International Journal of Genetics and Genomics
2024, Vol. 12, No. 4, pp. 110-116
https://doi.org/10.11648/j.ijgg.20241204.16

Review Article

Coffee Improvement by Interspecific Hybridization in Ethiopia

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Abstract

Ethiopia is fortunate in this aspect because it is the origin and genetic diversity center for Arabica coffee. This study's goal was to provide a succinct overview of Ethiopia's hybrid coffee variety development and successes. The main issue is a lack of improved hybrid types, despite the population of coffee having a high genetic variety, which offers enormous prospects for development programs. It is clear that current genetic and breeding research on coffee is insufficient to address the country's different agro-ecologies. Some of the fundamental breeding strategies to deal with such issues include combining ability analysis and hybridization investigation through heterosis. The presence of heterosis was reported in crosses of selected indigenous C. arabica L. varieties in Ethiopia under different set of studies, primarily due to the presence of diverse parental lines. Some studies had been conducted on assessment of heterosis and combining ability analysis for yield and morphological characteristics of coffee in Ethiopia. These findings unmistakably pointed to the potential for heterosis and combining ability analyses to significantly improve coffee. Generally, in Ethiopia starting from 1998 to 2023 only nine hybrid coffee variety released nationally. In order to create hybrids with improved performance and high yields for coffee with an Ethiopian origin, a continual crossing program should be necessary to obtain many additional cross combinations.

Keywords

Coffee Arabica, Combining Ability, Heterosis and Hybrid

1. Introduction

The genus Coffea and family Rubiaceae are the home to the coffee plant, Coffea arabica L. [12]. Arabica coffee and Robusta coffee (Coffea canephora P.), two of the 124 species in the genus Coffea, are the two important commercial species [14]. The former is the only tetraploid species (2n = 4x = 44), whereas the latter is diploid (2n = 2x = 22) and they both occupy about 10 million hectares of land worldwide [9]. Contrary to many other coffee varieties, coffee arabica is thought to be a 95% self-fertile and only a 5 % cross-fertile species, which means it can produce fruit from its own pollen [33]. A total of 700,474.69 acres in Ethiopia are thought to be covered with Arabica coffee, with an average annual yield of 469,091.1 tones, of which more than half is consumed locally [13].

The origin and diversity of C. arabica L. are both concentrated in Ethiopia [7]. The crop is grown extensively throughout the nation, from the riverbank of the Gambella Plain (550 m.a.s.l) to the country's central and eastern highlands, which reach elevations of up to 2600 m.a.s.l [5]. The

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Received: 18 October 2024; **Accepted:** 7 November 2024; **Published:** 28 November 2024

farmed and historically recognized land races of arabica coffee in Ethiopia exhibit significant genetic variability over this range of altitudes and ecological diversity [15].

Ethiopian coffee has been noted to possess a variety of significant qualities or attributes, such as resistance to the coffee leaf rust disease (Hemileia vastatrix) [37], Coffee berry disease (Colletotrichum kahawae), nematodes (Meloidogyneincognita) [1], as well as a wide variety of variations in the composition of green bean biochemical constituents (caffeine, chlorogenic acids, sucrose, and trigonelline) [24]. There are numerous more characters that are useful for development programs, such as bean size, shape and color [37] and tree size and shape. Ethiopian coffee is renowned around the world for its exceptionally high cup quality, distinctive aroma and flavor. Sidamo, Yirgachefe, Hararge, Ghimbi, and Limu are some well-known coffee varieties that are praised for having such distinctive and distinctive qualities [38]. Despite the vast genetic diversity of the coffee population, which offers enormous prospects for development programs, the main issue is a lack of better hybrid types [4, 7, 26]. It is clear that current genetic and breeding research on coffee is insufficient to address the country's different agro-ecologies. Hybridization research and heterosis analysis are some of the fundamental breeding tools used in any crop breeding program meant to solve issues like the ones stated above. However, there are few of this research on coffee both nationally and internationally. Additionally, the evaluation of combining ability is a crucial tool that is currently included in every breeding program. Knowing the sort of gene action involved in regulating the expression of a character and the ideal combining parent can help breeders make the right decisions [18, 19, 25, 30, 34]. In fact, one of the effective ways to supply the aforementioned information is the diallel analysis for combining ability proposed by [20]. Information on Arabica coffee in this regard is also relatively limited. As a result, this review was started in order to conduct methodical investigations by focusing on crosses between variable parental lines originating from different regions of Ethiopia, and contribute to identify the major achievements made and gaps of coffee hybridization study that leads to identify future breeding work and improving coffee productivity and quality over the long term.

