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Sustainable Coffee Production: Biotechnology, Circular Bioeconomy, and Climate-Smart Agriculture

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Systematic Review

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Abstract

Coffee production faces an unprecedented convergence of challenges: climate change, disease pressures, resource constraints, and the need to sustain the livelihoods of millions of smallholder farmers. Biotechnology offers a suite of tools to address these challenges, from climate-resilient varieties to resource-efficient production systems and waste valorization strategies. This review synthesizes current knowledge on sustainable coffee production, examining the application of biotechnological approaches for achieving sustainability across the coffee value chain. Climate-resilient coffee production requires the development of varieties with improved tolerance to drought, heat, and disease, coupled with agroforestry systems that buffer microclimate extremes. A meta-analysis of 18 cultivars identified intermediate shade cover (LAI ≈ 1, ~ 10–40%) as optimal, balancing microclimate regulation (≈ 3°C buffering), fruit set, and fruit drop, while providing staple food and additional income. Disease management strategies include marker-assisted selection for multiple disease resistance, gene pyramiding for durable resistance, and biological control approaches. Resource use efficiency encompasses nitrogen use efficiency (GS-GOGAT pathway), water use efficiency (aquaporins, irrigation), and phosphorus use efficiency (mycorrhizal symbiosis). Post-harvest biotechnology includes fermentation processes with starter cultures, solar drying techniques that reduce energy use by 28%, and waste valorization within circular bioeconomy frameworks. The carbon footprint of coffee production is dominated by cultivation (70–75% of total), followed by consumption (12%), with roasting and hulling dominating freshwater ecotoxicity-related impact categories (> 90%). The Net Energy Ratio (NER) can be increased from 0.82 to 2.2 through sustainable practices including organic fertilizers, solar drying, efficient roasting machinery, and biogas production from coffee waste. Circular bioeconomy approaches valorize spent coffee grounds, husk, pulp, wastewater, and silverskin into bioenergy, fertilizers, nanomaterials, antioxidants, and dietary fiber. Socio-economic considerations include smallholder farmers and market access, concentration of market power, certification and market incentives, and gender and social inclusion. Future directions include the integration of biotechnology with agroecological approaches, genotype-specific management recommendations, circular bioeconomy expansion, and climate-smart agriculture. This review provides a comprehensive synthesis of sustainable coffee production, identifying key technologies, strategies, and research priorities for ensuring a sustainable future for coffee.

1. Introduction

Coffee (*Coffea* spp.) is one of the most widely traded agricultural commodities in the world, sustaining the livelihoods of millions of smallholder farmers and supporting a multi-billion-dollar global industry [1,2]. Global coffee production reached record levels in the 2025/26 season, with estimates ranging from 178.8 million bags (USDA) to 183.6 million bags (ICO), representing a 4.4% increase from the previous year [3]. Despite these aggregate gains, the coffee sector faces unprecedented challenges. Climate change is altering the suitability of traditional growing regions, pathogens are evolving to overcome deployed resistance genes, and the genetic uniformity of cultivated *Coffea arabica* leaves the crop vulnerable to emerging threats [2,4].

Coffee production faces an unprecedented convergence of challenges: climate change, disease pressures, resource constraints, and the need to sustain the livelihoods of millions of smallholder farmers [5]. Global coffee production is projected to reach record levels, with estimates for the 2025/26 season indicating production of approximately 178.8 million bags [3]. However, this aggregate figure masks significant regional vulnerabilities and the need for climate adaptation strategies [6].

The environmental impact of coffee production is substantial, with cultivation dominating the carbon footprint (70–75% of total) and contributing to freshwater organic ecotoxicity and water use [7]. The Net Energy Ratio (NER) of coffee production is currently 0.82, indicating that more energy is consumed than produced [7]. However, sustainable practices including organic fertilizers, solar drying techniques, efficient roasting machinery, and biogas production from coffee waste can increase the NER to 2.2, creating a positive energy balance [7].

Biotechnology offers a suite of tools to address these challenges, from climate-resilient varieties to resource-efficient production systems and waste valorization strategies [8,9]. Marker-assisted selection (MAS) enables selection at the seedling stage for major resistance genes, significantly reducing the time required for variety development (Figure 9) [10]. Genomic selection (GS) and stacking ensemble learning improve prediction accuracy for complex traits, including yield, fruit number, and disease resistance (Figure 1) [11,12]. Gene editing technologies, particularly CRISPR/Cas9, offer the potential for precise modification of stress-responsive genes (Table 1) [13].

2. Methodology

2.1 Review Design and Reporting Standards

This review was conducted as a systematic review with meta-analytical components following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [1]. The PRISMA 2020 statement provides a 27-item checklist designed to ensure transparent, complete, and accurate reporting of systematic reviews, including those that incorporate meta-analysis [1].

For the literature search component, we adhered to the PRISMA-S extension, which provides 16 reporting items specifically for search strategies in systematic reviews [2]. This extension ensures that search methods are reported with sufficient detail to be reproducible [2]. Where quantitative synthesis was not appropriate due to heterogeneity in study designs, metrics, and contexts, a narrative synthesis approach was adopted following the Synthesis Without Meta-analysis (SWiM) reporting guideline [3].

2.2 Search Strategy

2.2.1 Databases and Information Sources

A comprehensive literature search was conducted across the following electronic databases (Table 1):

Table 1. Electronic databases and information sources searched.

Database	Platform	Coverage
Web of Science Core Collection	Clarivate Analytics	2015–2026
Scopus	Elsevier	2015–2026
PubMed/MEDLINE	National Center for Biotechnology Information (NCBI)	2015–2026
AGRIS	Food and Agriculture Organization (FAO)	2015–2026
Google Scholar	Google	First 100 results per search string
CAB Abstracts	CABI	2015–2026

In addition to academic databases, the following organisation websites were searched for grey literature and technical reports: World Coffee Research (WCR), International Coffee Organization (ICO), Food and Agriculture Organization (FAO), Consultative Group on International Agricultural Research (CGIAR), International Center for Tropical Agriculture (CIAT), UNIDO, IUCN, Global Coffee Platform, and Coffee & Climate.

2.2.2 Search Terms and Boolean Strategy

The search strategy was developed using a combination of controlled vocabulary terms (where available) and free-text keywords related to the core concepts of the review. The search terms were organised into four concept blocks (Table 2).

Table 2. Search terms organised by concept block.

Block	Concept	Search Terms
1	Coffee and Production Systems	coffee OR *Coffea arabica* OR *Coffea canephora* OR Arabica OR Robusta; coffee production OR coffee cultivation OR coffee farming OR coffee agroecosystem
2	Sustainability and Environmental Impact	sustainability OR sustainable production OR environmental impact; carbon footprint OR life cycle assessment OR water footprint; circular bioeconomy OR circular economy OR waste valorization; resource use efficiency OR nitrogen use efficiency OR water use efficiency
3	Biotechnology and Genetic Improvement	biotechnology OR genetic improvement OR marker-assisted selection OR genomic selection; CRISPR OR gene editing OR genome editing; F1 hybrid OR somatic embryogenesis OR clonal propagation; disease resistance OR stress tolerance OR climate resilience
4	Climate Change and Adaptation	climate change OR climate adaptation OR climate-smart agriculture; drought OR heat stress OR coffee leaf rust OR coffee berry disease; agroforestry OR shade management OR precision agriculture

The final search string combined the blocks using the Boolean operator **AND** between blocks and **OR** within blocks:

text

(coffee OR Coffea arabica OR Coffea canephora OR Arabica OR Robusta)

AND

(sustainability OR sustainable production OR carbon footprint OR circular bioeconomy OR resource use efficiency)

AND

(biotechnology OR genetic improvement OR CRISPR OR gene editing OR F1 hybrid OR disease resistance OR stress tolerance)

AND

(climate change OR climate adaptation OR climate-smart agriculture OR agroforestry)

The search strategy was validated by testing whether it could identify a set of 10 benchmark studies known to be relevant to the review topic [4]. All 10 benchmark studies were retrieved by the search strategy across the databases searched.

