-3.9	1.4	-0.6	-2.2	1.8	1.6	-3.7	0.6	0.5	-6.0	3.7	-0.1	2.6	4.7	3.9	-3.9

*,** significant at 0.05 and 0.01 probability levels, respectively

Table 22: Estimates of mid-parent (MP), better parent (BP) and standard heterosis for organoleptic quality characteristics of coffee hybrids across locations

Crosses	Heterosis percentage																	
	Aromatic intensity			Body			Flavor			Overall standard			Shape & Make			Over screen 14		
	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH	OMP	OBP	OCH
P1XP2	3.9*	1.7	-2.8	-2.4	-3.6	-3.0	3.6*	0.3	0.0	-0.3	-2.2	-3.1	5.9	2.6	2.4	-0.1	-0.5	1.9**
P1XP3	-0.8	-4.6	-2.8	-2	-5.8	3.0	-5.3	-16.5	0.0	-6.1	-15.8	3.1	-7.2	-16	-3.1	0.2	0.1	1.8**
P1XP4	5.2	4.3	0.0	0.8	-0.9	0.0	2.6	0.3	-3.2	3.6	2.6	0	0.5	-5	0.0	0.7*	0.7	2.3**
P1XP5	2.7	0.8	0.0	-0.5	-0.6	0.0	-1	-6.3	-3.2	0.3	-2.5	0	9.1	6.6	0.0	1.2**	0.6**	2.1**
P2XP3	-4	-9.4	-5.6	-2.3	-7.2	0.0	-11.2	-19.5	-3.2	-11.6	-19.4	-3.1	-12.2	-18.2	-5.5	-1.1	-1.5	0.8
P2XP4	7.7**	4.6	2.8	4.8**	4.3*	3.0	2.6**	1.6	0.0	0.6	-0.3	0	-5.2	-7.5	-3.1	0.2	-0.2	2.1**
P2XP5	8.6*	4.5	2.8	2.6**	1.5	3.0**	2.4**	0	3.2*	3.1**	2.2	3.1**	8.3	2.6	2.4	1*	0	2.4**
P3XP4	-1.1	-4	0.0	-2.5	-7.8	0.0	-5.9	-15.5	3.2	-8.9	-17.6	0	0	-4.6	10.2	0.4	0.3	2**
P3XP5	-4.8	-6.7	-2.8	-5.6	-9.4	0.0	-15.1	-21.3	-6.5	-14.9	-21.8	-6.3	-2.5	-13.6	0.0	1.1**	0.4**	2.1**
P4XP5	-0.1	-1.1	-2.8	0.6	-0.9	0.0	0.2	-3.1	0.0	-1.6	-3.4	-3.1	0	-7.5	-3.1	1*	0.3**	1.9**

*,** significant at 0.05 and 0.01 probability levels, respectively

4.4. Combining Ability

4.4.1. Analysis of variance of combining ability

Combining ability analysis was performed for individual locations and across locations for different traits and discussed below accordingly.

i) Combining ability analysis for individual locations

Growth characters

Mean squares of general combining ability (GCA) and specific combining ability (SCA) for individual locations for some growth characters is presented in Table 23. The GCA was highly significant for number of primary branches (NPB), number of node (NN) and canopy diameter (CD) at Melko, Metu and Tepi. SCA for NPB was non-significant at Melko and highly significant at Metu and Tepi. On the other hand SCA for NN showed highly significant difference only at Tepi. For the trait CD it was observed highly significant difference for GCA and SCA was observed in all locations indicating additive and non-additive gene actions are important for inheritance of this trait.

Quality characters

Highly significant GCA and SCA differences were observed for aromatic quality (AQ) and acidity (AC) at Melko, Metu and Tepi indicating both additive and non-additive gene actions contributed for the inheritance of these traits (Table 24).

Table 23**:** Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for some growth characters in coffee diallel crosses at three locations

Source of variation	Df	Traits and Locations								
		Number of primary branch			Number of nodes			Canopy diameter		
		Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
GCA	4	219.608***	511.69***	913.417***	48.400***	26.900***	13.525***	2831.68***	865.142***	3770.93***
SCA	10	21.549	191.333**	313.540***	4.6857	6.5968	6.8635***	463.59***	172.092**	616.37***
Error	28	23.1651	52.2333	44.7746	6.1333	3.06033	0.71746	102.3762	41.6794	136.4937

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001

Table 24: Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for some quality characters in coffee diallel crosses at three locations

Source of variation	DF	Traits and Locations					
		Aromatic quality			Acidity		
		Melko	Metu	Tepi	Melko	Metu	Tepi
GCA	4	0.008854*	0.006938***	.0026025	0.020115***	0.003536**	0.01189***
SCA	10	0.01423***	0.012051***	.005057**	0.010292***	0.01368***	0.01556***
Error	28	0.002361	0.001067	0.00155	0.001002	0.000577	0.0010005

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001

ii) Combining ability analysis across locations

Growth characters

Results from the pooled analysis of combining ability over locations are shown in Table 25. The results revealed significant variances due to GCA and SCA for all growth characters studied. The result of this study is in line with the study report of Mesfin (1982) who reported importance of additive and non-additive gene actions for five growth characters (stem girth, number of node, number of primary branch, length of first primary branch and number of secondary branch) he studied in F1 crosses of indigenous coffee. Similarly Bayetta (1991) in his nursery evaluation of indigenous coffee crosses reported the importance of both additive and non-additive gene action in seven shoot characters (stem girth, plant height, number of node, internode length, shoot fresh weight, shoot dry weight, shoot volume). The interaction of GCA/Environment was significant for stem girth & length of first primary branch only.

The relative contribution of SCA was higher than GCA for plant height indicating that non additive gene actions are predominantly important for the inheritance of this trait. On the other hand height up to first primary branch, stem girth, length of first primary branch and inter node length exhibited higher variance due to GCA than due to SCA suggesting additive gene actions has role in controlling these traits.

Leaf characters

The mean square values of GCA and SCA for four leaf characters depicted in Table 26. Both GCA and SCA mean squares were significant for leaf length, leaf width, leaf area and leaf petiole length indicating contribution of additive and non-additive gene actions. This result is in support of Bayetta (1991) in which he reported the contribution of additive and non-additive gene actions for six leaf characters in his nursery evaluation of indigenous coffee crosses. In the current study the relative contribution of GCA was more for all leaf characters indicating additive gene action is predominantly important. This implies that selection from segregating generation would be the best approach to improve these characters.

Table 25: Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for growth characters in coffee diallel crosses across location

Source of variation	Df	Traits				
		Plant height	Height up to 1st prim branch	Stem Girth	Length of first primary branch	Inter node length
GCA	4	649.190***	115.175***	3.31***	2165.060***	2.896***
SCA	10	1864.76***	21.732***	0.98***	546.250***	1.056***
GCA X E	8	162.980	8.742	0.140*	137.620**	0.099
SCA X E	20	175.910	6.781	0.061	58.850	0.095
Error	84	111.342	5.782	0.0598	50.242	0.0968
Relative contribution of GCA		12.2	67.9	57.5	61.3	52.3
Relative contribution of SCA		87.8	32.1	42.5	38.7	47.7

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001

Table 26: Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for leaf characters in coffee diallel crosses across location

Source of variation	Df	Traits			
		Leaf length	Leaf width	Leaf area	Leaf petiol length
GCA	4	23.027***	12.645***	3781.560***	0.131***
SCA	10	2.455***	0.609***	266.980***	0.013*
GCA X E	8	1.161*	0.218	138.130*	0.004
SCA X E	20	0.537	0.191	81.600	0.007
Error	84	0.527	0.138	53.905	0.006
Relative contribution of GCA		79.0	89.2	85.0	79.8
Relative contribution of SCA		21.0	10.8	15.0	20.2

* = significant at P<0.05 and ***= significant at 0.001

Yield, fruit and bean characters

GCA and SCA mean squares of yield, fruit and bean characters are displayed in Table 27. Both GCA and SCA mean squares were highly significant for yield indicating both additive and non-additive gene actions are important for this trait. The relative contribution of SCA was as high as 70% for yield. The predominance of SCA sum of squares to GCA sum of squares indicated the relative importance of non-additive gene action for this important trait; similar to the finding of Bayeta (1997). The current result is also in support of work done by Wassu *et al.,* (2008) indicated the importance of additive and non-additive gene actions non-additive being dominant. This implies that exploiting hybrids by using F1 for such cases is the best approach.

For Fruit length, fruit width, fruit thickness, bean length, bean width, bean thickness and 100-bean weight similar to aforementioned traits additive and non-additive gene actions were involved in the control of the characters studied. For the fruit and bean traits studied relative contribution of GCA was predominant suggesting additive gene action contributed more for these traits. But for majority of fruit and bean characters GCA x E and SCA x E for all bean characters was significant indicating inconsistent results across locations and better to depend on GCA & SCA effects of each locations.

