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Original Article

COFFEA CANEPHORA IN NIGERIA: HISTORICAL CONTEXT, AGRONOMIC PRACTICES, AND MOLECULAR INNOVATIONS FOR SUSTAINABLE PRODUCTION

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ABSTRACT

Coffea canephora (Robusta coffee) is a vital agricultural commodity in Nigeria, supporting rural livelihoods and foreign exchange earnings. This review synthesizes historical, agronomic, and molecular advancements in *Coffea canephora* cultivation in Nigeria, exploring the species' genetic diversity, economic significance, production constraints, and best practices, emphasizing the transformative potential of molecular breeding to address climate change, aging plantations, and market competitiveness. By integrating conventional breeding with marker-assisted selection (MAS) and genomic selection, Nigeria can enhance *Coffea canephora* productivity, quality, and resilience. Beyond these marker-based approaches, CRISPR/Cas genome editing is examined as a complementary tool for introducing precise, targeted changes, such as reduced caffeine content and improved disease resistance, directly into the genome, bypassing the lengthy backcrossing cycles that constrain conventional breeding in this slow-flowering perennial crop. The study also discussed socioeconomic impacts, policy frameworks, and sustainable practices, including agroforestry and climate-smart agriculture, that aligned with global sustainability goals. Emerging genomic tools, such as CRISPR/Cas9, transcriptomics, and precision agriculture technologies like artificial intelligence (AI) and remote sensing, were identified as offering new opportunities to overcoming production barriers. Research gaps, including limited genomic resources for Nigerian populations, underutilized wild germplasm, and the tissue-culture and biosafety infrastructure needed for genome editing, were highlighted as critical for future progress. This review provided a roadmap for revitalizing Nigeria's coffee sector, ensuring economic and environmental sustainability in a dynamic global market. By fostering interdisciplinary collaboration and policy support, Nigeria can strengthen its position as a key player in the global coffee industry.

Keywords: Robusta Coffee, Agronomic practices, Molecular markers, Sustainable farming, Nigeria, Genome editing, CRISPR/Cas9

INTRODUCTION

Coffee (*Coffea spp.*) is a cornerstone of global agriculture, generating over US$10 billion annually in trade and supporting the livelihoods of millions of smallholder farmers across 80 countries [1, 2]. *Coffea* comprises approximately 130 species, with *Coffea canephora* (Robusta) and *Coffea arabica* dominating commercial production due to their distinct agronomic and sensory profiles [3]. While *Coffea arabica* is prized for its complex flavor and high cup quality, *Coffea canephora* is valued for its high yield, disease resistance, and adaptability to diverse agroecological conditions, making it a critical crop in regions with challenging climates [4, 5].

In Nigeria, *C. canephora* accounts for 94% of coffee production, primarily serving the instant coffee market and contributing to rural economies across 14 states, including Kogi, Oyo, and Cross River [5]. Coffee cultivation has deep historical roots in Nigeria, dating back to the 1920s, when *C. liberica* and *C. abeokutae* were predominant [6]. Today, *C. canephora* dominates, supporting rural development, cultural practices, and foreign exchange earnings. However, Nigeria's coffee industry faces significant challenges, including declining yields, aging plantations, climate variability, low input use, and limited market access [7, 8]. These constraints highlight the need for innovative approaches to revitalize the sector and enhance its global competitiveness.

Globally, coffee production is under pressure from multiple factors. Climate change poses a further, compounding threat to yields worldwide, as detailed under constraints to coffee production below [9]. Pests and diseases, such as coffee leaf rust (*Hemileia vastatrix*) and coffee berry disease (*Colletotrichum kahawae*), cause significant losses, particularly in *Coffea arabica* [10]. Market dynamics, including fluctuating prices and increasing demand for high-quality and sustainably sourced coffee, further complicate production systems. In this context, *C. canephora*'s resilience and adaptability offer a strategic advantage, particularly for countries like Nigeria seeking to increase their share of the global coffee market, amid this rising global demand, discussed further under economic importance below [2].

Beyond its economic value, coffee provides health and social benefits. Rich in antioxidants, coffee consumption is linked to reduced risks of neurodegenerative diseases like Alzheimer's and Parkinson's, as well as enhanced cognitive function [11]. Its energizing properties make it a popular beverage among students, professionals, and diverse demographics, embedding it in global and local cultures. In Nigeria, coffee is consumed in traditional ceremonies and social gatherings, reinforcing its cultural significance [6].

Despite the long history and economic importance of *C. canephora* in Nigeria, the available literature remains fragmented across disciplinary lines, historical and economic accounts, agronomic recommendations, and the rapidly expanding molecular breeding literature are rarely considered together, and Nigerian-specific genomic resources and breeding outputs remain comparatively scarce relative to those for major producing countries. This fragmentation makes it difficult for researchers, breeders, and policymakers to identify where conventional agronomic interventions end and where molecular tools, such as marker-assisted selection (MAS) and genomic selection, can most usefully be deployed. This re-

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view therefore aims to synthesize historical, agronomic, and molecular perspectives on *C. canephora* cultivation in Nigeria into a single, integrated framework. Specifically, the review traces the historical and economic context of coffee production in the country, examines the principal production constraints and best-practice agronomic recommendations, evaluates molecular approaches particularly MAS, genomic selection, and emerging tools such as CRISPR/Cas9 for enhancing genetic diversity, yield, and resilience, and considers the socioeconomic and policy dimensions, including agroforestry and climate-smart agriculture, that will determine whether these technical gains translate into on-farm impact. By drawing these strands together, the review identifies priority research gaps and proposes a road map for revitalizing Nigeria's *C. canephora* sub-sector in a manner that is both scientifically grounded and responsive to the realities of smallholder production systems.