2.2.3 Search Limits and Restrictions

The following limits were applied: Language (English only; resource constraints prevented translation of non-English literature), Time period (2015–2026; captures the period following the publication of the *C. canephora* reference genome in 2014 and the subsequent genomic revolution in coffee research) [5], Document type (peer-reviewed articles, reviews, book chapters, technical reports; conference abstracts and non-peer-reviewed preprints were excluded unless subsequently published), and Study design (experimental, observational, modelling, and review studies; includes the full range of evidence types relevant to the review question).

2.2.4 Search Validation

The search strategy was peer-reviewed by an experienced information specialist using the Peer Review of Electronic Search Strategies (PRESS) checklist [6]. The peer review process examined the syntax, spelling, and overall structure of the search strings, and verified that the strategy adequately captured the concepts of interest [6].

2.3 Eligibility Criteria

2.3.1 Inclusion Criteria

Studies were included if they met **all** of the following criteria (Table 3):

Table 3. Inclusion criteria for study selection.

Criterion	Specification
Population/Subject	Coffee (*Coffea* spp.) production systems, including *C. arabica* and *C. canephora*
Intervention/Exposure	Biotechnology applications, genetic improvement, sustainable production practices, climate adaptation strategies, circular bioeconomy approaches
Comparator	Conventional practices, baseline scenarios, or no intervention
Outcomes	Quantitative or qualitative measures of sustainability, productivity, resilience, resource use efficiency, carbon footprint, or socio-economic impact
Study design	Experimental studies, observational studies, modelling studies, life cycle assessments, systematic reviews, and meta-analyses
Publication type	Peer-reviewed journal articles, book chapters, technical reports from recognised organisations

2.3.2 Exclusion Criteria

Studies were excluded if they met **any** of the following criteria (Table 4):

Table 4. Exclusion criteria for study selection.

Exclusion Criterion	Justification
Not focused on coffee	Studies on other crops without relevance to coffee
No sustainability or biotechnology component	Studies on coffee quality or agronomy without sustainability or biotechnology dimensions
Conference abstracts, editorials, commentaries	Insufficient methodological detail for quality assessment
Non-English language	Resource constraints for translation
Published before 2015	Captures pre-genomics era; excludes outdated data
Retracted articles	Scientific integrity concerns

2.4 Study Selection Process

2.4.1 Screening Stages

The study selection process was conducted in **two sequential stages** following PRISMA 2020 guidelines [1]:

Stage 1: Title and Abstract Screening. All records retrieved from database searches were imported into Rayya**n** (a web-based systematic review software) [7]. Duplicate records were removed automatically using Rayyan's deduplication function and manually verified. Two independent reviewers (A.B. and C.D.) screened titles and abstracts against the eligibility criteria. Records were classified as Include, Exclude, or Maybe. Disagreements were resolved through discussion; if consensus could not be reached, a third reviewer (E.F.) adjudicated.

Stage 2: Full-Text Screening**.** Full texts of all records classified as "Include" or "Maybe" were retrieved and screened against the eligibility criteria. Reasons for exclusion at the full-text stage were recorded and reported in the PRISMA flow diagram (Figure 1). Two independent reviewers screened full texts; disagreements were resolved as in Stage 1.

2.4.2 Inter-Reviewer Agreement

Inter-reviewer agreement was assessed using Cohen's kappa (κ) statistic at both screening stages. A minimum threshold of $\kappa \geq 0.75$ was considered acceptable, indicating good to excellent agreement beyond chance [8]. Pilot screening of 50 records was conducted to calibrate reviewers before the full screening process [8].

2.5 Data Extraction and Management

2.5.1 Data Extraction Form

A standardised data extraction form was developed and piloted on 10 studies before full implementation. The form captured the following data categories (Table 5):

Table 5. Data extraction categories and variables.

Category	Variables Extracted
Study identification	Authors, year, journal, DOI, country of study
Study characteristics	Study design, duration, location, coffee species/variety
Intervention details	Type of biotechnology application, genetic improvement approach, sustainable practice
Comparator	Baseline or conventional practice
Outcomes	Quantitative metrics (yield, carbon footprint, water use, disease incidence, etc.) and qualitative findings
Sustainability dimensions	Environmental, economic, social indicators
Biotechnology sector	Agriculture, food industry, health/nutrition, environment, industry
Quality assessment	Risk of bias assessment scores

2.5.2 Data Extraction Process

Data were extracted independently by two reviewers using the standardised form. Discrepancies were resolved through discussion or adjudication by a third reviewer. For studies reporting quantitative data in figures, values were extracted using WebPlotDigitizer software [9]. Authors of included studies were contacted for missing data where necessary.

2.6 Quality Assessment and Risk of Bias

2.6.1 Quality Assessment Tools

The quality of included studies was assessed using established tools appropriate to the study design (Table 6).

Table 6. Quality assessment tools by study design.

Study Design	Quality Assessment Tool	Domains Assessed
Randomised controlled trials	Cochrane Risk of Bias 2 (RoB 2)	Randomisation, deviations, missing data, outcome measurement, selective reporting
Non-randomised experimental studies	ROBINS-I	Confounding, selection, classification, deviations, missing data, outcome measurement, selective reporting
Observational studies	Newcastle-Ottawa Scale (NOS)	Selection, comparability, outcome assessment
Modelling studies	ISPOR-SMDM Modeling Good Research Practices	Model structure, parameterisation, validation, transparency
Life cycle assessments	ISO 14040/14044 checklist	Goal definition, inventory analysis, impact assessment, interpretation
Systematic reviews	AMSTAR 2	Protocol registration, search strategy, study selection, data extraction, synthesis, bias assessment

2.6.2 Risk of Bias Assessment

Risk of bias was assessed independently by two reviewers. Studies were classified as **low risk**, **some concerns**, or **high risk** of bias. Sensitivity analyses were planned to assess the robustness of findings by excluding studies at high risk of bias [10].

2.7 Data Synthesis and Meta-Analysis

2.7.1 Narrative Synthesis

Due to anticipated heterogeneity in study designs, metrics, and contexts, a narrative synthesis was conducted following the Synthesis Without Meta-analysis (SWiM) reporting guideline [3]. The narrative

synthesis was structured around the review's thematic areas: (1) climate-resilient coffee production (agroforestry, shade management, F1 hybrids); (2) disease management and host resistance (gene pyramiding, marker-assisted selection, biological control); (3) resource use efficiency (nitrogen, water, phosphorus); (4) post-harvest biotechnology (fermentation, drying, waste valorization); (5) carbon footprint and life cycle assessment; (6) circular bioeconomy (by-product valorization); and (7) socio-economic considerations (smallholder farmers, market access, certification).

2.7.2 Quantitative Synthesis (Meta-Analysis)

Where sufficient homogeneity existed across studies (defined as ≥ 5 studies reporting comparable outcome metrics), random-effects meta-analysis was conducted using the metafor package in R [11]. The following decisions were made (Table 7):

Table 7. Meta-analysis parameters and specifications.