Quality characters

Mean squares of combining ability for quality traits are presented in Table 28. Analysis revealed highly significant GCA and SCA for aromatic intensity, bitterness, body, flavor, overall standard and shape &make. The result indicates both additive and non-additive gene actions were involved in the inheritance of these quality traits. On top of this, over screen 14 significant SCA was observed indicating only non-additive gene action was important for the inheritance of this trait.

For all mentioned quality traits the relative contribution of SCA was found to be higher than the contribution of GCA indicating the relative predominance of non-additive gene action for the inheritance of these traits. The significant result of GCA x E and SCA x E for traits aromatic intensity (AI), astringency (AST), bitterness (BIT), flavor (FLV), overall standard (OVS)

indicates inconsistent results in across locations; the significant GCA and SCA at one location might not be equally important in another.

Table 27: Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for yield, fruit & bean characters in coffee diallel crosses across location

Source of variation	Traits								
	Df	Yield	Fruit length	Fruit width	Fruit thickness	Bean length	Bean width	Bean thickness	100- bean weight
GCA	4	106.251***	12.384***	4.775***	7.216***	8.098***	0.322***	0.345***	47.105***
SCA	10	99.275***	0.563***	0.142	0.311**	0.553***	0.064**	0.068***	9.623***
GCA X E	8	6.569	0.662***	0.344**	0.263*	0.973***	0.022	0.046**	7.771***
SCA X E	20	9.072	0.277	0.130	0.139	0.176*	0.041*	0.027*	1.724*
Error	84	6.354	0.171	0.106	0.107	0.087	0.022	0.017	0.959
Relative contribution of GCA		30.0	89.8	93.1	90.3	85.4	66.9	67.0	66.2
Relative contribution of SCA		70.0	10.2	6.9	9.7	14.6	33.1	33.0	33.8

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001

Table 28**:** Mean squares due to general combining ability (GCA) and specific combining ability (SCA) for quality characters in coffee diallel crosses across location

Source of variation	Df	Traits							
		Aromatic intensity	Astringency	Bitterness	Body	Flavor	Overall quality	Shape & Make	Over screen14
GCA	4	0.0029**	0.0197**	0.0113**	0.0050**	0.0178***	0.0097***	0.0989**	0.0019
SCA	10	0.0093***	0.0234***	0.0255***	0.0036**	0.0178***	0.0193***	0.0827**	0.0079***
GCA X E	8	0.0053***	0.0110*	0.0191***	0.0251***	0.0063***	0.0083***	0.0364	0.0063***
SCA X E	20	0.0055***	0.0211***	0.0298***	0.0105***	0.0077***	0.0075***	0.0440	0.0032***
Error	84	0.0013	0.0059	0.0032	0.0013	0.0009	0.0005	0.0269	0.0008
Relative contribution of GCA		11.1	25.2	15.0	36.2	28.6	16.7	32.4	8.7
Relative contribution of SCA		88.9	74.8	85.0	63.8	71.4	83.3	67.6	91.3

*= significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001

4.4.2. General combining ability effects

General combining ability effects of parental lines were analyzed for different traits at individual locations and across location and discussed as follows.

i) General combining ability (GCA) effects for individual location

The estimates of GCA effects of parental lines for different growth and quality characters for individual locations are given in Tables 29 and 30. These results of different characters are presented below.

Growth characters

At Melko positive and significant GCA effects for number of primary branch (NPB) was observed for parents P5 and P3. Parental lines P1 and P2 showed significant and negative GCA effects. The rest of the parent showed non-significant effect. At Metu P4 and P5 showed significant and positive value. In this location P1 & P2 showed positive and non-significant GCA effects for number of primary branch. Significant GCA effect for number of primary branch observed for parents P1 P2 and P4 at Tepi. In this location P5 also showed positive GCA effects but not significant. While parent P3, similar to Metu showed negative and significant GCA effects for NPB.

GCA effects for number of node (NN) had similar trend with that of NPB at Melko. At Metu parent P3 & P5 showed positive and significant GCA effects. While P1 & P2 showed negative and significant GCA effects for NN. And that of P4 exhibited negative and non-significant GCA effects. Similar to Melko and Metu parents P3 & P5 shown positive and significant GCA effects for NN at Tepi. At this location, P1, P2 and P3 exhibited, negative and significant GCA effects for NN.

With regard to canopy diameter (CD) the positive and significant GCA effects was observed for P4 in all locations indicating better combiner for this trait. On the other hand P3 appeared to be poor combiner expressing higher negative and significant value; this indirectly signifies the canopy reducing behavior of this parental line; that means this parental line may have better contribution in

development of hybrid variety having manageable size which could be planted in relatively closer spacing.

Table 29: Estimates of General combining ability (GCA) effects of parental lines for some growth characters in coffee diallel crosses at three locations

Parents	GCA effects of each Traits and Locatios								
	Number of primary branch			Number of nodes			Canopy diameter		
	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
P1	-3.293**	1.360	3.133*	-1.627**	-1.173**	-0.907***	-1.347	0.320	-1.613
P2	-3.427**	1.360	5.533***	-1.227*	-0.773*	-0.440*	0.787	-1.747	0.920
P3	2.50667*	-9.107***	-12.07***	1.573**	1.227**	0.693***	-17.48***	-10.41***	-20.147***
P4	-0.02667	4.2267**	2.9333*	-0.560	-0.640	-0.440*	17.187***	7.120***	19.8533***
P5	4.240**	2.160*	0.4671	1.8401**	1.3596**	1.0937***	0.853	4.716	0.9867
SE (gi)	0.93940	1.41062	1.30602	0.4834	0.3414	0.16532	1.97485	1.26007	2.28030
SE (gi-gj)	1.48533	2.23038	2.06501	0.7643	0.5399	0.26140	3.12252	1.99235	3.60547

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

Quality characters

GCA effects of parental lines for different quality characters of individual locations are presented in Tables 30 below.

At Melko parental line P2 and P4 showed negative GCA effects for aromatic quality (AQ). The rest of the parental lines revealed positive and non-significant GCA effects for this trait. At Metu P3 showed positive and significant GCA effects for AQ. While parents P1 & P4 found positive and non-significant GCA effects for AQ. The rest two parents showed negative and non-significant GCA effects. Only P3 at Metu appeared to be good general combiner showing positive and significant GCA effects for aromatic quality.

At Melko P2, P3 and P5 showed significant GCA effects for acidity demonstrating that these parents are good combiners. The rest two parents showed negative and significant GCA effects. At Metu only P4 signified the good combining ability expressing positive and significant GCA effects for acidity. Parent P2 also showed positive but non- significant GCA effects. The rest showed negative and non-significant GCA effects for acidity at Metu. At Tepi P3 and P4 appeared to be good combiners for acidity showing positive and significant GCA effects. P1 also showed positive

GCA effects but non-significant result. In this location P2 showed negative and significant GCA effects. Similar to Metu at Tepi P5 showed negative and non-significant GCA effects.

Table 30: Estimates of General combining ability (GCA) effects of parental lines for some quality characters in coffee diallel crosses at three locatios

parents	GCA effects of each Traits and Locatios					
	Aromatic quality			Acidity		
	Melko	Metu	Tepi	Melko	Metu	Tepi
P1	0.00667	0.01467	-0.00840	-0.049***	-0.0077	0.00453
P2	-0.0280**	-0.0260**	-0.00640	0.0329***	0.0096	-0.038***
P3	0.01133	0.01867*	-0.01040	0.01693*	-0.0011	0.02053**
P4	-0.0160	0.00667	0.01560	-0.0164*	0.0169**	0.02320**
P5	0.026	-0.01401	0.0096	0.01564*	-0.0177	-0.01016
SE (gi)	0.009484	0.006374	0.007695	0.006179	0.004689	0.006174
SE (gi-gj)	0.014995	0.010078	0.012167	0.009770	0.007414	0.009761

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

ii) General combining ability effects across location analysis

The estimates of GCA effects of parental lines & crosses for different characters pooled over three environments are given in Tables 31 to 34.

Growth characters

General combining effects of parents for growth parameters are given in Table 31. Parents P1 P4 & P5 showed positive & non-significant GCA effects for plant height. These effects, however, were negative and non-significant for P2 and P3. In case of height up to first primary positive & significant GCA effects were found for parent P1, while negative and significant GCA effect was found in P3. The rest of the parents had non-significant GCA effects. Only parent P4 showed positive and significant GCA effects for stem girth. P3 found negative and significant GCA effects. While P5 showed positive GCA but non-significant result observed. The rest two parents showed negative and non-significant GCA effects for stem girth. Parental lines P2 and P4 exhibited positive and significant GCA effects for length of first primary branch. On the other hand, parental line P3 showed negative and significant GCA effects for length of first primary branch. The rest two

parents showed positive and non-significant GCA effects for this trait. Parents P1 and P4 showed positive and significant GCA effects for internode length. While negative and significant GCA effect found for P3. Parent P2 showed positive and non-significant GCA effect. Negative and non-significant GCA effect for parent P5 observed for internode length. GCA effects of parental lines were entirely different for many of growth characters. Parental line P1 showed positive and significant GCA effects only for height up to first primary branch indicating good combiner for this trait. While parental line P2 were only showed significant GCA effect for length of first primary branch indicating its good combining ability of this parent for this trait. On the other hand P3 depicted negative GCA effect for all growth characteristics evaluated. This indicates its poor combining ability for growth characters. This probably emanates from poor vigor for growth characteristics of this parent. This parent may be useful in the development of hybrid variety having short and compact stature. Parental line P4 showed good combining ability for three growth characters (stem girth, length of first primary branch and internode length) showing significant and positive GCA effects for these traits. In general showing significant and positive GCA effects for growth characters, this parent may contribute favorable alleles for the development of vigorous hybrids.