2. Program for the Development of Hybrid Coffee Varieties in Ethiopia

Hybridization is the process of combining or transferring beneficial traits from two or more species, varieties, or lines [29]. Immediately following the introduction of the first batch of coffee berry disease (CBD) resistant varietals, Ethiopia's coffee hybridization program was launched. The major goals were to investigate the genetic inheritance of significant qualities, produce fundamental genetic data on coffee and create hybrid varieties that outperformed the pure lines selected for by selection. To achieve this, numerous combinations of crosses were made using parental lines that had been chosen through heterosis for traits including yield, resistance to the coffee berry disease (CBD) and coffee leaf rust (CLR), quality, vigor, and others. In order to achieve this, various combinations of crosses between parental lines were created using heterosis and combining ability analysis. The parental lines were chosen for their desirable traits such as yield, resistance to coffee berry disease (CBD) and coffee leaf rust (CLR), quality, vigor, and others.

3. Ethiopian Coffee Heterosis

Since C. arabica's hybridization studies only recently began, there is comparatively little information on heterosis in comparison to other crops. Another difficulty is that the crop is perennial, so it takes several years to see any real results [11]. As a result, there is a lack of research on the impact of heterosis. It has been determined that in heterosis breeding, the likelihood of heterosis expression increases with parental geographic isolation, ancestral relationships, gene frequencies and physical traits [17]. Heterosis over the superior parent for yield was reported to be up to 60% in Ethiopia, where the greatest diversity of C. arabica lines are anticipated to occur [28]. Only one of the nine F1 hybrids showed negative heterosis of -8 %. The highest yielding hybrids that have been authorized for distribution to growers, 7396 x F59 (Melko-CH2) and 741 x F59 (Ababuna), respectively, demonstrated 20% and 18% heterosis above the superior parent. On the basis of 2500 trees per hectare, these hybrids actually produced 23.97 and 23.68 quintals of coffee per ha, respectively, or 31.96 and 31.57 quintals of clean coffee on the basis of 3333 trees per hectare, respectively. Additionally, these hybrids contain up to 12% heterosis for principal nodes compared to the better parent [27].

There was a maximum better parent heterosis of 69% for inter node length in another 6 x 6 half diallel cross that considered 18 seedling characters (seven for shoot, six for leaf and five for root characters) [6]. Additionally, for fresh cherry yield and clean coffee, [7] observed mid and better parent heterosis of up to 68% and 53%, respectively. After several years of research, however, it was found that heterosis was absent in crosses of a few indigenous C. arabica L. types in Brazil [10], primarily as a result of the absence of varied parental lines. According to [8], hybrids with parents of comparable origin but clearly different development habits have shown a high and significant heterosis effect. As indicated by [35] came to the additional conclusion that the most heterotic coffee hybrids in terms of yield were those with origins and growth habits from dissimilar parents. The second most heterotic hybrids belonged to another group with distantly related parents but a similar growth pattern. The hybrids with parents who were comparable in origin and growth pattern had the lowest levels of heterosis. Wassu noted a strong correlation between rising parental distance and a rise in heterosis. This outcome made it abundantly evident that diversity among the parental lines is necessary for the formation of hybrid varieties. In their study of heterosis and combining ability for morphological characters in coffee of Western Ethiopian origin, [16] found that the proper selection of parental lines with distinct morphological variations is crucial in a breeding program to produce specific hybrids that outperform their parents or the desired character. The morphological features of parental lines that are morphologically comparable could not always result in hybrid vigor. The observed level of positive heterosis over the mid and better parent for the traits of plant height, canopy diameter, average length of primary branch, and number of primary branches may suggest that dominant and partially dominant genes were important in regulating the expression of those traits and that hybridization may be the best method to enhance the performance of these traits. As a result, selection is the best method as opposed to hybridization for improving those traits. In contrast, for characters' height up to the first primary branch, leaf length, and leaf width, in which the hybrids manifested negative mid and better parent heterosis, both partial and dominance effects of genes are probably lacking.