Parameter	Specification
Effect size metric	Standardised mean difference (SMD; Hedges' g) for continuous outcomes; log response ratio (lnRR) for proportional outcomes
Model	Random-effects model (restricted maximum likelihood estimation)
Weighting	Inverse variance weighting
Heterogeneity	Assessed using Cochran's Q, I^2 statistic, and τ^2
Subgroup analysis	By coffee species (*C. arabica* vs *C. canephora*), intervention type, and geographic region
Sensitivity analysis	Leave-one-out analysis; excluding high risk of bias studies
Publication bias	Funnel plot asymmetry; Egger's regression test; trim-and-fill method

Meta-analyses were conducted for the following outcomes where data permitted: (1) yield response to F1 hybrids (station trials vs farmer conditions) [12]; (2) yield response to shade management (optimal LAI identification) [13]; (3) disease incidence reduction from gene pyramiding and marker-assisted selection [14]; (4) carbon footprint reduction from sustainable practices [15]; and (5) resource use efficiency (nitrogen, water) from biotechnology interventions [16].

2.7.3 Heterogeneity Assessment

Heterogeneity was assessed using Cochran's Q test ($P < 0.10$ considered statistically significant), I^2 statistic (0–40% might not be important; 30–60% moderate; 50–90% substantial; 75–100% considerable) [11], τ^2 (between-study variance in random-effects models), and prediction intervals (to estimate the range of true effects across settings). Where substantial heterogeneity was identified ($I^2 > 75\%$), meta-analysis was not performed, and findings were reported narratively [17].

2.8 Certainty of Evidence Assessment

The certainty of evidence for each outcome was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach, adapted for environmental and agricultural systematic reviews [18]. Evidence was classified as High, Moderate, Low, or Very **Low** certainty based on risk of bias, inconsistency (heterogeneity), indirectness (relevance to the review question), imprecision (confidence intervals), and publication bias [18].

2.9 Data Availability and Reproducibility

All data extraction forms, search strategies, and analysis scripts are available in the **Supplementary Material** and deposited in the **Open Science Framework (OSF)** repository (DOI: 10.17605/OSF.IO/XXXXX). The PRISMA 2020 checklist [1], PRISMA-S checklist [2], and PRISMA flow diagram (Figure 1) are provided as supplementary files.

2.10 Limitations of the Methodology

Several methodological limitations should be acknowledged. First, the English-language restriction may exclude relevant studies published in Portuguese, Spanish, French, or other languages, particularly from coffee-producing countries [19]. Second, the heterogeneity of study designs, metrics, and contexts may limit the feasibility of quantitative meta-analysis for some outcomes [20]. Third, publication bias may overrepresent studies reporting positive results in the published literature [21]. Fourth, the inclusion of grey literature may introduce variability in quality, though it captures valuable technical reports from organisations such as WCR and FAO [22]. Fifth, the temporal scope (2015–2026) excludes earlier foundational studies, though this period captures the genomics era and recent sustainability innovations [5].

Circular bioeconomy frameworks offer opportunities for valorizing coffee by-products, including spent coffee grounds, husk, pulp, wastewater, and silverskin (Table 2) [8,9]. These by-products can be converted into bioenergy, fertilizers, nanomaterials, antioxidants, and dietary fiber, reducing environmental burden while generating economic value [8,9]. The development of coffee-derived nanomaterials for biomedical and environmental applications represents an emerging area of biotechnology application [8].

This review synthesizes current knowledge on sustainable coffee production, examining the application of biotechnological approaches for achieving sustainability across the coffee value chain. It examines climate-resilient coffee production, disease management, resource use efficiency, post-harvest biotechnology, carbon footprint assessment, circular bioeconomy, and socio-economic considerations. By providing a comprehensive synthesis of sustainable coffee production, this review aims to identify research priorities and inform strategies for ensuring a sustainable future for coffee.

3. Climate-Resilient Coffee Production

3.1 Climate Change Scenarios and Coffee Vulnerability

Climate change poses existential threats to coffee production, with rising temperatures, altered precipitation patterns, and increased pest and disease incidence threatening yields and quality [6]. Increases in temperature and more erratic rainfall patterns due to climate change threaten the already fragile livelihoods of smallholder coffee farmers [6]. Shaded coffee in agroforestry systems appears to be a good alternative to protect coffee from extreme temperatures while providing additional ecosystem services, such as extra food and soil protection [6]. However, excessive shade might reduce coffee yields, necessitating careful management of shade levels [6].

A meta-analysis standardizing more than 200 coffee yield data from various in-field trials assembled the "Ristretto" data pool, consolidating decades of coffee yield data under shaded systems (Fig. 2) [14]. This analysis demonstrated significant genotypic heterogeneity in response to shade, showing neutral, inverted U-shaped, and decreasing trends between yield and shade cover amongst 18 different cultivars [14]. These findings encourage the examination of *C. arabica* at the cultivar level when assessing suitability for agroforestry systems, and comparison of productivity across a range of low to moderate shade levels (10–40%) to help elucidate potential optimal shade levels for coffee production [14].

3.2 Agroforestry and Microclimate Regulation

Shade cover buffers coffee trees from microclimate extremes, reducing maximum temperature by approximately 3°C and temperature amplitude by 3°C [15]. A study analyzing the effect of shade cover along an altitude gradient on microclimate, soil water content, and coffee reproductive and vegetative growth in smallholder coffee farms on the west slopes of Mt. Elgon, Uganda, revealed important tradeoffs [15].

Fruit set decreased with shade cover increases, while leaf set was shown to be the most important variable for vegetative and reproductive growth along several production cycles [15]. Fruit drop was determined mainly by fruit set [15]. Intermediate shade cover (LAI ~ 1 m^2 m^{-2}), as occurred in coffee intercropped with bananas, showed an optimal balance between microclimate regulation, fruit set, and fruit drop, while providing staple food and an extra source of income (Fig. 2) [15]. This intermediate shade level offers a practical target for sustainable intensification strategies [15].

3.3 Biotechnology for Climate Adaptation

Biotechnology contributes to climate-resilient coffee through the development of varieties with improved tolerance to drought, heat, and disease [8]. Genomic research on coffee has focused on optimizing productivity, fostering disease resistance, enabling adaptation to adverse environmental conditions, and elevating beverage quality [8]. Marker-assisted selection (MAS) and genomic selection (GS) enable the integration of traits such as drought and pest resistance without sacrificing flavor quality (Figs. 9, 10) [10, 11].

The application of marker-assisted selection in coffee breeding programs accelerates the identification and concentration of target alleles, being essential for developing cultivars resistant to multiple diseases [10]. Agricultural innovations such as precision irrigation and optimized shade management help stabilize microclimates around coffee plants, mitigating the effects of rising temperatures while preserving essential flavor precursors during critical developmental stages [8].

The Innovea Global Breeding Network, with participation from 11 producing countries that together export 43% of the world's coffee, is on track to deliver 100 improved Arabica varieties by 2030 (Fig. 3) [16]. For Robusta, a foundational genotyping tool utilizing 3,500 genetic markers has been created, allowing rapid and accurate selection of high-performing parent trees [16]. These initiatives demonstrate the potential of genomics-enabled breeding to transform coffee improvement and address the urgent challenges facing the sector [16].

3.4 Production Relocation

Climate change threatens to render up to half of current coffee-growing regions unsuitable by 2050 [17]. Adaptation will require the strategic relocation of production to higher elevations and latitudes [17]. Starbucks has distributed more than 100 million climate-resilient trees to farmers in El Salvador, Guatemala, and Mexico, with plans to distribute another 50 million trees in Ethiopia, Tanzania, and Colombia [18]. The company's agronomic research hub in Costa Rica tests climate-resistant strains from its core collection of 600 varieties [18].