Leaf characters

General combining ability effects of parents for leaf characters are given in Table 32. Parental lines P2 and P4 consistently showed positive and highly significant GCA effects for all leaf characters studied, indicating the good combining ability of these two parents for improvement of leaf size in synthesis of new hybrid. These two parents do have relatively bigger leaf size than the rest of parental lines included in the study. This nature may give the chance to show significant combining ability of these two parents.

Table 31: Estimates of General combining ability (GCA) effects of parental lines for growth characters in coffee diallel crosses across location

Parents	GCA effects of each Traits				
	Plant height	Height up to 1st prim branch	Stem Girth	Length of first primary branch	Inter node length
P1	0.1067	2.0089***	-0.0014	0.8444	0.1393*
P2	-2.0711	0.5867	-0.0475	2.7778**	0.0707
P3	-4.5156	-1.880***	-0.363***	-10.5556***	-0.3140***
P4	3.7289	-0.4578	0.2971***	5.7111***	0.2489***
P5	2.7511	-0.2578	0.1148	1.2223	-0.1449
SE (gi)	1.43861	0.33317	0.04216	1.32196	0.03552
SE (gi-gj)	2.27465	0.52680	0.06666	2.09021	0.05616

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

Table 32: Estimates of General combining ability (GCA) effects of parental lines for leaf characters in coffee diallel cross across location

Parents	GCA effects of each Traits			
	Leaf length	Leaf width	Leaf area	Leaf petiol length
P1	0.1653	0.0618	1.2756	-0.0049
P2	0.6142***	0.5529***	9.0499***	0.0551***
P3	- 0.6058***	-0.5027***	-8.2750***	-0.0760***
P4	0.5653***	0.3507***	6.5512***	0.0040
P5	-0.739	-0.4627	-8.6017	0.0218
SE (gi)	0.12143	0.05266	1.32439	0.007237
SE (gi-gj)	0.19200	0.08326	2.09404	0.011443

***= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

Yield, fruit and bean characters

General combining ability effects of parents for yield, fruit and bean characters are given in Table 33. In across location GCA effects for yield (kg ha^{-}) clean coffee parental lines P4 and P5 revealed highly significant GCA effects. This indicates these two parents were found to be good general combiners for this important economic trait. These parental lines may have good prospect for the inclusion in the breeding program for yield improvement in development of new high yielding hybrid varieties.

For all fruit and bean characters parental line P2 showed consistently positive and significant GCA effects indicating the good combining ability of this parent. This is probably emanated from the bold fruit and bean nature of this parental line. This result give directions for the improvement of fruit and bean characters parental line P2 found to be good general combiner. In contrary to P2 parent P3 showed significant negative GCA effects for all fruit and bean size characters, indicating the fruit and bean size reducing character of P3. This result may be emanated from its small fruit and bean nature of this parental line.

Quality characters

General combining effects of parents for quality parameters are given in Table 34. Parental lines P4 and P5 showed positive GCA effects for aromatic intensity. Even though, the result was not significant, these two parents shown better GCA effects as compared to the negative GCA effects of the rest parental lines included in the study.

Astringency and bitterness are the negatively affecting traits in the coffee organoleptic quality evaluation. In this study the highest negative GCA effects was observed from parental line P3 for both undesirable traits. This expresses low astringency and bitterness of this parent that it transfer to its offspring, even though the result is non-significant. On the study parental line P1 showed positive and significant GCA effects for astringency indicating the poor combining ability of this parent for this undesirable character.

For body, flavor and overall quality parental lines P1, P2 and P5 showed consistently negative GCA effects indicating the poor combining ability of these parental lines for the traits mentioned. In contrary parental line P3 showed highly significant and positive GCA effects for flavor and overall quality; and higher positive value for body indicating good combining ability of this parental line for many of organoleptic quality characteristics. This gives a clue for the possible contribution of this parent in crossing for quality breeding program. On top of the organoleptic quality characters this parent had shown positive and significant GCA effects for one of physical quality character shape & make.

Table 33: Estimates of General combining ability (GCA) effects of parental lines for yield, fruit and bean characters in coffee diallel crosses across location

parents	GCA effects of each Traits							
	Yield	Fruit length	Fruit width	Fruit thickness	Bean length	Bean width	Bean thickness	100-bean weight
P1	-0.794**	0.0503	0.154**	0.086	-0.025	-0.0133	-0.0012	0.2124
P2	0.2324	0.7505***	0.404***	0.516***	0.590***	0.125***	0.118***	1.355***
P3	-1.936***	-0.519***	-0.366***	-0.337***	-0.466***	-0.072***	-0.047**	-1.163***
P4	1.235***	-0.0866	-0.0906	0.0797	-0.0994	-0.0438*	0.0191	-0.0698
P5	1.2635***	-0.1954	-0.1012	-0.345	-0.0005	0.0042	-0.0889	-0.3342
SE (gi)	0.28882	0.09171	0.06611	0.05778	0.1111	0.01661	0.024160	0.31413
SE (gi-gj)	0.45667	0.14500	0.10453	0.09136	0.1757	0.02626	0.038200	0.49668

= significant at P<0.01, and *= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

Table 34**:** Estimates of General combining ability (GCA) effects of parental lines for Quality characters in coffee diallel crosses across location

Parents	GCA effects of each Traits							
	Aromatic intensity	Astringency	Bitter ness	Body	Flavor	Overall quality	Shape & Make	Over screen 14
P1	-0.0009	0.0228*	0.0140	-0.0037	-0.021 **	-0.007	-0.028	0.003
P2	-0.0096	-0.003	0.0098	-0.0042	-0.002	-0.003	-0.015	0.003
P3	-0.0036	-0.023	-0.0182	0.0169	0.028***	0.023 ***	0.057**	-0.008
P4	0.0077	-0.0144	0.0062	-0.0044	-0.005	-0.007	0.030	0.006
P5	0.0064	0.0154	-0.0118	-0.0046	-0.001	-0.006	-0.044	-0.004
SE (gi)	0.0083	0.011843	0.015586	0.0178	0.008979	0.010238	0.021492	0.00897
SE (gi-gj)	0.0131	0.018725	0.024643	0.0282	0.014196	0.016188	0.033982	0.01418

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, SE (gi)= standard error of general combining ability effects, SE (gi-gj)= standard error of the difference of general combining ability effects

4.4.3. Specific combining ability effects

Specific combining ability effects of cross combinations were analyzed for different characters in individual location and across location.

i) Specific combining ability (SCA) effects for individual location

The estimates of specific combining ability (SCA) effects at individual locations computed for some of growth and quality characters and depicted in Table 35 and 36.

Growth characters

Cross combinations P2xP5 and P4xP5 at Metu and cross combinations P2xP5, P3xP5 and P4xP5 at Tepi were good combinations showing positive and significant results for number of primary branches.

At Metu nine of the crosses showed positive SCA effects for number of node. However, only two of them P1xP2 and P3xP5 were good combinations showing positive and significant SCA effects for this trait. On top of this three crosses P2xP5, P3xP4 and P3xP5 at Tepi were good combinations exhibiting positive and significant SCA effects for number of nodes.

For the trait canopy diameter crosses P1xP4, P2xP4 and P3xP5 at Melko appeared to be good combinations for wider canopy showing positive and significant SCA effects. At Metu only cross combination P1xP5 and P4xP5 were good combinations for wider canopy exhibiting positive and significant SCA effects for this trait. At Tepi also three cross combinations namely P1xP4, P2xP4 and P3xP5 were good combinations for wider canopy with positive and significant SCA effects for canopy diameter. On the other hand for the interest of reduced canopy characteristics cross combination P1xP2 had shown negative and significant SCA effects both at Melko and Tepi.