Table 1: Comparison of Major Coffee Species

Criteria	*Coffea arabica*	*Coffea canephora* (Robusta)	*Coffea liberica*
Morphology	Leaves: large, oval, dark green Flowers: small, white, fragrant Cherries: oval, small Beans: flat, oval, curved crease	Leaves: larger, broader, darker green Flowers: small, white, less fragrant Cherries: round, larger Beans: smaller, round, straight crease	Leaves: very large, elongated, leathery Flowers: large, white, fragrant Cherries: large, irregular Beans: large, irregular shape
Genetics	Diversity: higher Varietals: many (e.g., Bourbon, Typica)	Diversity: lower Varietals: fewer (e.g., Conillon, Nganda)	Diversity: moderate Varietals: few, less commonly grown
Sensory profile	Aroma: complex, floral, fruity Flavor: sweet, fruity, balanced acidity Body: medium to full Aftertaste: smooth, lingering	Aroma: earthy, woody, nutty Flavor: strong, bitter, high acidity Body: full, heavy Aftertaste: strong, lingering bitterness	Aroma: smoky, floral, woody Flavor: bold, full-bodied, unique Body: full, heavy Aftertaste: complex, lingering
Ecology / cultivation	Altitude: high (600–2000 m) Climate: cool, stable Soil: rich, well-drained Farming: often shade-grown, organic	Altitude: low (0-600 m) Climate: hot, humid Soil: varied, well-drained Farming: sun-grown, conventional	Altitude: low–medium (0-1200 m) Climate: tropical, humid Soil: rich, varied Farming: shade-grown, traditional
Pest/disease resistance	Resistance: low to moderate Common threats: leaf rust, berry borer Management: requires careful monitoring	Resistance: high Common threats: coffee berry disease Management: requires less monitoring	Resistance: moderate Common threats: leaf rust, pests Management: moderate monitoring

Source: Waller *et al* [12]

BOTANICAL AND GENETIC CHARACTERISTICS OF *COFFEA CANEPHORA*

Coffea canephora is an evergreen shrub native to the humid lowland forests of tropical Africa, typically growing to 5-10 meters but pruned to 2-3 meters for ease of harvesting in commercial cultivation [12]. Its shallow root system, primarily occupying the top 15 cm of soil, is highly plastic, adapting to varying soil depths based on environmental conditions [13]. Compared to *C. arabica*, *C. canephora* has larger, broader leaves and rounder, larger cherries, with beans exhibiting a straight crease [12]. These morphological traits, summarized in Table 1, contribute to its distinct sensory profile, characterized by earthy, woody, and nutty flavors with high acidity and a heavy body.

C. canephora is largely self-sterile, relying on cross-pollination by wind or insects, which enhances its genetic diversity and adaptability compared to the self-pollinating *C. arabica* [14]. Effective fruit setting in commercial settings is achieved through mixed clonal planting, which promotes cross-pollination and maximizes yields [15]. The species thrives in hot, humid climates at low altitudes (0-600 m), with modern varieties exhibiting increased sun tolerance due to selective breeding in drier regions [16].

Genetically, *C. canephora* is divided into two major groups: Congolese and Guinean, with the Congolese group further subdivided into five subgroups (A, B, C, E, O) and two additional subgroups (G, R) recently identified [17, 18]. These groups reflect the species' wide geographic distribution across tropical Africa, from Guinea to Uganda and Angola. The genetic diversity within these groups underpins breeding programs aimed at improving yield, quality, and resistance to

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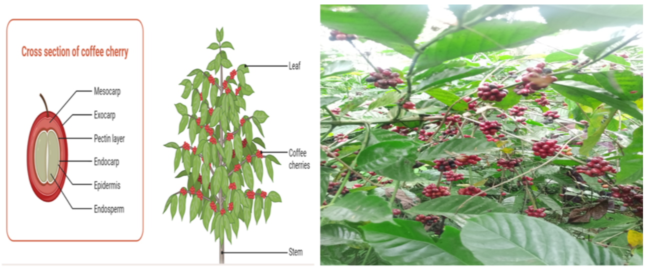
stresses such as drought, pests, and diseases. For example, the Congolese subgroup E, prevalent in the Democratic Republic of Congo, is noted for its high yield potential, while the Guinean group (D) exhibits superior disease resistance [18].



Coffee plant and cherry anatomy clusters

Ripening coffee cherries on the plant with of red berries and green leaves.

Figure 1 - Morphology of *Coffea canephora* showing anatomical features and ripening cherries.