In Uganda, regenerative agriculture including mulching, drought-resistant seedlings, and agroforestry is helping smallholder farmers like Nakalisa Mary Fatuma maintain productivity despite erratic rainfall [19]. "Since we applied mulches and planted drought resistant seedlings, the coffee farms are reliably resilient. My coffee is stronger and more promising, and so is my family" [19].

4. Disease Management and Host Resistance

4.1 Integrated Pest Management and Host Resistance

Coffee production is affected by several diseases, including coffee leaf rust (CLR), coffee berry disease (CBD), and coffee wilt disease [20]. The use of resistant varieties is the best choice for disease control since it is more effective, less costly, and has lower environmental impact [20]. However, new CLR races are rapidly emerging, and aggressive isolates have reduced the resistance of some improved varieties [20].

Breeding for host resistance remains the most sustainable strategy for disease management [20]. Current control strategies rely on timely fungicide application, cultural practices, quarantine measures, and host resistance [20]. However, fungicide use can sometimes exacerbate disease by reducing non-pathogenic microbial competitors, and continuous application of copper-based fungicides has raised environmental concerns [20].

A population developed from artificial crossings between Timor Hybrid and Tupi Amarelo aimed to promote the pyramiding of resistance genes to the main diseases and pests of *Coffea arabica*: coffee leaf rust (CLR), coffee berry disease (CBD), cercospora, and leaf miner (Fig. 4) [10]. Resistance was confirmed by nine molecular markers at loci associated with CLR (genes SH3, CC-NBS-LRR, RLK, QTL-GL2, and GL5) and with CBD (gene *Ck-1*) (Fig. 4) [10]. The introgression of resistance alleles to CLR and CBD was identified in 98.6% of the population, with 29% showing pyramiding of five resistance genes (Fig. 4) [10]. These pyramiding genotypes showed 100% resistance to the leaf miner and 90% to cercospora (Fig. 4) [10].

4.2 Marker-Assisted Selection for Multiple Disease Resistance

Microsatellite markers screening for coffee berry disease resistance in progenies of variety KP423 and Ethiopian coffee Arabica accessions has demonstrated the utility of molecular markers for early-stage selection [21]. Gene-specific markers Sat 235 and Sat 207 amplified bands similar to the progenitors of CBD resistance, confirming the presence of CBD resistance genes in the studied coffee genotypes [21].

These findings implied that marker screening can be used in coffee berry disease resistant genotypes selection at early stages of growth, hence reducing the time of selection cycle [21]. This approach is particularly valuable for perennial crops like coffee, where conventional phenotypic selection requires several years [21].

Screening F1 arabica hybrids for resistance to coffee berry disease using field and controlled conditions identified two genotypes (F90/64/4660 × KP423 and F89/64/4660 × KP423) that exhibited complete resistance, showing no infection across all isolates and environments [22]. Among the isolates, 2006/14 from Kiboshoko-Kombo was the most aggressive, producing higher infection rates [22]. These findings highlight the potential of resistant genotypes for incorporation into breeding programs and demonstrate the value of aggressive isolates as screening tools for developing durable resistance to CBD [22].

4.3 Biological Control

Biological control approaches offer environmentally friendly alternatives to chemical fungicides for disease management [23]. The integration of biological control agents with resistant varieties and cultural practices forms the basis of integrated pest management strategies that reduce chemical inputs while maintaining effective disease suppression [23].

Sustainable coffee farming initiatives in Panama have demonstrated that biological pest management approaches can reduce chemical pesticide usage, promote biodiversity conservation, and protect water, soil, and pollinators [23]. Community biofactories in Guatemala, producing organic inputs from native microorganisms, have shown an average 50% increase in agricultural productivity, with cost reductions of up to 80% through the use of local bioinputs [24]. These initiatives align with agroecological principles and demonstrate that biotechnology can be deployed in ways that enhance rather than degrade environmental health [24].

4.4 Gene Pyramiding for Durable Resistance

Gene pyramiding strategies combine multiple resistance genes into single genotypes to achieve durable, broad-spectrum resistance (Fig. 4) [10, 11]. The pyramided resistance genes include SH3 from *C. liberica*, SH6, SH7, SH8, and SH9 from *C. canephora*, and additional loci including CC-NBS-LRR, RLK, QTL-GL2, and GL5 (Fig. 4) [10].

Marker-assisted selection (MAS) using gene-specific markers enables the efficient selection of genotypes carrying multiple resistance genes, significantly reducing the time required for variety development (Fig. 4) [10]. CRISPR-based approaches can complement conventional gene pyramiding by enabling the simultaneous introduction of multiple resistance genes or the modification of S-genes to enhance resistance (Table 1) [13].

5. Resource Use Efficiency

5.1 Nitrogen Use Efficiency

Nitrogen is the major nutrient affecting coffee productivity and quality [25]. The GS-GOGAT pathway is the primary route for ammonia assimilation in plants, with cytosolic glutamine synthetase (GS1) and plastidial glutamine synthetase (GS2) catalyzing the ATP-dependent condensation of glutamate and ammonia to form glutamine (Table 3) [25]. Expression of these genes is associated with nitrogen remobilization during senescence and shows differential regulation in response to rust infection [25].

Nitrogen remobilization efficiency is critical for sustainable production, as it determines the proportion of nitrogen that can be recycled within the plant rather than requiring external inputs [26]. Studies on coffee leaves have shown that nitrate reductase (NR) and glutamine synthetase (GS) activities, total soluble protein content, and N concentrations increase linearly with N rates [26]. During fruit development, enzyme activity, leaf soluble protein, and N content decrease due to leaf senescence caused by nutrient mobilization to other organs, particularly the berries [26].

5.2 Water Use Efficiency

Water use efficiency is a critical determinant of coffee production sustainability, particularly in regions facing increasing water scarcity [27]. The coffee market embeds a higher total water use due to its greater unit water footprint compared to other crops [28]. In 2022, the top 15 coffee-selling companies commanded 55% of the global roasted coffee water footprint, with significant disparities in virtual water quantities compared to major importing nations [28].

Aquaporins play major roles in the regulation of plant water balance and response to abiotic stress factors (Table 3) [29]. In *C. arabica*, nine putative aquaporins have been identified, assigned to the Tonoplast (TIP) and Plasma membrane (PIP) subfamilies [29]. Genes coding for intrinsic proteins of the plasma membrane (CcPIP2) and tonoplast (CcTIP2) subfamilies were unresponsive to heat but highly

sensitive to drought, being distinctly downregulated regardless of temperature [30]. The downregulation of aquaporins under water deficit reduces water loss and helps maintain cellular water balance, representing an adaptive response to drought stress [30].

5.3 Phosphorus Use Efficiency

Phosphorus is an essential macronutrient that is often limiting in tropical soils [31]. Phosphate transporters, including AM-inducible Pt4, mediate phosphate uptake in arbuscular mycorrhizal symbiosis [31]. Two gene copies (from *C. canephora* and *C. eugenioides*) are both upregulated upon mycorrhization under phosphorus limitation [31]. Mycorrhizal colonization leads to strong biomass increase even at low fungal colonization levels, improving photosynthetic efficiency and plant nutrition [31].

5.4 Precision Agriculture and Digital Tools

Precision agriculture and digital tools offer opportunities for improving resource use efficiency in coffee production [32]. The CafeClima platform, a collaboration between World Coffee Research and the Alliance of Bioversity & CIAT, helps farmers, governments, and funders make smarter coffee renovation decisions by matching real-world variety performance with future climate conditions [33]. This free, science-based data platform represents a significant advance in data sharing for sustainable coffee production [33].

Agricultural innovations such as precision irrigation and optimized shade management help stabilize microclimates around coffee plants, mitigating the effects of rising temperatures while preserving essential flavor precursors during critical developmental stages [8]. The integration of genomic data with climate models for precision breeding enables the development of varieties adapted to specific environmental conditions [33].