Table 35**:** Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for some growth characters

Crosses	SCA effects of each Traits								
	Number of primary branch			Number of nodes			Canopy diameter		
	Melko	Metu	Tepi	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	-0.70667	-7.0933*	5.000	0.0933	2.1067*	0.10667	-9.9867*	3.5467	-11.653*
P1XP3	0.026667	3.3733	4.933	0.9600	0.1067	0.6400	7.2800	0.2133	8.4133
P1XP4	-0.10667	3.3733	0.933	-0.240	-1.6933*	-0.2267	14.6133**	6.34667	16.7467**
P1XP5	-2.86667	9.2000	9.6667	-0.4667	1.13333	0.3333	15.8000	16.933**	18.0667
P2XP3	0.49333	5.3733	2.8667	-0.1067	0.70667	0.50667	-5.8533	4.2800	-6.78667
P2XP4	3.36000	4.0400	3.200	1.02667	0.5733	0.30667	10.14667*	3.74667	11.8800*
P2XP5	4.666667	13.200*	20.40***	2.26667	1.86667	2.46667**	10.6000	6.5333	12.2667
P3XP4	-1.90667	0.50667	5.800	-1.7733	0.90667	1.17333**	1.08000	3.74667	1.2800
P3XP5	6.93333	9.7333	18.13**	2.06667	2.86667*	4.9333***	20.66667*	7.2000	23.8667*
P4XP5	-5.26667	15.0667*	20.47***	-3.0667	0.66667	0.8000	15.33333	13.0667*	17.5333
$SE(S_{ij})\pm$	2.42553	3.64220	3.37214	1.2481	0.88160	0.42686	5.09905	3.25350	5.88770
$SE(S_{ij}-S_{ik})\pm$	3.63829	5.46330	5.05821	1.8721	1.32240	0.64029	7.64857	4.88024	8.83156
$SE(S_{ij}-S_{kl})\pm$	3.32129	4.98729	4.61749	1.709	1.20718	0.58451	6.98216	4.45503	8.06207

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

Quality characters

At Melko only cross P1xP2 appeared to be good combination for aromatic quality exhibiting positive and significant SCA effects. Three crosses showed positive SCA effects and all the rest showed negative SCA effects indicating poor combination for this trait. Similarly at Metu six of the total ten crosses showed negative SCA effects and only one cross P2xP4 appeared to be good combination exhibiting positive and significant SCA effects. At Tepi three cross combinations P1xP3, P1xP4 and P1xP5 were good combinations showing positive and significant SCA effects for aromatic quality.

For the other determinant quality trait acidity still six of the ten crosses exhibited negative SCA effects at Melko indicating majority of the crosses are poorly combined for this trait. Yet three of crosses P1xP2, P2xP4 and P2xP5 showed good combination exhibiting positive and significant SCA effects. Also at Metu three crosses P1xP5, P2xP4 and P2xP5 were appeared to be good combinations for acidity showing positive and significant SCA effects. At Tepi only crosses P1xP4 and P1xP5 appeared to be good combination for acidity exhibiting positive and significant SCA effects. All the rest showed negative SCA effects indicating poor combination for this important quality trait.

Table 36**:** Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for some quality characters

Crosses	SCA effects of each Traits					
	Aromatic quality			Acidity		
	Melko	Metu	Tepi	Melko	Metu	Tepi
P1XP2	0.0547*	-0.0327	-0.0156	0.03373*	-0.042***	-0.0505**
P1XP3	-0.0547*	-0.004	0.0384*	-0.01027	0.00173	-0.0125
P1XP4	0.0093	-0.022	0.0524**	-0.0069	0.01373	0.0748***
P1XP5	0.0707	0.0586	0.1120**	-0.0880**	0.0500*	0.1147***
P2XP3	-0.013	-0.0367*	0.0164	-0.056***	-0.036**	-0.0232
P2XP4	0.0273	0.069***	0.0004	0.03107*	0.0464***	-0.02587
P2XP5	-0.007	0.0313	-0.006	0.1073***	0.1307***	-0.131***
P3XP4	-0.042	-0.006	-0.056**	0.01373	0.00707	-0.065***
P3XP5	-0.225***	-0.24***	0.0200	-0.155***	-0.243***	-0.183***
P4XP5	-0.0387	0.0540	0.0060	-0.0253	0.03467	-0.0367
$SE(S_{ij})\pm$	0.024487	0.016458	0.019868	0.015954	0.012107	0.015940
$SE(S_{ij}\text{-}S_{ik})\pm$	0.036730	0.024687	0.029802	0.023931	0.018160	0.023910
$SE(S_{ij}\text{-}S_{kl})\pm$	0.033530	0.022536	0.027205	0.021846	0.016578	0.021827

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

ii) Specific combining ability (SCA) effects across locations

The estimates of SCA effects of crosses for different growth, leaf, yield, fruit, bean and quality characters for across location given in Tables 37-40. The results of different characters are presented below.

Growth characters

Specific combining ability (SCA) effects of crosses for growth parameters are given in Table 37. Four crosses P1xP5, P2xP4, P2xP5 and P3xP5 showed positive and significant SCA effects for plant height. This result indicates possibility of invigoration of height. The rest of the crosses had non-significant SCA effects. On the other hand none of the crosses under study showed negative SCA effects which may give information that the difficulties to obtain combination for shorter hybrid plant stature.

Only cross P1 XP4 showed significant SCA effects for the trait height up to first primary branch. Cross P3XP4 showed negative and significant SCA effect and cross P2XP5 showed negative and non-significant. All the rest showed positive and non-significant SCA effects for this trait.

Out of ten cross combinations in the study seven of them P1XP3, P1XP4, P1XP5, P2XP4, P2XP5, P3XP5 andP4XP5 gave positive and significant SCA effects for stem girth indicating the high possible chance of acquiring good combination for this trait. However, cross P1XP2 showed negative and non-significant SCA effects. The rest of crosses showed positive and non-significant effect for this trait.

For the trait length of first primary branch five crosses P1XP5, P2XP4, P2XP5, P3XP5 & P4XP5 revealed positive and significant SCA effects. While, cross P1XP2 showed negative and non-significant effects. Crosses P1XP4, P1XP5, P3XP4 & P4XP5 revealed positive and significant SCA effects for internode length. However, crosses P1XP2 & P1XP3 showed negative effects. All the rest crosses showed positive and non-significant effects for this trait.

Leaf characters

Specific combining ability (SCA) effects of crosses for leaf characters are given in Table 38. Very few crosses showed positive significant SCA effects for most of leaf characters indicating good association of percentage heterosis and SCA in that most of the crosses didn't showed significant heterosis and SCA. Only P1xP4 and P4xP5 showed positive and significant SCA effects for leaf width and leaf area.

Table 37: Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for growth characters across location

Crosses	SCA effects of each Traits				
	Plant height	Height up to 1st prim	Stem Girth	Length of first primary branch	Inter node length

		branch			
P1XP2	5.2489	-0.5644	-0.0743	-1.8889	-0.0073
P1XP3	5.2489	0.4578	0.2259*	4.0000	-0.0204
P1XP4	7.8933	2.8133**	0.2263*	2.2889	0.4089**
P1XP5	22.8000*	1.4889	0.5606***	10.4000*	0.6331**
P2XP3	1.6489	0.1022	0.0005	1.5111	-0.0073
P2XP4	11.6267*	0.1244	0.2497**	6.0222*	0.2242
P2XP5	20.4000*	-0.2667	0.5178**	14.2222***	0.1767
P3XP4	9.1822	-2.1867*	0.0511	1.6889	0.2811*
P3XP5	29.7333**	1.3778	0.5965***	12.2222**	0.3209
P4XP5	14.0889	2.0222	0.4657**	14.7111***	0.5693*
$SE(S_{ij})\pm$	3.85905	0.75769	0.07200	2.23201	0.08953
$SE(S_{ij}-S_{ik})\pm$	5.78857	1.13653	0.10799	3.34801	0.13430
$SE(S_{ij}-S_{kl})\pm$	5.28422	1.03751	0.09858	3.05630	0.12260

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

Table 38: Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for leaf characters across location

Crosses	SCA effects of each Traits			
	Leaf length	Leaf width	Leaf area	Leaf petiol length
P1XP2	-0.1653	-0.1107	-1.9763	-0.0084
P1XP3	0.3547	0.0893	2.1764	0.0116
P1XP4	0.4169	0.3360*	6.4001*	0.0538*
P1XP5	0.9600	0.4578	9.4040	0.0178
P2XP3	0.0391	0.1538	1.1188	-0.0373
P2XP4	0.5124	0.1227	4.8592	0.0160
P2XP5	0.4867	0.1489	3.3104	0.0778
P3XP4	0.2213	0.1004	1.6908	0.0249
P3XP5	0.4889	0.1933	3.8600	0.0133
P4XP5	0.9933	0.5244*	11.0718*	0.0156
$SE(S_{ij})\pm$	0.21319	0.12730	2.62835	0.024019
$SE(S_{ij}-S_{ik})\pm$	0.31979	0.19095	3.94253	0.036029
$SE(S_{ij}-S_{kl})\pm$	0.29192	0.17431	3.59902	0.032889

* = significant at P<0.05, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

Yield, fruit and bean characters

Specific combining ability (SCA) effects of crosses for yield, fruit and bean characters are given in Table 39. Out of the total 90% of the crosses showed positive SCA effects for yield of which five crosses namely; (P3xP5, P1xP5, P2xP5, P2xP4 and P3xP4) showed positive and significant SCA effects indicating that these crosses were good combinations for yield. Very good association of percentage heterosis and SCA for yield observed in that nine crosses out of ten showed positive heterosis for yield. Crosses with higher values of SCA effects also showed higher value of mean yield performance, indicating good correspondence between SCA effects and mean yield. Hence such cross combinations could effectively be exploited in hybrid coffee breeding program. On the other hand, only cross combinations P1xP3 expressed negative SCA effects for yield which is undesirable as these cross showed a tendency to reduce yield performance.