HISTORICAL AND ECONOMIC SIGNIFICANCE IN NIGERIA

Historical Overview

Coffee cultivation in Nigeria began in the early 20th century, with the Federal Department of Agriculture (FDA) reporting its introduction around 1920 [6]. Initially, *Coffea liberica* and *C. abeokutae* (a variant of *C. liberica*) were the dominant species, native to Nigeria and well-suited to local conditions. By the mid-20th century, *C. canephora* emerged as the primary species due to its higher yield and resilience, accounting for 94% of current production, followed by *C. arabica* (4%) and *C. liberica* (2%) [19]. The Mambilla Plateau (Taraba State), Jos Plateau (Plateau State), and Obudu Cattle Ranch (Cross River State) are notable for *C. arabica* cultivation, while *C. canephora* dominates in states like Oyo, Ogun, Ondo, Ekiti, Kwara, Kogi, Edo, Delta, Abia, Cross River, Akwa Ibom, Taraba, and Plateau.

The Cocoa Research Institute of Nigeria (CRIN) played a pivotal role in coffee breeding, with genetic materials introduced around 1966 and formal breeding programs initiated in 1969 [20]. Robusta varieties, particularly Java (85%) and Quillou (15%), became the backbone of Nigeria's coffee industry, targeting the instant coffee market. Despite this foundation, production has fluctuated significantly, peaking at 4,000 tonnes in 1966 but declining to 1,712 tonnes in 1967 due to political unrest and further to 1,117 tonnes in 2019 due to environmental and market challenges [7].

Beyond the broad Java/Quillou groupings, CRIN's *C. canephora* germplasm has been further characterized using both biochemical and molecular tools. Early morphological surveys described the collection as comprising up to six varietal groups, but genotyping-by-sequencing analysis of accessions from the CRIN genebank later resolved this to three genetically distinct varietal groups, corresponding to the Java Robusta/Java Robusta ex Gamba, Kouillou/Java Robusta, Uganda/Gold Coast, and Niaouli lineages [19]. Biochemical characterization of Nigerian Robusta clones has also identified genotypes with comparatively low caffeine content alongside high yield potential, illustrating the scope for combining quality and productivity traits within the existing germplasm base [20]. These findings provide a practical starting point for clonal selection and for targeting parents in future crossing programs.

Economic Importance

Coffee is a vital export crop in Nigeria, contributing to foreign exchange earnings and rural development. Globally, coffee is the second most popular beverage after water, with 3.5 million cups consumed daily and an industry supporting millions of livelihoods, particularly in Africa, where 95% of production comes from smallholder farmers [8]. In Nigeria, coffee cultivation employs thousands of farmers and laborers, particularly in states like Kogi, a major Robusta producer [21]. The crop's economic significance extends to rural poverty alleviation, with coffee farming providing stable income for households and supporting community development through infrastructure and education initiatives [5].

Despite its potential, Nigeria's coffee industry has not fully capitalized on global market opportunities. The global coffee trade saw exports increase from 10.47 million bags in July 2020 to 10.61 million in July 2021, reflecting rising demand [2]. Nigeria's low production limits its market share, but strategic interventions, such as improved varieties and better processing, could enhance competitiveness. Coffee's health benefits, including antioxidant properties linked to reduced neurodegenerative disease risks, further increase its market appeal [11].

The decade summarized in Table 2 shows that national coffee production has remained largely static at around 1,750-2,100 tonnes per annum, with both planted area and yield (kg/ha) essentially flat (approximately 1,280-1,320 kg/ha throughout the period). This stagnation, occurring against a backdrop of rising global demand, indicates that Nigeria's coffee output is constrained less by short-term price signals than by structural factors such as the aging plantation base and limited adoption of improved planting material discussed in subsequent sections. Notably, import quantities have generally exceeded export quantities since 2020, a reversal of the historical pattern, which may reflect both declining export-quality supply and growing domestic demand for processed coffee products. These trends reinforce the case for sustained investment in varietal improvement and agronomic rehabilitation rather than reliance on area expansion alone.

Table 2: Production and export data of coffee production in Nigeria from 2013-2024

Year	Production (t)	Area Harvested (ha)	Yield (kg/ha)	Import quantity (t)	Export quantity (t)
2013	2100	1639	1281.1	8	39
2014	1972.17	1520	1297.4	4.99	81.37
2015	1754.52	1345	1304.5	4.51	152.52
2016	1942.23	1501	1293.6	17.63	74.71
2017	1889.64	1455	1298.3	88.14	97.72
2018	1862.13	1434	1298.6	19.68	89.82
2019	1852.02	1421	1302.9	4.69	42.83

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Year	Production (t)	Area Harvested (ha)	Yield (kg/ha)	Import quantity (t)	Export quantity (t)
2020	1,806.08	1,380	1,308.80	65.18	30.27
2021	1,798.95	1,367	1,315.80	111.23	7.91
2022	1,819.02	1,390	1,309.10	142.37	14.02
2023	1,808.01	1,379	1,311.20	115.90	21.74
2024	1,808.66	1,379	1,312.00	201.37	25.71

Source: Food and Agricultural Organization (2013-2024) [7]

GLOBAL DISTRIBUTION AND GENETIC DIVERSITY

Global Distribution

Coffea canephora originates from the humid lowland forests of tropical Africa, with a natural distribution spanning Guinea to Uganda and Angola [22]. Cultivation began around 1870 in the Congo, using material from the Lomami River region, now the Democratic Republic of Congo (DRC). A subtype, "kouillou" (later renamed "conilon" in Brazil), was identified in 1880 along the Kouilou-Nari River. By 1895, botanist Louis Pierre formally named the species based on a Gabon sample.

