Coffee (Coffea arabica L.) Breeding in Ethiopia

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Contributor: Yebirzaf Yeshiwas

Coffea arabica L. belongs to the Rubiaceae family, and the genus Coffea is believed to have a primary center of origin and genetic variability in the highlands of southwestern Ethiopia. It is a vital beverage commodity across the world and a valuable export product, ranking second in international trade after petroleum. Ethiopia is among the top five major coffee-producing countries and is Africa's leading producer. However, its full production capacity has not yet been exploited, and research efforts to reduce biotic and abiotic factors through reproduction have been extremely limited. Hence, improvement through different breeding methods is essential to overcome the constraints in its production.

Keywords: coffee ; genetic diversity ; coffee breeding ; improved varieties ; hybrid varieties

1. Introduction

Coffee (*Coffea arabica* L.) belongs to the family *Rubiaceae*, and the genus *Coffea* is mostly grown in subtropical and tropical regions [1] and consists of 90 to 124 species [2][3]. *Coffea canephora* Pierre and *Coffea arabica* L. are the only two species that are economically important and widely cultivated across the world. *Coffea liberica* is also cultivated on a small scale to satisfy local consumption [4]. The primary center of origin and genetic diversity for *Coffea arabica* L. is the highlands of southwestern Ethiopia, where it occurs naturally in the undergrowth of the Afromontane rainforests between 1000 and 2000 m above sea level [1][5][6][7][8][9][10].

Almost all coffee species are diploid (2n = 2x = 22) and most are self-incompatible, except for *Coffea arabica*, which is a self-fertile species and a natural allotetraploid (2n = 4x = 44). *Coffea arabica* is a self-pollinating species with a common outcrossing rate of less than 10%, which is sufficient to induce some variation in offspring and free-pollinating cultivars [1].

Coffee is one of the world's most important beverage crops and a valuable agricultural export commodity; it is the second-most commonly traded commodity in the world, after oil [11]. Arabica coffee represents 70% of the world's coffee production [12]. It is cultivated in over 80 countries and covers over 10.2 million hectares of land in the tropical and subtropical regions of the world, particularly in Africa, Asia, and Latin America [13].

Globally, the coffee trade generates about USD 10–12 billion annually for the producing countries and provides job opportunities for some 20–25 million people, who grow, process, distribute, and market the product [14][15][16][17].

In 2016, from the total national annual export revenues, coffee represented a 10% increase in earnings for Brazil (USD 4.84 billion) [18].

Ethiopia is one of the five largest coffee-producing countries in Africa [19]. The percent share of Ethiopian coffee to the world coffee market in four consecutive years has been 4.1, 4.1, 4.4, and 4.3 in 2013, 2014, 2015, and 2016, respectively [20]. In Ethiopia, coffee accounts for 60–70% of the national foreign exchange income and the livelihoods of some 20–25% of the population, directly or indirectly [21]. During the 2018/19 Meher Season, 764,863.16 ha of land was allotted for coffee production and 494,574.36 tones were obtained, with average productivity of 0.64 tones/ha^{-1} [22][23]. According to Tefera and Bickford [24] coffee exports reached 248,129 MT valued at USD 821,140.00 during 2019/20.

Despite its importance, the presence of great genetic diversity, and diverse agronomic species and suitable soils, coffee production in Ethiopia is lower compared to high-yielding countries such as Brazil, Colombia, Indonesia, and Vietnam. The estimated yield is less than 200 kg ha^{-1} for forest coffee and around 450–750 kg ha^{-1} for semi-modern coffee plantations [23], which is less by far than the 2443 kg ha^{-1} yield obtained by Brazil [25]. Arabica coffee production is affected by poor crop management practices, low yields, poor soils, diseases, pests, limited access to market information, lack of physical infrastructure, lack of improved hybrids, poor extension services, and climate change [26][27][28].