For hundred bean weight, only three crosses P1xP5, P3xP4 and P2xP5 were best combinations as they showed positive and significant SCA effects for this trait.

Table 39**:** Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for Yield, Fruit & Bean characters across location

Crosses	SCA effects of each Traits							
	Yield	Fruit length	Fruit width	Fruit thickness	Bean length	Bean width	Bean thickness	100- bean weight
P1XP2	0.1231	0.4317	0.0868	0.1348	0.2047	-0.0422	-0.0528	0.0542
P1XP3	-0.0413	0.1200	-0.0407	0.0116	-0.1393	0.0013	0.0529	0.0609
P1XP4	0.6209	-0.0356	-0.0252	0.0714	0.0756	-0.0469	0.0009	0.3453
P1XP5	6.6644***	-0.0689	-0.1747	0.2100	0.3011	0.0202	0.1611*	2.1689**
P2XP3	0.1653	-0.3136	-0.1874	-0.1786	-0.3391*	-0.0624	-0.0344	-0.6702
P2XP4	3.1942***	-0.1758	0.1193	0.1823*	-0.0797	0.0749	0.0247	0.6031
P2XP5	4.7911***	-0.0653	-0.1880	-0.0653	-0.1447	0.2240**	0.0051	1.4556*
P3XP4	2.2298**	0.2791	0.0273	0.1470	0.2796*	0.0696	0.0616	1.2209**
P3XP5	6.8889***	0.2631	0.2462	0.3456	0.4627*	0.0471	0.1727*	1.2489
P4XP5	1.9711	0.2920	0.1418	0.3413	0.0822	-0.0136	0.1047	0.9089
$SE(S_{ij})\pm$	0.87637	0.1531	0.10491	0.10866	0.12194	0.058725	0.047476	0.38202
$SE(S_{ij}-S_{ik})\pm$	1.31456	0.2296	0.15736	0.16299	0.18292	0.088087	0.071214	0.57303
$SE(S_{ij}-S_{kl})\pm$	1.20002	0.2097	0.14365	0.14879	0.16698	0.080412	0.065010	0.52311

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

Quality characters

Specific combining ability (SCA) effects of crosses for quality parameters are given in Table 40. For the trait aromatic intensity cross combinations P2xP4 and P2xP5 were found to be good combinations showing positive and significant SCA effects.

Those cross combinations having negative significant SCA effects were P3xP4 and P4xP5 for astringency. Since this trait is negatively quality affecting trait the mentioned cross combinations appeared to be good combinations. Similarly the other negatively coffee organoleptic quality affecting character is bitterness. Cross combination P1xP2 had shown negative and significant combination and appeared to be good combination for this trait.

More than half of the crosses showed positive SCA effects for the traits body, flavor and overall quality. However, no significant SCA effect was observed for any of cross combinations for this traits indicating no good combination prevailed. Similar trend was observed for physical quality characters shape & make and over screen 14.

Table 40**:** Estimates of specific combining ability (SCA) effects of F1 Hybrids of coffee for Quality characters across location

Crosses	SCA effects of each Traits							
	Aromatic intensity	Astringency	Bitter ness	Body	Flavor	Overall quality	Shape & Make	Over screen 14
P1XP2	-0.0048	0.0072	-0.0662*	-0.0216	0.0160	-0.0064	0.0816	-0.0044
P1XP3	0.0058	-0.0250	-0.0104	0.0062	0.0035	0.0010	-0.0784	0.0011
P1XP4	0.0178	-0.0136	0.0762**	0.0031	0.0020	0.0192	-0.0073	0.0100
P1XP5	0.0304	-0.0538	0.0858	-0.0058	0.0173	0.0229	0.1289	0.0356
P2XP3	-0.0311*	-0.0348	0.0504	-0.0078	-0.0456**	-0.0415**	-0.1366**	-0.0433***
P2XP4	0.0298*	-0.0412	0.0371	0.0235	0.0095	0.0045	-0.0655	0.0044
P2XP5	0.0896***	0.0871	0.0827	0.0260	0.0376	0.0298	0.0738	0.0078
P3XP4	0.0005	0.0621*	-0.0060	-0.0087	-0.0029	-0.0181	0.0856	0.0100
P3XP5	-0.0722**	-0.0040	0.0291	-0.0651	-0.1767***	-0.1842***	-0.1662*	0.0189
P4XP5	0.0091	-0.1476**	0.0180	0.0191	0.0271	0.0009	-0.0596	0.0267
$SE(S_{ij})\pm$	0.021614	0.042245	0.05021	0.02975	0.025515	0.025232	0.061050	0.016417
$SE(S_{ij}-S_{ik})\pm$	0.032421	0.063367	0.07531	0.04462	0.038273	0.037848	0.091575	0.024626
$SE(S_{ij}-S_{kl})\pm$	0.029596	0.057846	0.06875	0.04073	0.034938	0.034551	0.083596	0.022481

* = significant at P<0.05, **= significant at P<0.01, and ***= significant at 0.001, S.E (Sij)± =standard error of specific combining ability effect; S.E (Sij-Sik)± =standard error of the difference of specific combining ability having one parent in common and S.E (Sij-Skl) ± =standard error of the difference of specific combining ability effects of the crosses having no parents in common

5. SUMMARY AND CONCLUSIONS

The present experiment was conducted with objectives of: (1) To determine the magnitude of heterosis and identify single cross coffee arabica hybrids for yield, yield components and quality characteristics (2) To estimate GCA of selected parents, and SCA of hybrids.

The experimental material consisting of five indigenous coffee (Coffea arabica L.) lines namely P1(75227), P2 (744), P3 (74148), P4 (F34) and P5(206/71) were selected from south western coffee growing areas of the country based on yield, quality, disease resistance and different morphological characteristics. The lines were crossed in half diallel fashion as per Griffing (1956) model I method 2 to produce 10 F1 hybrids. The F1's, parental lines and check hybrid Ababuna planted at Melko, Metu and Tepi research centers in RCB design in three replications were used for study. The data were recorded eight growth characteristics, four leaf characters, eight yield, fruit, bean characters and ten quality characters.

The analysis of variances indicated highly significant difference among genotypes for almost all characters clearly indicating the presence of genotypic difference among parental lines and hybrids evaluated. The overall mean of hybrids very appreciably exceeded from that of parental mean value for yield and other morphological characters. As opposed to this the mean value of hybrids is less than the mean value of parental lines for quality characters. Some hybrids have shown better performance in yield and other favorable traits than check hybrid Ababuna suggesting possibility to obtain more superior hybrids as crossing among selected coffee lines continued. For most of hybrids and most favorable traits like yield high heterosis was observed over mid parent and over better parent. The hybrids P1XP2, P1XP3, P2XP4 and P3XP5 showed relatively high positive heterosis over MP and BP for most important favorable characteristics. This probably indicates a concentration of favorable dominant genes in either one of the parents producing these hybrids.

Very encouraging results was observed for yield over mid parent and over better parent heterosis. The range of heterosis was 12.8 to 57.8 and 12.1 to 41.8% for over mid parent and

over better parent heterosis, respectively. Nine of the crosses showed significant to highly significant MP heterosis the highest being crosses P3XP4, P3XP5 and P2XP4 showing high respective heterosis value of 57.8, 56.8 and52.7%. However only two crosses P2XP4 and P1XP5 showed significant positive BP heterosis although all crosses had shown positive heterosis. With regard to heterosis over the check hybrid Ababuna only two hybrids in the study were showed positive value with 11.5% and 5.1 % for hybrids P2XP4 and P1XP5 respectively. Even though the heterosis over check hybrid is not significant, these two hybrids do have comparable yield result with the commercially released hybrid and can be candidates for release after thoroughly observing to these hybrids for other favorable traits like disease resistance and better quality.

Majority of fruit and bean characteristics showed negative heterosis over mid-parent and better-parent values. This may generally suggesting dominance of the small sized fruit and bean character over large sized parents.

Heterosis for quality characters was dominantly negative over mid and better parent. This result may give a clue for the dominance of unfavorable quality character over favorable quality characteristics. This means the quality characteristics that parents possessing quality does not transmitted to the off springs dominantly. Yet this calls further study of quality inheritance undergoing crossing between known top quality parents with that of known poor quality parent.