Robusta's global spread accelerated in the late 19th century, driven by its resistance to coffee leaf rust, which devastated *C. arabica* plantations in Southeast Asia. Seeds from Congo were sent to Brussels and Java, Indonesia, where the species gained popularity for its productivity. Additional genetic material from Gabon and Uganda was introduced, and selected wild populations were cultivated in Ivory Coast, Guinea, and Uganda. By the early 20th century, Robusta reached India, Madagascar, Ghana, and Ivory Coast, often blending endemic and introduced variants. In Latin America, Brazil became a major producer, with Central America (e.g., Guatemala, Costa Rica) adopting Robusta between 1930 and 1983. Today, Asia and Oceania produce 60% of global Robusta (41.5 million 60 kg bags annually), followed by South America (28%, 19.8 million bags) [2].

Genetic Diversity

Coffea canephora exhibits significant genetic diversity, divided into Congolese and Guinean groups, with the Congolese group comprising subgroups A (Benin, Gabon), B (eastern Central African Republic), C (Cameroon, western Central Africa), E (DRC), O (Uganda), G (Angola), and R (southern DRC) [17, 18]. This diversity is critical for breeding programs targeting traits like yield, disease resistance, and climate resilience. Major germplasm collections, such as the Centre National de la Recherche Agronomique (CNRA) in Ivory Coast (>1,000 genotypes) and the Coffee Research Centre (COREC) in Uganda, provide valuable resources [23].

Single nucleotide polymorphism (SNP) markers, including DArTSeq and genotyping-by-sequencing (GBS), have revolutionized diversity studies, revealing population structures and trait associations [24, 19]. For example, a study in Nigeria identified 433,048 GBS SNPs across 44 *C. canephora* accessions, highlighting moderate diversity and potential for breeding [19].

CONSTRAINTS TO COFFEE PRODUCTION IN NIGERIA

Nigeria's coffee sector faces multiple challenges that limit its productivity and competitiveness:

1. Aging Plantations

Most coffee plantations in Nigeria consist of trees over 40 years old, far exceeding their productive lifespan [25]. Aging trees exhibit reduced yields and increased susceptibility to pests and diseases. While pruning and rehabilitation techniques can extend productivity, replacing old trees with high-yielding, disease-resistant varieties is a long-term solution [26]. The cost and labor required for replanting deter many farmers, necessitating support through subsidies or extension services [21].

2. Climate Change

Climate change poses a significant threat, with prolonged droughts and irregular rainfall reducing yields by up to 20%

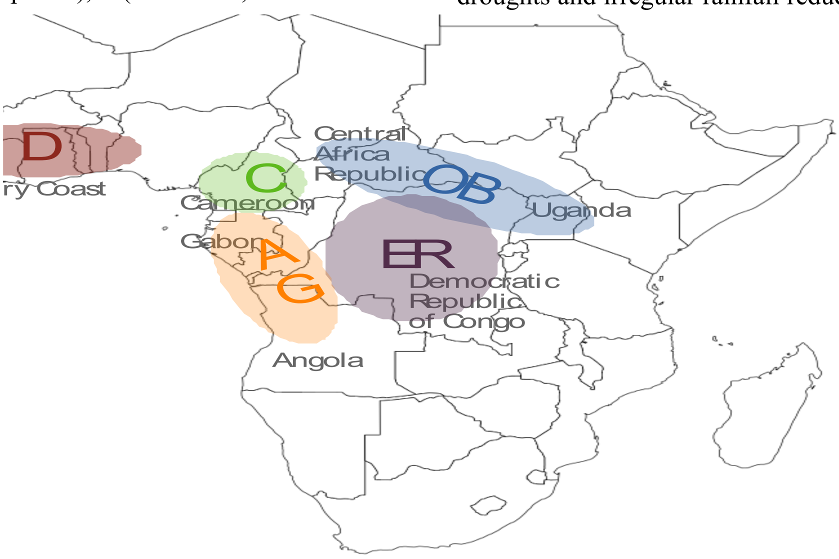

Figure 2 - Global genetic distribution of *Coffea canephora* accessions.

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[9]. Drought disrupts photosynthesis and other physiological processes, compromising bean quality and quantity. Adaptation strategies, such as drought-tolerant varieties, water harvesting, mulching, and crop diversification, are essential but underutilized due to limited farmer awareness and resources [27].

3. Low Input Use

Limited access to fertilizers, fungicides, and pesticides contributes to low productivity, with diseases causing up to 50% yield losses [28]. High input costs and inadequate training discourage adoption, exacerbating the problem [29]. Training programs and affordable input schemes could improve yields and quality.