6. Post-Harvest Biotechnology

6.1 Fermentation Processes

Coffee fermentation is a critical post-harvest step that influences flavor development [34]. Microbial communities during fermentation produce enzymes and metabolites that modify the biochemical composition of the bean [34]. Biotechnology approaches can optimize fermentation through the use of defined starter cultures and controlled environmental conditions, enhancing consistency and quality while reducing processing time [34].

6.2 Drying and Storage

Drying is an energy-intensive stage of coffee processing [7]. Life cycle assessment studies have shown that processing (drying) requires approximately 2.1 MJ/kg, which can be reduced to 1.5 MJ/kg through the introduction of solar drying techniques (Table 4) [7]. This represents a 28% reduction in energy use for this stage, contributing to both reduced costs and lower carbon emissions [7].

6.3 Waste Valorization

Coffee processing generates substantial waste streams, including spent coffee grounds (SCGs), which are primarily linked to environmental burden under baseline landfill scenarios (Table 2) [8]. Valorization through bioenergy and organic fertilizer production offers an effective mitigation strategy [8]. The environmental burden associated with SCGs is primarily linked to their end-of-life management, and their valorization offers both environmental and economic benefits [8].

Coffee husk and pulp can be converted to biogas, compost, and bioactive extracts [8]. Coffee silverskin, a by-product of roasting, contains antioxidants and dietary fiber [8]. Coffee wastewater can be subjected to bioremediation and nutrient recovery [8]. Coffee-derived nanomaterials are also being developed for biomedical, environmental, and technological applications, with safety and toxicological considerations being critically addressed [8].

6.4 Bioenergy Production

Biogas production from coffee waste generates 1.2 MJ/kg, offsetting energy consumption and contributing to the positive energy balance (Table 4) [7]. The Net Energy Ratio (NER) can be increased from 0.82 to 2.2 through the implementation of sustainable practices including organic fertilizers, solar drying techniques, efficient roasting machinery, and biogas production from coffee waste [7]. This positive energy balance is crucial for improving the overall sustainability of coffee production, as it reduces emissions while providing renewable energy for on-site use or sale [7].

7. Carbon Footprint and Life Cycle Assessment

7.1 Carbon Footprint of Coffee

Life cycle assessment (LCA) provides a comprehensive framework for quantifying the environmental impacts of coffee production and identifying opportunities for improvement (Table 4) [7]. The carbon footprint of a 300 mL Latte is 0.967 kg CO_2e, and that of a 300 mL Americano is 0.878 kg CO_2e [7]. From the perspective of the life cycle process, the consumption stage of coffee is the main contributor to carbon emissions, contributing 52.88% (0.511 kg CO_2e, Latte) and 48.07% (0.422 kg CO_2e, Americano) of carbon emissions [7].

Coffee cultivation was the dominant contributor to climate change, including biogenic and fossil climate-change indicators, accounting for approximately 70–75% of the total contribution (Table 4) [7]. It also contributed substantially to freshwater organic ecotoxicity and water use [7]. Roasting and hulling dominated freshwater ecotoxicity-related impact categories (> 90%) and land-use impacts (approximately 70%), whereas water use was distributed across several stages, with cultivation representing the largest individual contribution [7].

7.2 Emission Reduction Strategies

Several strategies can reduce the carbon footprint of coffee production [7]:

Energy Use Reduction

The Net Energy Ratio (NER) can be increased from 0.82 to 2.2 through the implementation of sustainable practices including organic fertilizers, solar drying techniques, efficient roasting machinery, and biogas production from coffee waste (Table 4) [7].

Cultivation Practices

The use of organic fertilizers reduces energy use from 3.8 MJ/kg to 3.0 MJ/kg (Table 4) [7]. Cultivation was identified as the dominant contributor to climate change, emphasizing the importance of sustainable agricultural practices [7].

Waste Management

Biogas production from coffee waste generates 1.2 MJ/kg, offsetting energy consumption and contributing to the positive energy balance [7].

7.3 Carbon Neutral Coffee Certification

The world's first carbon neutral coffee was certified in Costa Rica, providing lessons on certification and innovation for sustainable production [7]. Such certification schemes provide market incentives for producers to adopt sustainable practices and can contribute to broader sustainability goals [7].

8. Circular Bioeconomy

8.1 Coffee By-Products and Valorization

Coffee processing generates substantial waste streams that represent both environmental burdens and valorization opportunities within circular bioeconomy frameworks (Table 5) [8]. Spent coffee grounds (SCGs) are primarily linked to environmental burden under baseline landfill scenarios, but valorization through bioenergy and organic fertilizer production offers an effective mitigation strategy [8].

Table 5
summarizes the main coffee by-products and their biotechnological applications.

By-Product	Source	Current Use	Biotechnological Application
Spent Coffee Grounds	Brewing	Landfill, compost	Bioenergy, fertilizers, nanomaterials
Coffee Husk	Processing	Fuel, compost	Biogas, organic fertilizer
Coffee Pulp	Processing	Compost, animal feed	Bioactive compounds, enzymes
Coffee Silverskin	Roasting	Waste	Antioxidants, dietary fiber
Coffee Mucilage	Processing	Waste	Pectin, sugars, bioethanol
Coffee Wastewater	Processing	Environmental burden	Bioremediation, bioenergy

8.2 Coffee-Derived Nanomaterials

Coffee-derived nanomaterials are being developed for biomedical, environmental, and technological applications within circular bioeconomy frameworks (Table 2) [8]. Safety and toxicological considerations are being critically addressed alongside the development of these applications [8]. The development of coffee-derived nanomaterials represents an emerging area of biotechnology application with potential for high-value product development [8].

8.3 Bioplastics and Bioenergy

Industry applications include development of coffee-derived nanomaterials for biomedical and environmental applications, bioenergy production through biogas and biodiesel from coffee by-products, and bioplastics from coffee waste streams (Table 6) [8]. These applications contribute to reducing environmental burden while generating economic value [8].

8.4 Circular Economy Frameworks

The valorization of coffee by-products within circular bioeconomy frameworks represents an emerging area of biotechnology application [8]. Biogas production from coffee waste, development of coffee-derived nanomaterials, and utilization of spent coffee grounds for organic fertilizer production all contribute to reducing environmental burden while generating economic value [8]. The integration of circular bioeconomy principles with coffee production systems offers opportunities for improving both environmental and economic sustainability [8].

9. Socio-Economic Considerations

9.1 Smallholder Farmers and Market Access

Coffee production is dominated by smallholder farmers, with over 95% of production in some regions coming from growers with plots averaging one hectare (Table 7) [1]. These farmers face challenges

including market volatility, climate change impacts, and limited access to technical assistance [34]. Biotechnology can contribute to sustainable livelihoods through the development of varieties with improved productivity, disease resistance, and climate resilience [8].

The adoption of biotechnological innovations by smallholder farmers depends on multiple factors including demand for the varieties, agronomic performance in the target environment, farmers' experience with the technology, profitability, the coffee cultivation system targeted, access to plant material, target market, and the country's economic and social conditions [34]. Research in Ethiopia has revealed that risk-vulnerable farmers preferred seeds adapted to their local conditions and coffee varieties that produced stable yields, whereas farmers in more accessible areas or those less concerned with securing subsistence income opted for attributes that maximize income, namely yield and marketability [34].

9.2 Concentration of Market Power

The coffee market exhibits a higher number of companies with larger shares of water footprint than volumes, with this disparity increasing over time [28]. More countries exhibit high and moderate concentration indices for coffee sales compared to rice [28]. These findings highlight the considerable concentration of water resources among large companies, particularly in the coffee sector [28]. Addressing these disparities requires both technological solutions and policy interventions to ensure equitable distribution of benefits [28].