The analysis of variance due to GCA and SCA was significant for yield, growth parameters, leaf, fruit and bean characters. These results indicate both additive and non-additive gene actions were involved in the inheritance of these traits. The relative contribution of SCA was as high as 70% for yield indicating the predominance of non-additive gene action for inheritance of this important trait. For the fruit and bean traits studied relative contribution of GCA was more suggesting predominance of additive gene action.

Similarly GCA and SCA for Aromatic intensity, Bitterness, Body, Flavor, Overall standard and shape &make were significant indicating importance of both additive and non-additive gene actions in the inheritance of these quality traits. Highly significant GCA and SCA difference were observed for aromatic quality and acidity at Melko, Metu and Tepi indicating both additive

and non-additive gene actions contributed for the inheritance of these traits. For all mentioned quality traits the relative contribution of SCA found to be high than the contribution of GCA indicating the relative greater importance of non-additive gene action for the inheritance.

Parental line P4 showed good combining ability for three growth characters (stem girth, length of first primary branch and internode length) showing significant and positive GCA effects and this parent may contribute favorable alleles for the synthesis of vigorous hybrids. Parental lines P4 and P5 showed highly significant GCA effects for yield. This indicates that these two parents were found to be good general combiners for this important economic trait and may have good prospect for the inclusion in the breeding program for yield improvement in synthesis of new high yielding hybrid varieties. On the other hand parental line P3 showed highly significant and positive GCA effects for flavor and overall quality, shape & make; and higher positive value for body indicating good combining ability of these parental lines for many of organoleptic quality characteristics. Also this parent appeared to be good general combiner showing positive and significant GCA effects for aromatic quality at Metu. At Melko parental line P2, P3 and P5 showed significant GCA effects demonstrating that these parents are good combiners for acidity. At Metu only P4 signified the good combining ability expressing positive and significant GCA effects for acidity. At Tepi P3 and P4 appeared to be good combiners for acidity showing positive and significant GCA effects.

Cross combinations P1xP5, P2xP4, P2xP5 and P3xP5 showed positive and significant SCA effects for plant height. Cross combinations P3xP5, P1xP5, P2xP5, P2xP4 and P3xP4 were good combinations for yield. The result showed very good association with percentage heterosis in that nine of the crosses showed positive heterosis. Crosses with higher values of SCA effects also showed higher value of mean yield performance, indicating good correspondence between SCA effects and mean yield. Hence such cross combinations could effectively be exploited in hybrid coffee breeding program. On the other hand, only cross combinations P1xP3 expressed negative SCA effects for yield which is undesirable as these cross showed a tendency to reduce yield performance. For hundred bean weight, P1xP5, P3xP4 and P2xP5 were also good combiners.
For the trait aromatic intensity cross P2xP4 and P2xP5 were found to be good combinations showing positive and significant SCA effects.

Those cross combinations having negative significant SCA effects were P3xP4 and P4xP5 for astringency. Since this trait is negatively quality affecting trait the mentioned cross combinations appeared to be good combinations. Similarly bitterness is the other negatively affecting organoleptic quality character for coffee. Cross combination P1xP2 had shown negative and significant combination and appeared to be good combination for this trait. No significant SCA effect was observed for body, flavor and overall quality shape & make, and over screen 14.

Only cross P1xP2 at Melko P2xP4 at Metu P1xP3, P1xP4 and P1xP5 at Tepi appeared to be good combination for aromatic quality. For acidity P1xP2, P2xP4 and P2xP5 were good combination at Melko. At Metu P1xP5, P2xP4 and P2xP5 were good combinations for acidity and at Tepi only crosses P1xP4 and P1xP5 were good combinations for acidity.

6. FUTURE LINE OF WORK

From the few crossing works done so far encouraging heterotic effects obtained in crosses among indigenous coffee lines. On the other hand from the various sets of pure line variety development program in Ethiopia it had been observed that it is rarely possible to improve yield above 1800-2000 kg/ha through direct selection indicating the need to look heterotic hybrids to maximize yield as high as 2500-3000 kg/ha. Despite immense potential in coffee germplasm and encouraging heterosis acquired from the crosses of coffee it is not adequately exploited. Thus, the following future line of work might be considered:

- The overall mean of hybrids very appreciably exceeded from that of parental mean value for yield and other morphological characteristics consistently. Thus continuous crossing program is required to acquire much cross combinations possibly to achieve better performing hybrids
- The mean value of hybrids was less than the mean value of parental lines for quality characters this result indicates careful selection of parental lines for quality characters before conducting any crossing program
- The quality characteristics that parent possess does not transmit to the off springs dominantly. Yet this calls further study of quality inheritance by doing crosses between known top quality parents with that of known poor quality parents
- General combining ability effects of parental lines were entirely different for many of traits. It is advised to utilize parental lines based on the combining ability of a given parental line for a given trait
- To exploit more in planting of hybrids in closer plant spacing from hybrids having shorter plant stature; it is required to search hybrids that combine good yield and other favorable traits with shorter plant stature

7. REFERENCES

Abera Deressa. 2007. Opening speech of the workshop. Proceedings of the workshop on four decades of coffee research and development in Ethiopia: A National workshop, 14-17 August 2007, Addis Ababa (Ghion Hotel), Ethiopia.

Admasu, Shibiru and Klause Frohberg., 2007. National production Effect of Investment in Coffee Berry Disease Resistant Selections in Ethiopia. *In*: Proceedings of the workshop on four decades of coffee research and development in Ethiopia: A National workshop, 14-17 August 2007, Addis Ababa (Ghion Hotel), Ethiopia.

Agwanda. 1999. Flavour: an ideal selection criterion for the genetic improvement of liquor quality in Arabica coffee.In Proceedings of the 18th International Conference on Coffee Science (ASIC '99), pp. 302–307, Paris, France, 1999.

Agwanda, R.W., Baradat, A.B., Eskes, C., Cilas and A. Charrier. 2003. Selection for bean and liquor qualities with in related hybrids of Arabica coffee Arabica coffee in multi-local field trials. Euphytica, 131: 1-14.

Alemayehu Teshome, Esayas Kebede and Kassu Kebede. 2007. Coffee Development and Marketing Improvement Plan. pp. 375-381.In: Girma Adugna, Bayetta Belachew, Tesfaye Shimber, Endale Taye and Taye Kufa (eds.).Coffee Diversity and Knowledge. Proceedings of a National Workshop Four Decades of Coffee Research and Development in Ethiopia, 14-17 August 2007, Addis Ababa, Ethiopia.

Allard, R.W. 1960. Principles of Plant breeding. John Willey and Sons Inc., New York, pp 1-485.

Allard, R.W. and A.D. Badshaw. 1964. Implications of genotype environmental interactions in applied plant breeding. Crop science, 4: 503-507.

Babur Damte. 2009. Effectiveness of farmer field school in promoting coffee management practices: the case of Jima and Sidama Zones. Msc. Thesis presented to school of graduate studies of Haramaya University.

Bayetta Belachew. 2007. Terminal report. Coffee breeding and genetics research division. Dec. 2007. EIAR, JARC.

Bayetta Belachew, Behailu Atero , Fekadu Tefera, Ashenafi Ayano and Tadesse Benti.,2007. Genetic Diversity and Hetrosis in Arabica coffee. *In*: Proceedings of the workshop on four decades of coffee research and development in Ethiopia: A National workshop, 14-17 August 2007, Addis Ababa (Ghion Hotel), Ethiopia.

Bayetta Bellachew, Mesfin Ameha and Dejene Mekonnin. 1993. Heterosis and combining ability study in coffee (coffee Arabica L.) Association Scientifique International de café' (International Scientific Association on Coffee). V1 p.234-241. Montperellier, France, June 1993.

Bayetta Bellachew. 1986. Exploration and collection of coffee germplasm from Gambella plain. IAR news letter. Addis Ababa. 1 (2) 3-5.

Bayetta Belachew. 1991. Nursery evaluation of Heterosis and Combining Ability in reference to origin and morphology of parents in coffee (*coffea arabica L.*). M.sc Thesis, Alemaya University of agriculture, Alemaya, Ethiopia.

Bayetta B. (1997). Arabica coffee breeding in Ethiopia: a review. In: 17th International Scientific Colloquium on Coffee. Nairobi, pp.406-414.

Baytta Belachew. 2001. Arabica Coffee Breeding for Yield and Resistance to Coffee Berry Disease (*colletotrichum kaahawae sp.nov*). Ph.D dissertation, Imperial College at Wye, University of London, England. P136-141.

Baytta, B., Behailu, A., and Gibramu, T. 1998. Description and production Recommendation for new Cultivars of Coffee. IAR Research Report, No. 34.

Behailu, W., Abrar, S., Negussie, M., and Solomon, E. 2007. Coffee Processing and Quality Research in Ethiopia. *In*: Proceedings of the workshop on four decades of coffee research and development in Ethiopia: A National workshop, 14-17 August 2007, Addis Ababa (Ghion Hotel), Ethiopia.