4. Marketing Challenges

Poor pricing, limited market information, and low-quality beans due to inadequate processing hinder profitability [8]. The absence of a robust quality control system results in beans that fail to meet international standards, reducing Nigeria's global competitiveness [21]. Pre- and post-harvest practices contribute 40% each to coffee quality, highlighting the need for improved processing and marketing channels [30].

5. Land Scarcity

Population growth and urbanization have reduced available farmland, with coffee farms converted to residential areas [31]. High land acquisition costs and farm abandonment further limit production [21]. Policies promoting land conservation, reforestation, and communal ownership could address this issue.

BEST AGRONOMIC PRACTICES

1. Site Selection

Ideal sites for *C. canephora* feature flat or gently sloping terrain with well-drained, friable soils containing 15-20% clay and a pH of 5.5-7.0 [32]. Routine soil testing ensures optimal fertilization with nitrogen (vegetative growth), phosphorus (root and flower development), and potassium (fruiting).

2. Nursery Management

Coffee seeds germinate in 30-50 days in shaded, organic-rich nursery beds with consistent moisture [33]. Seedlings are maintained for 3-6 months, undergoing regular watering, weeding, and pest management. Hardening by gradual sunlight exposure prepares them for transplanting.

3. Field Management

Transplanting at the rainy season's onset ensures moisture for establishment, with 3.1 x 3.1 m spacing and compost-enriched planting holes. Mulching with organic materials (e.g., plantain trash) maintains soil moisture and suppresses weeds, while shade trees like plantains reduce water stress [34]. Manual weeding (3-4 times annually) and pre-emergence herbicides (e.g., Gramazone) control competition.

4. Pruning and Harvesting

Pruning removes unproductive branches and deadwood, promoting new growth. Tools like pruning saws and secateurs are used, with wounds treated to prevent infection [35]. Harvesting ripe cherries ensures optimal flavor, with mechanized pulping improving post-harvest efficiency.

5. Post-Harvest Processing

Two main primary-processing routes are used for *C. canephora*: the dry (natural) method, in which whole cherries are sun-dried on raised beds or clean concrete drying floors before hulling, and the wet (washed) method, in which the skin and mucilage are removed mechanically and by fermentation before drying the resulting parchment. The dry method is less capital-intensive and remains the dominant practice among Nigerian smallholders, but it is highly sensitive to weather during drying and is more prone to over-fermentation and mould-related defects if cherries are not turned regularly. The wet method generally produces a cleaner cup and commands a price premium, but requires reliable water supply and pulping equipment that are often beyond the reach of individual smallholders. A semi-washed (pulped natural) approach, in which mucilage is partly removed before drying, offers an intermediate option that can improve bean quality at relatively modest additional cost. Strengthening farmer access to shared pulping and drying infrastructure, alongside training on cherry selection (harvesting only ripe, red cherries) and drying-floor hygiene, would directly address the post-harvest quality gap identified under Marketing Challenges and complement the varietal and agronomic improvements discussed elsewhere in this review.

MOLECULAR APPROACHES IN *COFFEA CANEPHORA* RESEARCH

Genetic Diversity

Genetic diversity is critical for improving *C. canephora*'s agronomic traits, disease resistance, and quality [36]. SNP markers (Table 3), including DArTSeq and GBS, provide insights into population structure and trait associations [19, 24]. Whole-genome sequencing, RADSeq, and GBS target specific genomic regions, identifying traits like caffeine content and disease resistance [37].

Table 3: Studies on Local Genetic Diversity of Coffee in Different Regions Using SNPs

Region	Species	Source of plants	Markers	Reference
Mexico and Vietnam	*87 C. canephora*	Wild and cultivated	4,021 DArTSeq SNPs	Garavito *et al.* [24]
Nigeria	*44 C. canephora, 1 C. arabica, 1 C. abeokutae, 1 C. liberica, 1 C. stenophylla*	Conserved and cultivated	433,048 GBS SNPs	Anagbogu *et al.* [19]
Reunion Island	*25 C. mauritiana, 16 C. canephora, 1 C. eugenioides, 1 C. liberica, 1 C. bertrandii*	Wild	3,953 DArTSeq SNPs	Garot *et al.* [38]

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Region	Species	Source of plants	Markers	Reference
Africa	*27 C. canephora, 17 C. arabica, 6 C. eugenioides*	Wild and cultivated	Coffee 8.5K SNP array (8,580 SNPs)	Mérot-L'Anthoëne *et al.* [18]
China	*48 C. arabica, 34 C. canephora, 11 C. excelsa*	Cultivated	15,367,960 whole-genome SNPs	Huang *et al.* [39]
Ethiopia, Yemen, etc.	*736 C. arabica*	Wild and cultivated	698 GBS SNPs	Scalabrin *et al.* [40]
Mexico	*3 C. canephora, 83 C. arabica, 1 C. liberica*	Cultivated	1,739 DArTSeq SNPs	Spinoso-Castillo *et al.* [41]
Ghana	*400 C. canephora*	Cultivated	192 KASPar SNPs	Akpertey *et al.* [42]
Kenya	*91 C. canephora*	Cultivated	2,280 DArTSeq SNPs	Gimase *et al.* [10]
Ethiopia, Yemen, etc.	*130 C. arabica*	Wild and cultivated	96 KASPar SNPs	Zhang *et al.* [43]
Uganda	*207 C. canephora*	Wild	SNPs in 323 candidate genes	de Aquino *et al.* [44]