The Arabica coffee grown in Ethiopia is organic, fertilizers, pesticides, and herbicides are not applied, and the coffee is grown wild in the forests. Additionally, the seedlings used during planting are not grafted and need frequent and timely pruning. Similarly, the development of a disease-resistant and high-yielding variety by the traditional breeding approach is lengthy and inefficient. The multiplication of high-yielding, disease-free seedlings depends solely on hand pollination and, to a lesser extent, on advanced breeding methods such as clonal propagation by cutting and grafting. This is due to delays in protocol optimization for mass multiplication using tissue culture techniques [29]. Other major coffee producing countries have widely applied molecular breeding approaches to introduce new traits into selected coffee genotypes and develop new cultivars with desirable traits and a high yield [13].

Moreover, Ethiopia's full production capacity has not been exploited, and research and breeding efforts are limited and insufficient to respond to the diverse agroecologies of the country [30]. Consequently, the yield per hectare remains too low, at 0.673 tons ha^{-1} [31]. The development and improvement of high-yield and stress-tolerant coffee varieties are the main objectives for conventional and molecular breeding methods. Hence, it is evident that the improvement of coffee through different breeding methods is essential and is a critical task to address in order to overcome the constraints of coffee production. There have been research studies conducted over the last two to three decades in Ethiopia to improve coffee in terms of important traits such as productivity, resistance to disease and insect pests, and quality. Thus, reviewing and summarizing the recent research output on coffee breeding will help scientists to identify the research gaps and propose a future line of work for exploiting the potential of the crop.

2. Coffee Growth, Floral Biology, and Fruit Characters

2.1. Coffee Growth

Coffea arabica is a dicotyledon evergreen that reaches 8 to 10 m in height. Each node produces two, opposite leaves and therefore has two leaf axils residing on opposite sides of the node, each containing a series of buds. Branching is dimorphic as there are two kinds of buds: 'serial buds' and 'head of series buds'. The head of series buds develop into 'plagiotropic' (horizontal) branches, whilst the lower serial buds produce more 'orthotropic' (vertical) shoots, commonly called 'suckers', when the tip of the main orthotropic shoot is damaged. The shoot system of the coffee plant is illustrated in **Figure 1**. Inflorescences develop from serial buds at each node on the plagiotropic branches [32][33][34].

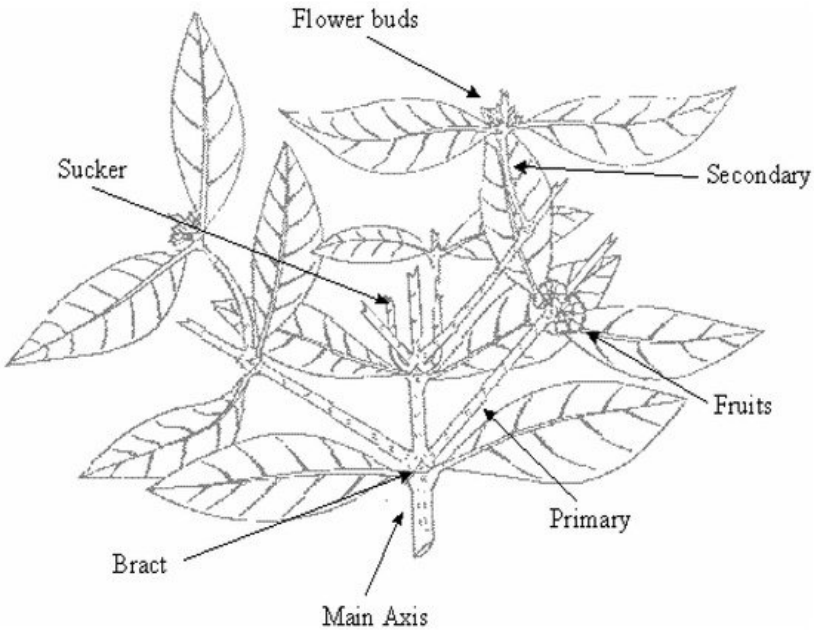

Figure 1. Morphology of mature Arabica coffee plant; Source: Obso [35].