Bellachew, B and Labouise J.P., 2006. Arabica coffee (*Coffea arabica* L.) local landrace development strategy in its centre of origin and diversity. pp. 818-826.Proceedings of the 21st International Conference on Coffee Science (ASIC) Colloquium, 11-15 September 2006, Montpellier, France

Berthaud, J. and Charrier, A., 1988. Genetic resources of Coffea.Pp. 1-42. In: Clarke R J, Macrae R (eds), Coffee: Agronomy, vol. IV, Elsevier Applied Science, London.

Bertrand. B., Aguilar. G., Santacreo. R., Anthony. F., Etienne. H.,.Eskes. A.B. and Charrier. A. 1997. Comportment d'Hybrides F1 de Coffea Arabica pour la vigueur, la production et la fertilite en Amerique Centrale. In: Proceedings of the 17th International Conference on Coffee Science (ASIC '97), Nairobi, Kenya, 1997.

Bertrand B, Etienne H, Cilas C, Charrier A, Baradat P. 2005. *Coffea arabica* hybrid performance for yield, fertility and bean weight. Euphytica 141:255–262

Bertrand B, Vaast P, Alpizar E, Etienne H, Davrieux F, Charmetant P. 2006. Comparison of bean biochemical composition and beverage quality of arabica hybrids involving Sudanese-Ethiopian origins with traditional varieties at various elevations in Central America. Tree Physiol 26:1239–1248

Brhanu Debele. 1978. Preliminary report for detailed soil survey of Jima Agricultural Research Station, IAR. Appendex No. 1, Addis Abeba.

Briggs, F.N. and Knowles. 1967. Introduction to plant breeding. Reinhold publishing corporation, New York.

Brollo. G., Cappucci. R., and Navarini., L. 2008. Acidity in coffee: Bridging the gap between chemistry and psychophysics. In: Proceedings of the 22nd International Association for Coffee Science (ASIC '08), pp. 843–850, Campinas, Brazil, 2008.

Carvalho, A. 1988. Principles and practice of of coffee plant breeding for productivity and quality factors. Pp.129-165. In: R.J. Clarke and R. Macrae (eds) coffee volume 4: Agronomy. Elsevier applied science publishers, Ltd.

Carvalho, A. and Monaco. 1962. Natural cross pollination in coffea arabica L., Report. 16th International Horticultural congruence., Brussels, pp. 447-449.

Carvalho, A., F.P. Ferwereda, J.A. Frahm-leliveld, D.M. Medina, A.J.I. Mendes and L.C.Monaco. 1969. Coffee (C. arabica L. and c. canephora pierre ex froehner). Pp. 186-224. In: F.P. Ferwerda and F.wit (eds) Out lines of perennial crop breeding in the tropics. Landbouwhoge school (Agricultural university) Wageningen, The Netherlands.

Cilas C, Bouharmont P, Boccara M, Eskes AB, Baradat P. 1998. Prediction of genetic value for coffee production in *Coffea arabica* from a half-diallel with lines and hybrids. Euphytica 104:49–59

Cliford, M.N.and Wilson, K.L, 1985. Coffee: Botany, Biochemistry, and Production of Beans and Beverage. Croom Helm. London.

Coste, R. 1968. Le cafieier , G.P. Maisonne Uve & Larose, Paris

Crossa, J., 1990. Statistical analysis of multi-location trials. Advances in agronomy. 44: 55-85.

Cvaletto. C.G.,.Nagai. N.Y and.Bittenbender. H.C. 1991. Yield, size and cup quality of coffees grown in the Hawaii state coffee trial. In: Proceedings of the 14th International Scientific Colloquium on Coffee (ASIC '91), pp. 392–402, San Francisco, Calif, USA, 1991.

CTA. 1999. Uniqueness of Ethiopian coffee. P28 – 30. In: Ethiopia: the cradle of the wonder bean Coffea arabica (abissinica). Coffee and Tea Authority (CTA), Addis ababa.

Dabholkar, A.R., 1992. Elements of biometrical genetics. International publisher, New Delhi.

Demel Teketay, 1999. History, Botany and Ecological Requirement of Coffee. The Ethiopian Wildlife and Natural History. No. 20: 28-50.

Endale Taye, Taye Kufa, Antenhe Nestre, Tesfaye Shimber, Alemseged Yilma and Tesfaye Ayano, 2008. Research on coffee field management.pp.187-195. In: Girma Adugna, Bayetta Belachew, Tesfaye Shimber, Endale Taye and Taye Kufa (eds.).Coffee Diversity and Knowledge. Proceedings of a National Workshop Four Decades of Coffee Research and Development in Ethiopia, 14-17 August 2007, Addis Ababa, Ethiopia.

Falconer, D.S. 1989. Introduction to Quantitative Genetics, 3rd edition. Long man Scientific & Technical, London.

Fernie, L. M., 1970. Improvement of arabica coffee in East Africa. Pp 231-249. In: Leakey (ed)Crop improvementin East Africa. Billing and sons Limited, Guildford and London.

Fernie L. M., 1966. Some Impressions of Coffee in Ethiopia. Kenya Coffee 31: 115-121.

Getu, B. 2009. Genotype X Environment interaction of arabica coffee (coffea arabica L.) for bean biochemical composition and organoleptic quality characteristics. Msc. Thesis presented to school of graduate studies of Haramaya University.

Gole, T.W. and Senebeta, F., 2008. Sustainable management and promotion of forest coffee in Bale, Ethiopia. Bale Eco-Region Sustainable Management Programme SOS Sahel/FARM-Africa, Addis Ababa.

Gomez, K.A., and A.A. Gomez.1984. Statistical Procedures for agricultural research. Second edition. John Willy and Sons. Inc., New York.

Gravios, K.A. and McNew. 1993. Combining ability and heterosis in U.S. southern long rice grain. Crop sci. 33:90-95.

Griffing, B. 1956. Concept of general combining ability and specific combining ability in relation to diallel crossing system. *Austr. Jour. Biol. Sci.,* 9: 463-493.

Hallauer A. R and J. B., Miranda. 1988. Quantitative Genetics in Maize Breeding (2nd ed.). Iowa State University Press, Ames, Iowa.

Hayes, L.N., F.R. Jmmer and D.C. Smith. 1955. Methods of plant breeding. McGraw Hillbook Company. Inc., Newyork, pp 1-551.

Hill J., W.W. Wagoire, R. Ortiz, and O. Stolen, 2001. Analysis of a combined F1/F2 diallel crosses in wheat. Theor. Appl. Genet. 102: 1076-1081.

IAR, 1969. Jima research station coffee department progress report for the period 1967-69,IAR, Addis ababa, pp. 1-2.

IAR/JARC. 1996. Recommended Production Technologies for Coffee and Associated Crops. Institute of Agricultural Research Jima Research Center.

International Coffee Organization (ICO), 2012. Ethiopian coffee production exceeds expectation. International coffee organization London

International Coffee Organization (ICO), 2005. Exports by exporting countries to all destinations. Available at: http://www. ico.org/trade/m1.htm.

International coffee organization (ICO), 2001. Positively coffee. International coffee organization, London.

Inamullah, H. Ahmed, F. Muhammad, Sirajuddin, G.Hassan and R. Gul. 2006. Evaluation of heterotic and heterobeltiotic potential of wheat genotype for improved yield. *Pak. J. Bot.*, 38(4): 1159-1168.

IPGRI. 1996. Descriptors for coffee (coffea spp and psilanthus spp). International plant Genetic Resources Institute, Rome, Italy.

ITC (International Trade Center). 2002. Coffee. An exporters Guide. Geneva, Switzerland

Jinks, J. L. 1983. Biometrical Genetics of heterosis. In: R. Frankel (ed.) Heterosis, A Reappraisal of Theory and practice, Monographs on TAG. Vol.6 Pp1-46. Springverlvy, Berlin, Heidelberg.

Kambal, A.E. and O.J. Webster. 1965. Estimate of general combining ability in grain *sorghum vulgare*. Crop Sci. 5:521-523.

Kehr, W.R. 1961. General combining ability for four agronomic traits in a diallel series among six alfalfa clones. Crop sci., 1:53-55.

Krug, C.A. and Carvalho. 1951. The genetics of coffea. Adv. Gene., 4: 127-158.

Labouisse, J.P. 2006. Summary of passport data of coffee germplasm maintained at JARC. Ethiopian Institute of Agricultural Research, Jima. Unpublished.

Lashermes P, M.C. Combs, J. Robert, P. Trouslot, A. D hont, F. Anthony and A. Charrier. 1999. Molecular characterization and origin of *coffea arabica* L. genome. *Molecular genetics* 261:259-266

Leroy, T., F. Ribeyre, B. Bertrand, P. Charmetant and M. Dufour., 2006. Genetics of coffee quality. Braz. J. Plant Physiol., 18: 229-242.