Source: adapted from Vi *et al.* [45]

Marker-Assisted Selection (MAS) in Coffee Breeding

Marker-Assisted Selection (MAS) has emerged as a groundbreaking strategy in coffee breeding, offering a highly efficient and precise alternative to conventional methods. Traditional coffee breeding, particularly for species like *Coffea canephora*, is hindered by the crop's perennial nature, with flowering cycles spanning 3-6 years and breeding programs often requiring decades to achieve desired traits such as disease resistance, enhanced yield, or superior cup quality [46]. Conventional approaches rely heavily on phenotypic evaluations and visual selection, which are not only time-consuming but also susceptible to environmental variability and high field trial costs. Moreover, interspecific crosses in coffee breeding can introduce unwanted chromosomal regions, reducing offspring viability and further complicating the process [46]. MAS overcomes these challenges by utilizing molecular markers to identify and select genotypes with targeted traits at early developmental stages, significantly accelerating the breeding process and reducing resource demands.

Molecular markers, such as Sequence-Related Amplified Polymorphism (SRAP), Start Codon Targeted Polymorphism (SCoT), Simple Sequence Repeats (SSRs), Random Amplified Polymorphic DNA (RAPD), and Amplified Fragment Length Polymorphisms (AFLPs), have revolutionized coffee genetics by enabling breeders to assess genetic diversity and pinpoint markers linked to agronomically valuable traits. For example, Arun *et al.* [47] demonstrated the efficacy of SRAP and SCoT markers in evaluating the genetic diversity and population structure of *C. canephora*, facilitating the identification of elite accessions for breeding programs aimed at improving pest resistance, yield, and bean quality. Similarly, SSRs, known for their high reproducibility and co-dominant inheritance, have been extensively used to study gene introgression and genetic variation within and between coffee species, such as detecting *C. canephora* DNA fragments in *C. arabica* lines [48, 49]. AFLP markers, valued for their robustness and ability to detect numerous polymorphisms without prior sequence knowledge, have also proven effective in constructing linkage maps and analyzing genetic diversity in coffee germplasm [50].

The primary advantage of MAS lies in its ability to shorten breeding cycles and enhance selection accuracy, addressing the inefficiencies of conventional breeding. By identifying molecular markers associated with specific traits, MAS allows breeders to screen seedlings or young plants, bypassing the need for prolonged field evaluations. This is particularly critical for complex, polygenic traits such as drought tolerance, disease resistance, and environmental adaptability, which are challenging to assess through traditional morphological or agronomic methods. Genomic selection, an advanced application of MAS, further amplifies these benefits by using genome-wide molecular markers to predict an individual's genetic merit, offering a powerful tool for quantitative trait improvement [51]. For instance, genomic selection has shown promise in enhancing traits related to coffee leaf rust resistance and climate resilience, enabling breeders to develop varieties that thrive under changing environmental conditions.

Unlike traditional morphological markers, molecular markers are abundant, span the entire genome, and are unaffected by environmental factors, ensuring consistent and reliable results [52]. However, the choice of marker depends on the research objective and the specific traits targeted. For example, RAPD markers, despite their sensitivity to reaction conditions, are cost-effective and widely used for genetic diversity studies in coffee due to their simplicity and minimal DNA requirements. In contrast, SSRs require prior sequence information but offer superior reproducibility, making them ideal for precise genetic mapping and marker-trait association studies [53].

By integrating molecular tools, MAS not only accelerates the development of improved coffee varieties but also enhances the precision of breeding programs. It mitigates challenges such as the retention of undesirable chromosomal segments in interspecific crosses and reduces the dependency on extensive backcrossing, which can delay progress in conventional breeding. As global demand for sustainable, high-quality coffee grows amid challenges like climate change and emerging pests, MAS provides a forward-looking solution, enabling breeders to develop resilient, high-performing varieties in a fraction of the time required by traditional methods. This paradigm shift in coffee breeding highlights the transformative potential of molecular technologies in addressing the evolving needs of the coffee industry.

Genome Editing and CRISPR/Cas Technology in Cof-

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fee Improvement

While MAS and genomic selection rely on naturally occurring genetic variation, CRISPR/Cas gene-editing technology allows breeders to introduce precise, targeted changes directly into the coffee genome, bypassing the lengthy introgression and backcrossing cycles that limit conventional and marker-assisted approaches in a slow-flowering perennial crop [54]. Proof-of-concept studies in *Coffea canephora* have demonstrated that Agrobacterium-mediated delivery of CRISPR/Cas9 constructs into embryogenic calli can generate targeted knockouts of the phytoene desaturase (CcPDS) gene, confirming that the editing machinery functions efficiently in this species [54, 55]. Breitler et al. [54] first validated this approach in *Coffea canephora* by targeting exon 14 of CcPDS, achieving mutation rates of around 30% using single sgRNAs, though without producing a fully albino phenotype. Casarin et al. [55], working with the same species, later used a multiplexed vector targeting two different exons of CcPDS simultaneously and recovered mutations in 77% of regenerated *Coffea canephora* seedlings, this time producing the expected albino phenotype. The improvement illustrates how methodological refinements, such as multiplexing, promoter optimisation, and adjusted co-cultivation temperature and light regimes, can substantially increase editing efficiency in this recalcitrant perennial crop.