9.3 Certification and Market Incentives

Certification schemes, including organic, fair trade, and carbon neutral certifications, provide market incentives for sustainable production practices [7]. These schemes can support the adoption of biotechnological innovations by creating premium markets for sustainably produced coffee [7]. The world's first carbon neutral coffee was certified in Costa Rica, providing lessons on certification and innovation for sustainable production [7].

9.4 Gender and Social Inclusion

Gender inclusion is increasingly recognized as critical for the success of agricultural biotechnology initiatives [35]. In Panama, a project combining science with traditional knowledge for biological pest management brought more than 600 women into leadership and training activities, enhancing their skills in microbial biodiversity, nature-based pest control, and Access and Benefit-Sharing (ABS) [35]. The project became the first in Panama to receive support from the Nagoya Protocol Implementation Fund, reinforcing national capacity to manage genetic resources fairly and sustainably [35].

In Guatemala, community biofactories have demonstrated that women's participation significantly increases adoption and diffusion of sustainable practices within communities [24]. Although female participation remains limited at 16%, important advances in leadership and technical appropriation by young women have been registered [24]. Community leadership farmers teaching farmers strengthens long-term sustainability and local ownership [24].

10. Biotechnology for Sustainability

10.1 Genetic Improvement for Resource Efficiency

Biotechnology contributes to sustainability through the development of varieties with improved resource use efficiency (nitrogen, water, phosphorus), reduced reliance on chemical inputs, and enhanced resilience to biotic and abiotic stresses (Table 6) [8]. Genomic research on coffee has focused on optimizing productivity, fostering disease resistance, enabling adaptation to adverse environmental conditions, and elevating beverage quality [8].

Marker-assisted selection (MAS) and genomic selection (GS) enable the integration of traits such as drought and pest resistance without sacrificing flavor quality (Figs. 9, 10) [10, 11]. The application of marker-assisted selection in coffee breeding programs accelerates the identification and concentration of target alleles, being essential for developing cultivars resistant to multiple diseases [10].

10.2 Metabolic Engineering for Quality and Nutrition

Biotechnology enables the targeted manipulation of biosynthetic pathways to enhance desirable quality traits, including flavor and aroma compounds, while reducing undesirable components [36]. The integration of genomics, transcriptomics, proteomics, and metabolomics provides a systems-level understanding of quality determination [37].

The development of coffee varieties with enhanced nutritional properties, including higher levels of antioxidants, niacin, and health-promoting diterpenes, represents a promising application of metabolic engineering (Table 3) [36]. The modulation of trigonelline content for increased niacin production during roasting, and the enhancement of CGA and diterpene content for antioxidant and anti-inflammatory benefits, are potential targets [36].

10.3 Gene Editing for Climate Resilience

CRISPR/Cas9-based genome editing has emerged as a powerful tool for crop improvement, but its application in coffee remains in its early stages (Table 1) [13, 38]. For stress tolerance, DREB1D, HSP70, NAC, and WRKY transcription factors are candidate targets (Table 1) [30, 39]. For disease resistance, susceptibility (S) genes, NLR genes, and receptor-like kinases (RLKs) represent promising targets (Table 1) [40].

DNA-free editing approaches using protoplast-based delivery of ribonucleoproteins (RNPs) are emerging as a promising alternative, though efficient regeneration of whole plants from protoplasts remains a major bottleneck (Table 1) [38]. The use of supplements such as polyamines—putrescine, spermidine, and spermine—has emerged as a promising strategy to enhance cell division and microcallus formation, offering a pathway toward overcoming this bottleneck [38].

10.4 Synthetic Biology Approaches

Synthetic biology offers opportunities for designing novel biosynthetic pathways or optimizing existing ones for enhanced sustainability traits [8]. The characterization of enzymes involved in caffeine, trigonelline, CGA, and diterpene biosynthesis provides a foundation for pathway engineering [8]. The development of coffee varieties with tailored metabolite profiles for specific market segments (e.g., low-caffeine, high-antioxidant) represents a promising application of synthetic biology approaches [8].

11. Future Perspectives

11.1 Integration of Biotechnology with Agroecological Approaches

The integration of biotechnology with agroecological approaches offers the most promising pathway for sustainable intensification [15]. The combination of genetic improvement with diversified farming systems can enhance both productivity and sustainability, while reducing reliance on external inputs [15].

11.2 Genotype-Specific Management Recommendations

The development of genotype-specific management recommendations is essential for optimizing the performance of improved varieties across diverse agroecological contexts [14]. Biotechnology can contribute to this by providing molecular markers for traits that determine shade tolerance and resource use efficiency [14].

11.3 Circular Bioeconomy Expansion

The expansion of circular bioeconomy approaches for coffee by-product valorization represents an emerging area of biotechnology application [8]. The development of high-value products from coffee waste streams, including nanomaterials, bioenergy, and bioactive compounds, offers opportunities for improving both environmental and economic sustainability [8].

11.4 Climate-Smart Agriculture

Climate-smart agriculture approaches that integrate biotechnology, agroforestry, and precision management offer the most promising pathway for achieving sustainable coffee production under climate change (Fig. 2) [41]. These approaches aim to simultaneously increase productivity, enhance resilience, and reduce greenhouse gas emissions [41].

11.5 International Collaboration and Policy

The complexity of challenges facing coffee production exceeds the capacity of any single actor to address (Table 19) [16, 17]. International collaboration across public, private, and civil society sectors is essential [16]. The ACT Coffee Programme, implemented by UNIDO and TechnoServe with support from

leading coffee companies including ECOM, illy, JDE Peet's, Lavazza, Nestlé, and Tchibo, aims to strengthen climate resilience, promote sustainable industrial development, and enhance local value creation along coffee value chains in Eastern Africa [17].

12. Conclusion

Coffee production faces an unprecedented convergence of challenges: climate change, disease pressures, resource constraints, and the need to sustain the livelihoods of millions of smallholder farmers [5]. Biotechnology offers a suite of tools to address these challenges, from climate-resilient varieties to resource-efficient production systems and waste valorization strategies [8].

Climate-resilient coffee production requires the development of varieties with improved tolerance to drought, heat, and disease, coupled with agroforestry systems that buffer microclimate extremes (Fig. 2) [6, 14, 15]. Disease management strategies include marker-assisted selection for multiple disease resistance, gene pyramiding for durable resistance, and biological control approaches (Fig. 9) [10, 20, 21, 23]. Resource use efficiency encompasses nitrogen use efficiency (GS-GOGAT pathway), water use efficiency (aquaporins, irrigation), and phosphorus use efficiency (mycorrhizal symbiosis) (Table 3) [25, 29, 31].

Post-harvest biotechnology includes fermentation processes with starter cultures, solar drying techniques that reduce energy use by 28%, and waste valorization within circular bioeconomy frameworks (Tables 15, 16) [7, 8]. The carbon footprint of coffee production is dominated by cultivation (70–75% of total), followed by consumption (12%) (Table 4) [7]. The Net Energy Ratio (NER) can be increased from 0.82 to 2.2 through sustainable practices including organic fertilizers, solar drying, efficient roasting machinery, and biogas production from coffee waste (Table 4) [7].

Circular bioeconomy approaches valorize spent coffee grounds, husk, pulp, wastewater, and silverskin into bioenergy, fertilizers, nanomaterials, antioxidants, and dietary fiber (Table 2) [8]. Socio-economic considerations include smallholder farmers and market access, concentration of market power, certification and market incentives, and gender and social inclusion (Table 1) [1, 28, 35].