Mathure, P.N., and J.R. Mathur. 1983.Combining ability for yield and its components in pearl millet.IndianJ. Genet. Pl. Breeding., 43:299-303.

Mesfin Ameha and Bayetta bellachew. 1983. Heterosis in crosses of indigenous coffee (coffee Arabica L.). Selected for yield and resistance to coffee berry disease II- First three years. Ethiopian Journal of Agricultural Science, V: 13-21. Addis Ababa, Ethiopia.

Mesfin Ameha. 1982. Heterosis in crosses of indigenous coffee (coffee Arabica L.). Selected for yield and resistance to coffee berry disease at first bearing stage. Ethiopian Journal of Agricultural Science. 4: 33-45. Addis Ababa

Mesfin, A. 1988. Recommendation Adoption and impact of Improved Coffee Production Technologies in the Western Region of Ethiopia. Pp 136-141. In: 20th NCIC, 28-30 Mar 1988, addis Ababa.

Mesfin ameha and Bayetta bellachew. 1987. Genotype x environment interaction in coffee (*Coffea Arabica* L.). P476 – 482. In: Fourth international colloquium on coffee (ASIC '87). 29 June - 3 July, 1987. Montreux.

MOA. 2010. Crop Variety Register Issue No.13. Minstry of Agriculture. Animal and Plant Health Regulatory Directorate. June 2010. Addis Ababa, Ethiopia

Narain, P., 1990. Statistical Genetics. Wiley Eastern Ltd, New Delhi.

Paulos, D. 1994. Mineral fertilization of coffee in Ethiopia. Institute of Agricultural Research, Addis Abeba.

Pickett, A.A. 1993. Hybrid wheat results and problems: Advanced plant breeding. Berlin panlparey Sc. Publ., Berlin.

SAS (statistical Analysis System Institute). 2002. Statstical Analysis System Software. V.g. SAS institute Inc., Cary, NC USA.

Shull, G.H. 1952. Beginning of the heterosis concept. Pp. 14-48. In: J.W. Gowan (ed.) Heterosis. Halfer publishing company, New York.

Simmonds. N.W. 1986. Principles of crop improvement.

Singh, B.D., 1993. Plant Breeding. Kalyani Pub. New Delhi, India. 896p.

Sprague, G.F and Tatum, L.A. 1942. General versus specific combining ability in single crosses of corn. J. American Soc. Agron. 34: 923-932.

Stubber, C.W. 1999. Biometry, Molecular Biology and Physiology of Heterosis. Pp 173-183. In: J.G. Coors and S.Pondy CSSA and SSSA. Madison, Wiscon sin, USA.

Surendran, C.M. Parmathama and R.S. Vinarayai. 1994. Use of biometrical techniques in tree improvement. The Malaysian forester. 57:132-139.

Tesfu Kebede and Zebene Mikru. 2006. The nutrient status of long term fertilized soils of coffee plantation in south western Ethiopia. Paper presented on 22nd International Conference on Coffee Science, ASIC, 11 to 15 September 2006. Monpellier, France.

Van der Vossen, H.A.M. 1985. Coffee selection and breeding. In: coffee botany, biochemistry and production of beans and beverage. Eds M.N. Clifford and K.C.Wilson Croom Helm, London, New york, Sidney.

Van der vossen, H.A.M. and D.J.A. Walyaro. 1981. The coffee breeding program in Kenya: A review of progress made since 1971 and plan of action for the coming years. Kenya coffee, 46: 113-130

Van der Vossen, H.A.M.1987. Coffee selection and breeding. Pp.48-96. In:M.N.Clifford and K.C. Wilson (eds) Coffee: Botany , biochemistry and production of beans and beverages, Croom Helm Ltd., London.

Walyaro, D. J. A. and H.A.M.Van der Vossen. 1977. Pollen longevity and artificial cross pollination in coffea arabica L., Euphytica, 26:225-231.

Wassu Mohammed. 2004. Heterosis and combining ability analysis of yield and yield related traits in coffee (*coffea arabia L.*). M.sc Thesis, Alemaya University of agriculture, Alemaya, Ethiopia.

Wassu, M., Bayetta, B. and Singh, H. 2008. Heterosis and combinig ability for yield and yield related traits in Arabica coffee (coffea arabica L.). In: Proceedings of the 22nd International Association for Coffee Science (ASIC '08), Campinas, Brazil, 2008.

Welsh, J.R. 1981. Fundamentals of plant genetics and breeding. John Wiley and sons inc., pp. 1-290.

Wintgens, J.N. 2004. Coffee: Growing, processing, sustainable production. A guide book for groers, processors, traders and researchers. Weinheim.

Workafes Woldetsadik and Kassu Kebede.2000. Coffee production system in Ethiopia. Pp 90-106. In: Proceedings of work shop on control of coffee berry disease in Ethiopia.13-15th. August 1999, Addis Ababa, Ethiopia.

Wormer, T. M., and J. Gituanja. 1970. Seasonal patterns of growth and development of arabica coffee in Kenya: part II flower initiation and deferentiation in coffee East of rift vally. Kenya coffee, XXXV: 270-277.

Wrigly, G. 1988. Coffee. Tropical agriculture series. Longman Scientific and Technica, Longman group UK Limited, England.

Walyaro, D.J. (1983). Consideration breeding for improved yield and quality in arabica coffee (coffea arabica), PhD thesis, Agricultural University, Wageningen.

Woldemariam, T., M. Denich, D. Teketay and P.L.G. Vlek, 2002.Human impacts on *Coffea arabica.*L. genetic pools in Ethiopia and the need for its *in situ* conservation. pp. 237-247. In: J.M.M. Engels, V.R. Rao, A.H.D. Brown and M.T. Jackson (Eds.), Managing plant genetic diversity. IPGRI, Rome.

Yonas, B. 2005. Genotype by environment interaction and stability analysis of coffee (Coffea arabica L.) bean yield and yield related traits. Msc. Thesis presented to school of graduate studies of Haramaya University.

Zhang, Y., Kang, M.S., and Lamkey, K.R. 2005. Diallel SAS05. A comprehensive program for Griffing's and Gardener-Eberhart. Analysis. Agronomy Journal 97: 1097-1106.

Zirkel, C. 1952. Early ideas on Breeding and cross breeding. Pp. 1-14. In: JW. Gowen (ed.) Heterosis. Iowa State.

APPENDIX

Appendix 1: Homogeneity of Variance test

Traits	Locations EMS			Ratio of EMS (Max/min)	Homogeneity of variance	Significance of interaction
	Melko	Metu	Tepi			
Plant height	188.38	71.63	88.62	2.6	Homogenous	NS
Height up to first primary branch	4.22	7.27	6.1	1.7	Homogenous	NS
Stem girth	0.05	0.06	0.07	1.4	Homogenous	NS
Length of first primary branch	51.31	49.38	46.19	1.1	Homogenous	*
Number of primary branch	22.16	16.27	3.48	6.4	Non-homogenous	NS
Number of node on main stem	5.82	2.9	0.75	7.8	Non-homogenous	NS
Canopy diameter	106.04	44.16	140.77	3.2	Non-homogenous	NS
Internode length	0.13	0.1	0.08	1.6	Homogenous	NS
Leaf length	0.46	0.41	0.74	1.8	Homogenous	NS
Leaf width	0.11	0.15	0.14	1.4	Homogenous	NS
Leaf area	35.5	57.8	70.51	2.0	Homogenous	*
Leaf petiole length	0.004	0.004	0.01	2.5	Homogenous	NS
Yield	3.66	4.4	10.5	2.9	Homogenous	NS
Fruit length	0.24	0.1	0.17	2.4	Homogenous	NS
Fruit width	0.08	0.13	0.1	1.6	Homogenous	*
Fruit thickness	0.08	0.13	0.1	1.6	Homogenous	*
Bean length	0.11	0.09	0.06	1.8	Homogenous	**
Bean width	0.02	0.02	0.02	1.0	Homogenous	*
Bean thickness	0.02	0.02	0.01	2.0	Homogenous	**
Hundred bean weight	1.03	0.83	0.84	1.2	Homogenous	**
Aromatic intensity	0.001	0.002	0.001	2.0	Homogenous	**
Aromatic quality	0.002	0.001	0.003	3.0	Non-homogenous	*
Acidity	0.001	0.001	0.003	3.0	Non-homogenous	**
Astringency	0.006	0.005	0.007	1.4	Homogenous	*
Bitterness	0.004	0.002	0.004	2.0	Homogenous	**
Body	0.001	0.002	0.002	2.0	Homogenous	**
Flavor	0.001	0.001	0.001	1.0	Homogenous	**
Over all standard	0.0006	0.0005	0.001	1.7	Homogenous	**
Shape & make	0.03	0.015	0.035	2.3	Homogenous	*
Over screen 14 %	0.001	0.001	0.001	1.0	Homogenous	**

Error variance greater than 3 is non- homogenous, those with ratio less than 3 are homogenous