2.2. Floral Biology and Fruit Characters

After 3–4 years of transplanting, fragrant white flowers grow in clusters in the axils of coffee leaves. The inflorescence has a short axis, two pairs of bracts at its base, and varying in number from one to twenty per leaf axil on the primary and secondary branches. The corolla is white and has five expanded petals. The five stamens are epipetalous and inserted in the corolla tube between the petals on short filaments; this facilitated emasculation. The anthers are bilocular, opening vertically/longitudinally. The pollen grains are numerous and small in size. Under normal conditions, pollen loses its viability very rapidly [36]. It is, however, possible to keep the viability for more than two years by storing it under vacuum

conditions at −18 °C. The ovary is inferior with a long terminal style and two stigmatic branches and is made up of two united carpels with one ovule per carpel [37].

The flowering of the coffee plant involves two separate processes, bud initiation and flower opening, also known as antithesis. The coffee buds that will develop into flowers are usually produced 4 to 5 months before anthesis. Initiation of the flower buds occurs when the serial buds on plagiotropic branches are induced to differentiate into floral buds. The floral buds open on sunny days in the early morning, and pollen removal begins soon after. The style is receptive when the bud opens and remains receptive for three to four days depending on climatic conditions [38]. However, Walyaro and Van der Vossen [37] report that stigmas are receptive for at least nine days and recommend that the vesicles should not be removed for two weeks after pollination for successful hybridization.

Buds can reach 4 to 6 mm and then enter a dormancy period. Dry periods are necessary to break the dormancy of floral buds and their final development and fruiting are often triggered by rainfall after a dry period. This occurs because after several weeks of water stress, rain stimulates floral growth, which will then open in eight to ten days. Fertilization takes place before or just at flower opening and then after pollination, where the fusion of one male nucleus and the polar nuclei forms an endosperm, and this endosperm then forms the coffee bean [39]. About 6 to 8 weeks after each coffee flower is fertilized, cell division occurs and the coffee fruit remains as a pinhead for a climate-dependent period of time.

Likewise, Cannell [40] explained that phytohormone levels in the coffee plant were affected by an extended dry season. During the first 3 to 4 days after a water stimulus, meiosis cell division occurs and there is an increase in the levels of endogenous, active, gibberellic acid in the floral bud. Coffee flowers are ephemeral, usually only lasting for two days.

According to Carvalho and Monaco [41], Van der Vossen [42], Arabica coffee is the only autogamous (self-compatible) species of the genus *Coffea* with only up to 10% of natural cross-pollination, whereas all other species are allogamous with gametophytic self-incompatibility. Pollination is affected by both wind (anemophily) and insects (entomophily). Having 10% natural cross-pollination could be adequate to retain heterozygosity within the population to a certain level. Therefore, selfing for one or two generations is important to guarantee sufficient homozygosity in parental lines destined to be used in a crossing program. William [43] reported that at Jimma Agricultural Research Center 10–40% outcrossing was recorded. Bud flower emasculations were performed 2–3 days before anthesis. Pollination was performed during the next day of emasculation. Labeling was conducted with the recording of details of the male and female parents, the date of emasculation, the date of pollination, and the name(s) of the breeders.

Prado et al. [44] explain that several floral morphological traits differ significantly between species and farm types. *C. arabica* plants grown in the shade had a corolla diameter 1.4% larger and an anthers height of 12.8% greater than those grown in the sun. Only the length of the tube was significantly longer in the sunny plantations; 8.7% longer in the sun than in the shade (**Figure 2**). In contrast, for *C. canephora*, there was no significant main effect on the type of exploitation of floral reproductive traits.