Beyond loss-of-function proof-of-concept work, CRISPR/Cas approaches are being explored across other perennial and semi-perennial crops, including citrus and sugarcane, to accelerate trait introduction while avoiding the decades-long breeding cycles typical of tree and cane crops [56]. For coffee specifically, priority targets extend beyond simple knockouts to traits of direct commercial relevance, most notably the N-methyltransferase genes that catalyse the final steps of caffeine biosynthesis, whose disruption could yield naturally decaffeinated *C. canephora* lines without the flavour losses associated with industrial decaffeination [55]. Editing of genes controlling plant architecture, flowering time, and stress-response pathways offers further scope for developing compact, drought-tolerant, or disease-resistant Robusta genotypes suited to Nigerian growing conditions.

For Nigeria, realising this potential will require investment in the tissue-culture and Agrobacterium-transformation capacity discussed under Clonal Propagation and Tissue Culture below, since efficient embryogenic callus regeneration is a prerequisite for any CRISPR delivery system in *C. canephora*. It will also require engagement with national biosafety and regulatory frameworks, as the classification of genome-edited (as opposed to transgenic) plants continues to evolve internationally and will shape how quickly edited Nigerian Robusta lines could reach farmers [56]. Coupling this capacity-building with the genomic resources described under Genetic Diversity above would position CRIN to move from marker-based selection toward targeted trait editing as a complementary, rather than substitute, tool in the national breeding program. Figure 3 summarizes how these four approaches, conventional breeding, MAS, genomic selection, and genome editing, relate to one another, illustrating that each successive tool builds on, rather than replaces, the genetic resources and selection gains established by the approaches before it.

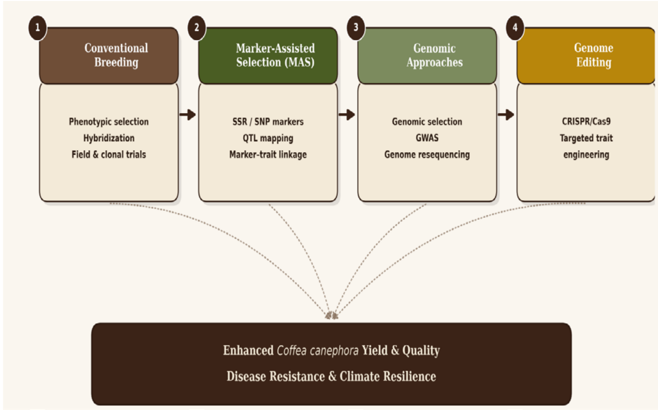

Figure 3 - Breeding continuum for *Coffea canephora* improvement, from conventional breeding through MAS and genomic approaches to genome editing, converging on improved yield, quality, disease resistance, and climate resilience.

Clonal Propagation and Tissue Culture

Once superior genotypes are identified through phenotypic evaluation or MAS, they must be multiplied true-to-type for distribution to farmers. Conventional vegetative propagation of *C. canephora* is achieved mainly through single- or multi-node stem cuttings rooted under high-humidity propagators, and through grafting of elite scions onto vigorous rootstocks. Micropropagation via somatic embryogenesis and tissue culture offers a complementary route for rapid, large-scale multiplication of elite clones and for the rejuvenation of aging plantation material, although the technique remains capital- and skill-intensive and is not yet widely deployed in Nigerian seed gardens. Strengthening clonal multiplication capacity, whether through conventional cuttings at the community level or through tissue-culture facilities at research institutes is therefore essential if the genetic gains from MAS and genomic selection are to reach the aging plantations described under Constraints to Coffee Production.

SOCIOECONOMIC AND POLICY PERSPECTIVES

Coffee cultivation supports rural livelihoods, particularly in states like Kogi, and holds cultural significance in Nigeria [21]. It provides employment, enhances household incomes, and supports community development through schools and infrastructure. However, limited extension services, high input costs, and poor market access hinder growth.

Policy interventions, such as subsidies, training programs, and quality control systems, could enhance productivity and competitiveness. For example, establishing cooperatives could improve market access and bargaining power for farmers.

SUSTAINABILITY AND CLIMATE RESILIENCE

Sustainable practices, such as agroforestry, organic farming, and carbon sequestration, enhance *C. canephora*'s resilience and align with global sustainability goals. Agroforestry systems, integrating coffee with shade trees like plantains, improve soil health, reduce water stress, and sequester carbon [34]. Climate-smart agriculture, including drought-tolerant varieties and water harvesting, mitigates climate risks [27].

Precision agriculture technologies, such as AI-driven yield prediction and remote sensing for pest monitoring, offer new

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opportunities. For example, satellite imagery can optimize irrigation, improving water use efficiency [57].