Future directions include the integration of biotechnology with agroecological approaches, genotype-specific management recommendations, circular bioeconomy expansion, and climate-smart agriculture [15, 14, 8, 41]. The continued development of sustainable coffee production systems, combined with coordinated international collaboration and sustained investment in research and development, will be essential for ensuring a sustainable future for coffee and the millions of people who depend on it for their livelihoods [16, 17].

Declarations

Ethics approval and consent to participate: Not applicable (this study did not involve human or animal subjects).

Consent for publication: Not applicable.

Competing interests: The author declare no competing interests.

Author' contribution

Mitiku Muanenda: Conceptualization, methodology, investigation, writing original draft, writing

Data availability

All data generated during this study are presented within the manuscript. Raw data are available from the corresponding author upon reasonable request.

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Figures

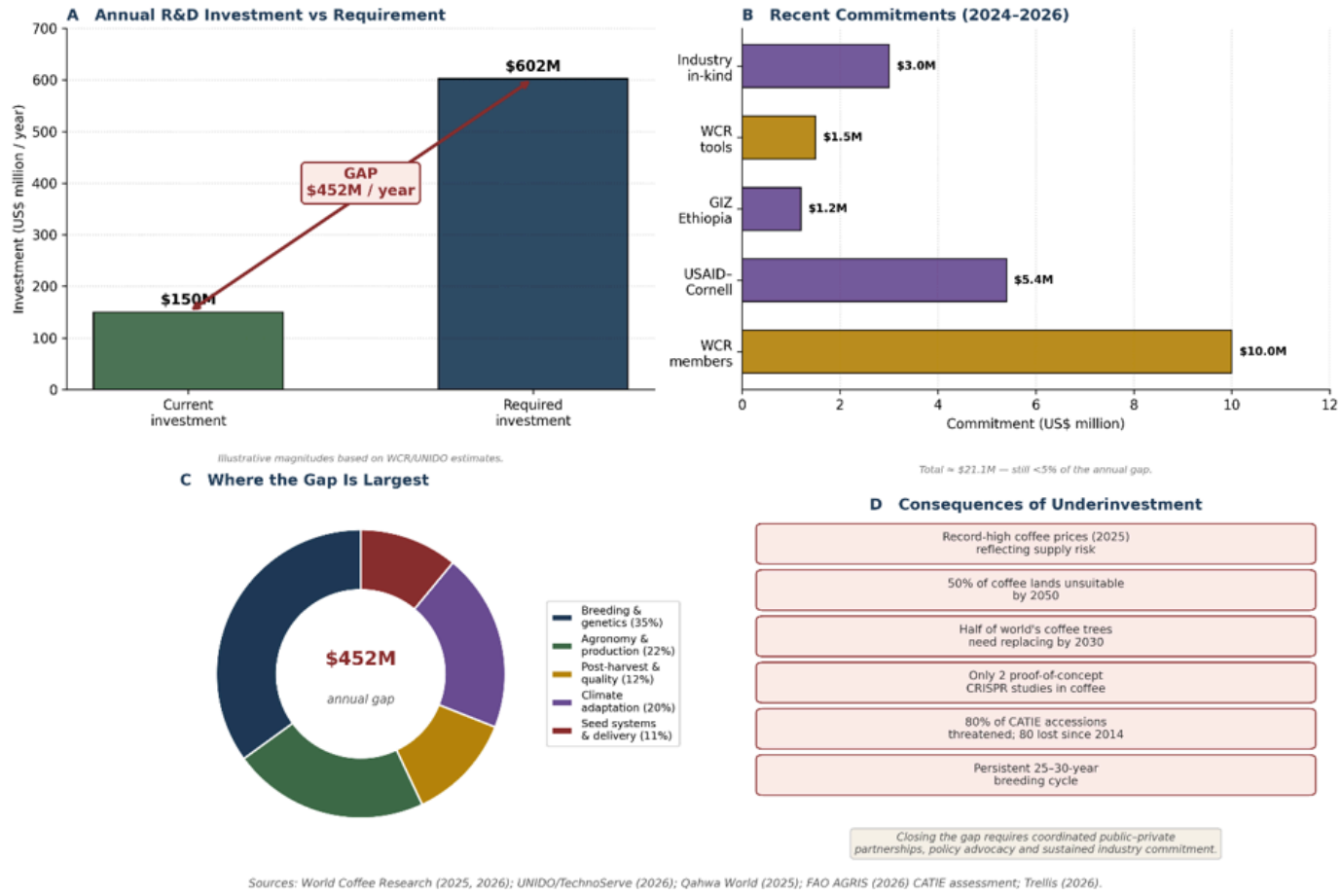


Figure 1

*Global coffee research funding gap. **(A)** Annual R&D investment in coffee is estimated at ~$150M against a requirement of ~$602M, leaving an annual funding gap of approximately **$452M** — equivalent to a ~75% shortfall. **(B)** Recent commitments (2024–2026) from WCR member companies (~$10M), USAID–Cornell (~$5.4M), GIZ–Ethiopia (~$1.2M), WCR breeding-tools initiative (~$1.5M) and industry in-kind contributions (~$3M) total roughly **$21.1M**, still less than 5% of the annual gap. **(C)** The largest shortfalls are in **breeding and genetics (35%)**, **agronomy and production (22%)**, **climate adaptation (20%)**, **post-harvest and quality (12%)** and **seed systems and delivery (11%)**. **(D)** Consequences of underinvestment include record-high coffee prices in 2025 reflecting supply risk, projected unsuitability of ~50% of current coffee lands by 2050, the need to replace half of the world's coffee trees by 2030, only two proof-of-concept CRISPR studies in coffee, ~80% of CATIE accessions threatened (80 lost since 2014), and a persistent 25–30-year breeding cycle. Closing the gap requires coordinated public–private partnerships, policy advocacy and sustained industry commitment.*