In Tanzania, heterosis over the better parent for stem diameter and yield was reported to be 53 and 11%, respectively, over the mean of two standard varieties. 16 q/ha of clean coffee were produced by the superior hybrid. The same author claimed that coffee from Uganda and Costa Rica contained hybrid vigor. From the crosses Agaro x 2045 and Chochie x 1934, [31] in India reported yield heterosis of 86% and 100% over the superior parent, respectively. The complimentary parents of the hybrids in Tanzania and India that displayed considerable heterosis were VC496 and Chochie, both of Ethiopian descent. These findings strongly suggested that coffee of Ethiopian origin contains a significant amount of genetic diversity. In addition, [8] noted that if the two parents are essentially low yielders, the hybrids with the highest mid and better parent heterosis do not always have the best yield. The degree of mid and better parent heterosis alone is deceiving in light of the commercial value of the hybrids, particularly if the parents are poor yielders, adding that economically sound heterosis is the standard heterosis, i.e. heterosis that surpasses the typical check. This outcome demonstrated that before being released as commercial variety considerable heterosis effect, potential hybrids for release must be evaluated against the routine checks. All of the hybrids that showed the highest heterosis % in the studies on coffee hybridization that were examined above did not necessarily have the maximum yield, indicating that choosing hybrids based solely on the level of heterosis is deceptive.

4. Ethiopian Analysis of Coffee Amalgamation Skills

Genetic information addressing the inheritance of quantitative characters, in particular the type and extent of gene activity governing the inheritance of the character, should be ascertained before to starting any improvement effort. For instance, the combined ability studies for yield and morphological qualities in coffee by multiple researchers showed that both additive and non-additive forms of gene activities are significant in the inheritance of these traits [2, 7, 16, 23, 36]. However, for the majority of features, the non-additive gene activity was more significant than the additive elements. Even though they weren't substantial, some combining ability tests in Ethiopia had been done on coffee for yield and a few key morphological qualities that may serve as the foundation for the upcoming research.

In diallel crosses among five parental lines originating from south-western Ethiopia, [2] investigated the ability to combine yield and morphological traits. According to his research, both additive and non-additive gene activities are crucial for the inheritance of this economic feature. The mean squares for both GCA (general combining ability) and SCA (specific combining ability) effects in across location analyses were highly significant for yield. The significant percentage contribution of SCA compared to GCA may, however, suggest that non-additive gene activity predominates. The control of fruit length, fruit width, fruit thickness, bean length, bean width, bean thickness, and 100-bean weight were likewise found to depend on both additive and non-additive gene effects.

As described by [3] said that the relative contribution of GCA was predominant for the fruit and bean attributes investigated, indicating a stronger influence of additive gene action for these traits. However, GCA with environmental interaction (GCA x E) and SCA with environmental interaction (SCA x E) were significant for the majority of fruit and bean characters, indicating inconsistent results across sites and the necessity to rely on GCA and SCA effects of each location. Investigated by [35] the ability of five parents from southwest Ethiopia (Kaffa type) and south-eastern Ethiopia to combine for coffee quality in parallel crosses (Sidamo type). For the majority of the parameters examined, he saw that the hybrids showed positive and considerable heterosis ranging from 14 to 33 % relative to the commercial Sidamo coffee type. The best particular combinations for all coffee quality characteristics were two hybrids, specifically 7440 x 75227 and 744 x 1681, which were both found to have highly acceptable Sidamo coffee quality. He discovered two Kaffa coffee parents, 7440 and 75227, which were effective combiners and created hybrids that were superior to the Sidamo commercial coffee variety. Additionally, he stated that the importance of non-additive gene activities for acidity, body, cup quality and overall quality. He discovered two Kaffa coffee parents, 7440 and 75227, which were effective combiners and created hybrids that were superior to the Sidamo commercial coffee variety. Additionally, he stated that additive gene action for flavor and non-additive gene action for acidity, body, cup quality and overall quality. These researches revealed that an essential breeding strategy to increase the quality of coffee in a certain location or region is the selection of parents based on their quality performance and crossing among them. The genetic analysis of GCA and SCA reported by [36] also revealed that mean squares of both GCA and SCA were significant for stem girth, plant height, the typical number of nodes on the main stem, the number of secondary and tertiary branches, clean coffee production, and single berry weight. This finding indicated that the expression of these traits was controlled by both additive and non-additive gene activities. With the exception of average inter-node length, non-additive gene activities were found to be the most significant for all characters. The non-additive gene actions were likely of primary importance in the inheritance of all the morphological traits studied, according to [16]. observation that the extent of mean squares due to SCA were higher than that due to GCA and the components of variances ratios were less than unity. He added that selection is ineffective for enhancing the aforementioned character when non-additive gene action predominates in the manifestation of the trait. This conclusion may therefore indicate that the selection method's limited ability to improve the characters under consideration and the need to consider alternative breeding techniques, including hybridization, which makes it possible to take advantage of dominant gene effects.