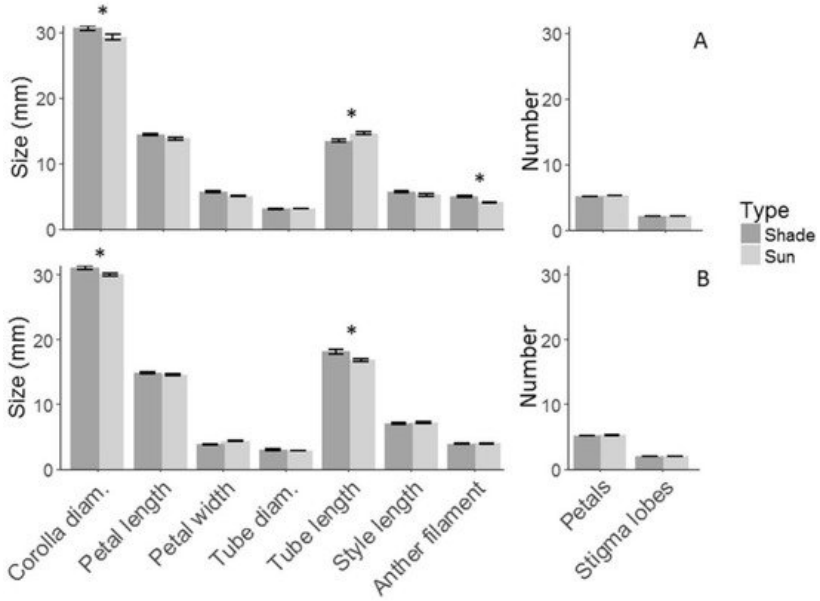

Figure 2. Average (±standard error) floral traits of (**A**) *Coffea arabica* and (**B**) *Coffea canephora*. * = significant differences between means of shade and sun at ($p < 0.05$). Source: Prado et al. [44].

Coffee fruit's pericarp is composed of exocarp, mesocarp, and endocarp, in which the seeds are enclosed. Immature berries have a dull green color; however, on ripening the skin color changes from yellow to bright pink. Each coffee berry contains two seeds with a length 8.5–12.5 mm, which are ellipsoidal and pushed together by a flattened surface that is deeply grooved; the outer surface is convex. Thin, silvery testa follow the outline of endosperm, so fragments are often found in the ventral groove after preparation. Seeds contain mainly green corneous endosperm and a small embryo near the base. Dried beans, after removal of the silver skin, provide the coffee beans for commercial purposes [45].

3. Production and Productivity of Coffee in Ethiopia

In Ethiopia, coffee grows between 550 and 2750 m above sea level. However, most Arabica coffee grows best at altitudes between 1300 and 1800 m above sea level. It requires annual rainfall ranges from 1500 to 2500 mm with minimum and maximum ideal air temperatures of 15 °C and 30 °C, respectively. In places where there is less rainfall, such as in the eastern part of the country (about 1000 mm), the coffee is supplemented with irrigation water. It also grows best in the shady environments of Ethiopia's highland forests [21][46][47].

The average yield of green coffee beans per year is 0.7 tons, which is lower than the global average and the Brazilian average 0.8 tons ha^{-1} and 1.3 tons ha^{-1}, respectively [48]. Coffee is cultivated by over 4 million small farm holders (**Table 1**). CSA [49] reported that more farmers cultivate and produce coffee than fruit. Almost 95% of coffee is grown on small plots, often less than half a hectare.

Table 1. Estimated number of coffee growers, area coverage, and yield (t/ha) over six years.

Year	Coffee Growers	Area in ha	Percentage Change in Area	Production in Quintal	Percentage Change in Production	Yield q/ha	% Change in Yield
2012/13	4,217,961.00	528,751.11	-	373,940.642	-	0.707	-
2013/14	4,546,785.00	538,466.80	2.00	392,006.222	5.00	0.728	3.00
2014/15	4,723,483.00	561,761.82	4.00	419,980.156	7.00	0.748	3.00
2015/16	5,270,777.00	653,909.76	16.00	414,596.455	−1.00	0.634	−15.00
2016/17	6,455,194.00	700,474.69	7.00	469,091.124	13.00	0.67	6.00
2017/18	5,019,513.00	725,961.24	4.00	449,229.808	−4.00	0.619	8.00

Ethiopia's coffee production is generally characterized by four production systems. That is forest coffee, semi-forest coffee, garden coffee, and plantation coffee. The main coffee growing areas and denominations as international trade in Ethiopia are Limu, Jimma (commercially Djimma), G(h)imbi and Lekempti, Sidamo, Yirgachefe, Illubabor, Harar, Tepi, and Bebeka. The additional coffee specialty has been recently identified in Amaro, Amhara, Arsi, Balé forest, Borena, Guji, Kaffa forest, Omo, and many other areas [50][51].

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