RESEARCH GAPS AND PRIORITIES

Several priority gaps emerge from the foregoing synthesis. First, Nigerian *C. canephora* populations remain under-represented in genomic databases relative to germplasm from East Africa, Southeast Asia, and Latin America; expanding SNP- and GBS-based characterization of CRIN's genebank accessions and farmer-cultivated landraces, building on the work of Anagbogu *et al.* [19], would provide the foundation for marker-assisted and genomic selection programs tailored to local conditions. Second, the wild relatives and underutilized *Coffea* species native to Nigeria (*C. liberica*, *C. abeokutae*, and *C. stenophylla*) represent a largely unexploited reservoir of stress-tolerance and quality alleles that could be introgressed into *C. canephora* breeding pools. Third, there is a lack of multi-location, multi-year agronomic trial data linking specific clones to yield and quality performance under Nigerian conditions, which limits the evidence base for the varietal recommendations farmers need. Fourth, post-harvest processing infrastructure and its effect on cup quality and price premiums has received little formal research attention locally, despite its identified importance to market competitiveness. Finally, the socioeconomic and policy levers that would translate technical gains into farmer adoption, extension delivery models, input-financing schemes, and cooperative marketing structures require dedicated study, as technology alone will not resolve the structural stagnation evident in the production data (Table 2).

CONCLUSION

The adoption of Marker-Assisted Selection (MAS) in *Coffea canephora* breeding marks a transformative step forward for Nigeria's coffee industry, overcoming the limitations of conventional breeding methods that are slowed by extended flowering cycles, environmental variability, and costly field trials. MAS harnesses molecular markers like SRAP, SCoT, SSRs, RAPDs, and AFLPs to enable precise and rapid selection of traits such as disease resistance, enhanced yield, and superior bean quality, significantly reducing breeding timelines and resource demands. The application of genomic selection further enhances this process by predicting genetic merit for complex traits, offering a powerful tool to address challenges like coffee leaf rust and climate adaptability. Coupled with Nigeria's rich genetic diversity in *C. canephora*, MAS provides a pathway to develop resilient, high-performing coffee varieties that meet the rising global demand for sustainable, high-quality coffee.

Complementing these marker-based strategies, CRISPR/Cas genome editing extends the breeding toolkit further by enabling precise, targeted modification of the *C. canephora* genome itself. Proof-of-concept studies have already demonstrated efficient CRISPR/Cas9-mediated mutagenesis in this species, achieving mutation rates as high as 77% through multiplexed vector design, with priority targets such as the N-methyltransferase genes governing caffeine biosynthesis, together with genes controlling plant architecture, flowering time, and stress response, pointing toward naturally decaffeinated, compact, and climate-resilient Robusta lines. Realising this potential in Nigeria will depend on strengthening tissue-culture and Agrobacterium-transformation capacity alongside engagement with evolving national biosafety frameworks, positioning genome editing as a complementary, rather than a substitute, tool within the national breeding programme.

Despite these advancements, challenges such as aging plantations, climate change, and limited genomic resources for local germplasm persist, alongside the tissue-culture and regulatory capacity that genome editing will additionally require, revealing the need for continued innovation and strategic interventions to fully realize the potential of molecular breeding.

FUTURE RESEARCH DIRECTIONS

Looking ahead, the future of *Coffea canephora* cultivation in Nigeria hinges on a concerted effort to integrate advanced genomic tools, such as CRISPR/Cas9 and SNP-based markers, to develop climate-resilient varieties capable of withstanding drought, pests, and diseases. Expanding germplasm collections to include underutilized wild Nigerian populations will broaden the genetic base, unlocking novel traits for quality and adaptability. Coupling MAS with precision agriculture technologies, including AI-driven yield prediction and remote sensing, will optimize breeding and cultivation processes, enhancing water use efficiency and pest management in alignment with climate-smart agriculture principles. Strengthening interdisciplinary collaboration among geneticists, agronomists, policymakers, and farmers will ensure that molecular innovations translate into tangible benefits, supported by training programs and extension services. Policy interventions, including subsidies for breeding technologies, quality control systems, and cooperative models, will further drive market access and competitiveness.

Building the genomic and tissue-culture infrastructure needed to complement MAS with emerging genome-editing tools, as outlined under Genome Editing and CRISPR/Cas Technology, will be essential for keeping pace with global advances while remaining grounded in the realities of Nigerian smallholder production. Prioritising these efforts within a sustainability framework, one that safeguards agroforestry systems, wild germplasm reservoirs, and smallholder livelihoods, will determine whether molecular gains translate into a resilient and internationally competitive Nigerian coffee sub-sector.

Through these integrated efforts, Nigeria can revitalize its coffee sector, securing economic and environmental sustainability while establishing itself as a key player in the global coffee industry.

AUTHOR CONTRIBUTIONS

Conceptualization, B.O.P. and O.C.F.; methodology, B.O.P., O.C.F. and A.O.J.; investigation, B.O.P., O.C.F., A.O.J., E.T.E. and A.M.W.; literature search and data curation, O.C.F., A.O.J., E.T.E. and A.M.W.; writing—original draft preparation, B.O.P., O.C.F. and A.O.J.; writing—review and editing, B.O.P., O.C.F., A.O.J., E.T.E. and A.M.W.; visualization, E.T.E. and A.M.W.; supervision, B.O.P.; project administration, B.O.P. All authors have read and agreed to the pub-

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