The significance of both additive and non-additive gene activity in regulating the inheritance of yield, fruit length, and morphological features was further discussed by [7]. He did, however, point out that for the majority of the analyzed characters, higher GCA mean squares than SCA mean squares suggested that additive gene action was likely predominate. He also noted that good general combiners have several benefits, including the ability to create synthetic varieties, a high probability of good particular combining abilities and the best choice for parents in a hybrid program. Additionally, the hybrids with the largest SCA effects were seen to evolve from any potential pairing of parents with opposing GCA effects, with negative x positive crosses more frequently resulting in the highest SCA effects than other pairings. Additionally, [16] noted that some crossings involving parents with strong general combiners resulted in weak particular combinations. This finding may imply that parents with high general combining ability effects (GCA) may not always produce crosses with high specific combining ability effects (SCA), and conversely, parents with low GCA may not always produce hybrids with low SCA for all relevant agronomic variables. [11] showed that there was no link between the performance of lines and their GCA effect when used as parents, which is in keeping with this. While one high yielding variety (Java) was categorized as a bad parent for the same attribute in this study, some low yielding lines (two Ethiopian lines Et3 and Et7) performed better as parents. These two studies would suggest that any feasible parental combination with favorable or unfavorable GCA effects could result in a coffee hybrid with desirable features. Additionally, when employed as a parent in crossing, a parent that performed well as a pure line may not be a good general combiner. This demonstrated that parents' average combining abilities could not be predicted based on their average performance.

5. Achieved Successes

Numerous insightful findings came from the numerous hybridization research. There are several factors that influence how CBD is regulated, including partial to complete dominance of the CBD susceptible alleles over the resistance alleles, involvement of two to five recessive genes at most, absence of cytoplasmic inheritance, a sizable amount of heterosis for yield, and a few significant growth characteristics. The first three hybrid varieties that combine high yield, moderate resistance to CBD and CLR, and acceptable quality for production at medium altitude coffee growing regions were released in 1997 and 2002. This was due to the importance of both additive and non-additive gene actions in controlling inheritance of CBD and the expression of yield and some yield related growth characters, as well as the importance of testing different sets of crosses in different locations over several years.

The introduction of an additional three new hybrid varieties in 2016 and one hybrid variety in 2018 that were suggested for production at low, medium, and high-altitude coffee growing locations were the results of ongoing efforts in the hybridization study to boost coffee yield [21, 22]. On the other hand, efforts are being made to increase quality through hybridization and selection. As part of the local landrace variety development initiative, elite parental lines were discovered and crossed to create hybrid varieties with high quality for the coffee-producing regions of Limu, Harerghe, and Wollega [21] and the continuous efforts in the hybridization study to improve coffee output and quality for the coffee-producing regions of Sidama, Gedio, and Wolyita resulted in the release of two more novel hybrid types in 2022, which were recommended for production at medium coffee growing locales [39]. The results of several studies on hybridization have generally established a fantastic basis for the current and future national breeding programs in the creation of hybrid coffee types. Through the development of pure line and hybrid coffee varieties, the results thus far obtained have also amply demonstrated the capability of enhancing the productivity and growth performance of the crop. However, it has been noted from the numerous sets of pure lines variety development programs in Ethiopia that increasing yield above 1800–2000 kg/ha through direct selection is uncommon, indicating the necessity to hunt for heterotic hybrids to maximize yield as high as 2500–3000 kg/ha. Through hybridization, this strategy is particularly suited for creating enhanced variations for Ethiopia's various coffee-growing regions with their varied coffee kinds, agro ecologies and quality profiles.

Table 1. *Ethiopian hybrid coffee varieties.*

No.	Varieties Released	Year of Release	Yield Q/ha (Clean coffee)	Area of Adaptation		
				Recommended altitude m.a.s.l	Rainfall (mm)	Temperature (oc)
1	Ababuna	1998	23.80	1000 – 1750	1500 - 1800	11.00 – 28.00
2	MelkoCH2	1998	24.00	1000 – 1750	1500 – 1800	11.00 – 28.00
3	Gawe	2002	26.10	1000 – 1750	1500 – 1800	11.00 – 28.00
4	EIAR50/CH	2016	26.00	1000 – 1400	1500 – 1700	15.00 – 30.00
5	Melko-Ibsitu	2016	23.40	1000 – 1400	1500 – 1700	15.00 – 30.00
6	TepiHC5	2016	21.60	1000 – 1400	1500 – 1700	15.00 – 30.00
7	GeraCH-1	2018	24.41	1750 – 2100	1500 - 1700	11.00 – 28.00
8	Awada CH1	2022	30.23	1550 – 1750	1231.00	10.01 – 27.21
9	Rori	2022	34.91	1550 – 1750	1230.60	10.00 – 27.21

N.B: Altitude 1000-1500 Lowland; 1550-1750 Medium; 1750-2100 Highland Source: [21-23]

6. Ethiopian Coffee Hybridization: Opportunities and Challenges

The initial breeding goals of Ethiopia's C. arabica hybridization development program was to promote vigroursity, productivity and adaptability to local conditions. Breeding tactics were used to identify superior plants in the population in order to create enhanced pure line cultivars and to cross the superior cultivars to create hybrid varieties [7]. The main breeding methods in Ethiopia for achieving these goals include a variety of instruments on breeder hands heterosis and combining ability study. On the other hand, breeding programs for Arabica coffee are restricted in almost all coffee-producing nations, with the exception of Ethiopia, primarily due to limited genetic bases. This has significantly hampered the rapid development of improved varieties with high yields, quality, insect pest and disease resistance, and other desirable traits [32]. Ethiopia is fortunate in that it is the hub of origin and genetic diversity for Arabica coffee, but due to the lack of adequate human, physical and financial resources for coffee research, it was not feasible to fully take advantage of this chance. The coffee hybridization program using heterosis, integrating aptitude analysis and other available breeding technologies, has so received very little attention. In order to fulfill human, physical and financial resources in coffee research for morphological, molecular and biochemical characterization for future coffee hybridization work and efficient usage of the available genetic variations, immediate action is required.

7. Conclusion

The origin and variety of Arabica coffee are both concentrated in Ethiopia. Despite the vast genetic diversity of the coffee population, which offers enormous prospects for development programs, the main issue is a lack of better hybrid types. Heterosis and combining ability assessments are two fundamental breeding strategies in every crop breeding program meant to solve issues like the ones listed above. However, there are few of this research on coffee both nationally and internationally. On the other hand, some investigations had been concentrated on Ethiopian coffee hybridization development assessment by heterosis and combining ability analysis for yield and morphological characteristics.

This research concluded that the prevalence of heterosis in crossings of particular native C. arabica L. types in Ethiopia under various sets of crosses evaluated was mostly caused by the existence of different parental lines. So, in 1997 and 2002, the first three hybrid varieties were made available for cultivation in the country's medium altitude coffee growing regions. These types combine high yield, moderate resistance to coffee berry disease and coffee leaf rust, and acceptable quality. Additionally, three new hybrid types that were suggested for production at low and medium altitudes as well as one hybrid variety were added in 2016 for coffee growing regions at high altitudes. Additionally, one hybrid variety in 2018 that were suggested for production at low, medium, and high-altitude coffee growing locations were the results of ongoing efforts in the hybridization study to boost coffee yield Furthermore, two additional hybrid kinds were added in 2022 specifically for the Sidama, Gedio, and Wolyita coffee-growing districts. It was advised to produce these hybrid types at middle altitudes. In Ethiopia, special attention is paid to high-quality hybrid types in the main coffee-producing regions.

8. Advice

It has been noted from the numerous sets of pure lines variety development programs in Ethiopia that increasing yield above 1800-2000 kg/ha through direct selection is uncommon, indicating the necessity to hunt for heterotic hybrids to maximize yield as high as 2500-3000 kg/ha. In order to discover high yielding, disease resistant, insect pest tolerant, quality and robust hybrids for commercial usage, it may be helpful to further examine the performance of the best performing hybrids for yield and growth traits at full bearing stage.

Abbreviations

CBD Coffee Berry Disease
CLR Coffee Leaf Rust
GCA General Combining Ability
SCA Specific Combining Ability

Author Contributions

Meseret Degefa Regassa is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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