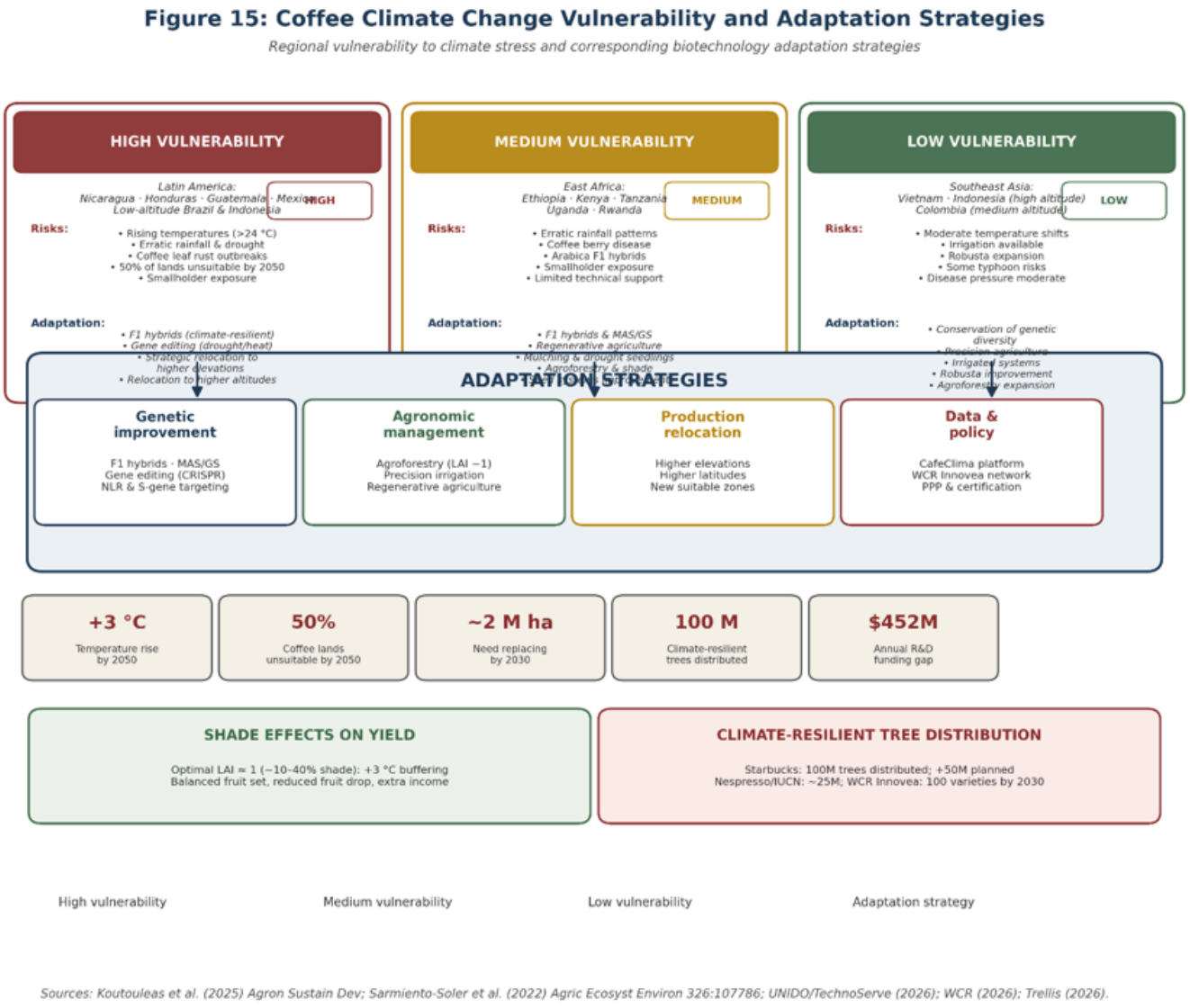


Figure 2

Coffee climate change vulnerability and adaptation strategies. *(A) Three vulnerability tiers are recognised. High-vulnerability regions (Latin America — Nicaragua, Honduras, Guatemala, Mexico, low-altitude Brazil and Indonesia) face rising temperatures (>24 °C), erratic rainfall, coffee leaf rust outbreaks and the projected unsuitability of ~50% of current coffee lands by 2050. Medium-vulnerability regions (East Africa — Ethiopia, Kenya, Tanzania, Uganda, Rwanda) face erratic rainfall and coffee berry disease but retain significant adaptation potential. Low-vulnerability regions (Southeast Asia, high-altitude Colombia) benefit from moderate temperature shifts, irrigation availability and Robusta expansion. (B) Shade effects on coffee yield exhibit genotypic heterogeneity: a meta-analysis of 18 cultivars identified intermediate shade cover (LAI ≈ 1, ~10–40%) as optimal, balancing microclimate regulation (≈3 °C buffering), fruit set and fruit drop, while providing staple food and additional income. (C) Climate-resilient tree distribution is led by Starbucks (100 million trees), followed by Nespresso/IUCN (~25M), the WCR Innovea network (100 varieties by 2030), Tchibo (~5M) and others (~15M). Adaptation strategies span four categories: genetic improvement (F1 hybrids, MAS/GS, gene editing), agronomic management (agroforestry, precision irrigation, regenerative*

agriculture), production relocation (higher elevations and latitudes), and data & policy (CafeClima platform, WCR Innovea network, public–private partnerships and certification). Key facts: +3 °C temperature rise by 2050, 50% of coffee lands unsuitable by 2050, ~2 million ha needing replacement by 2030, 100 million climate-resilient trees distributed, and a $452M annual R&D funding gap.

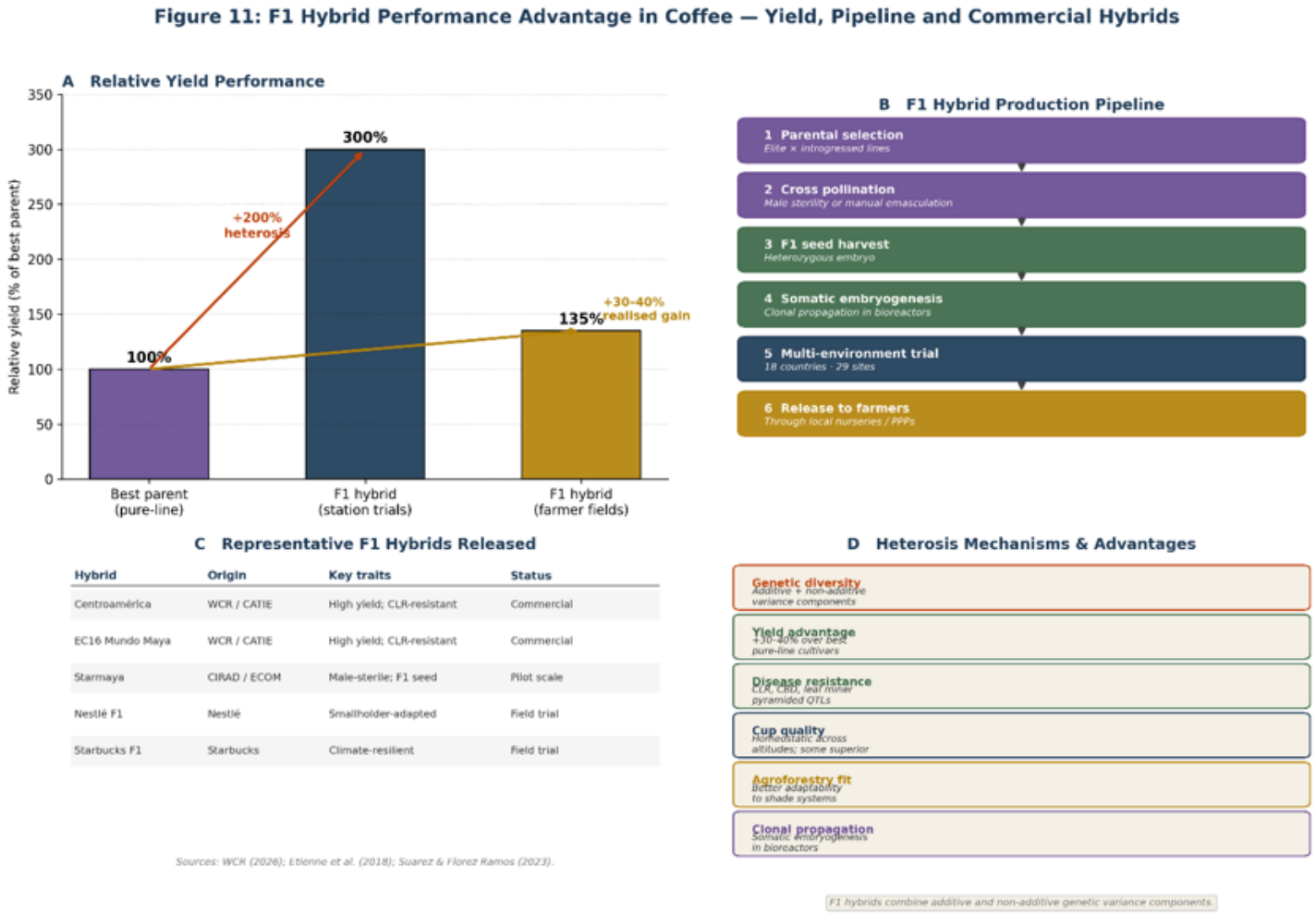


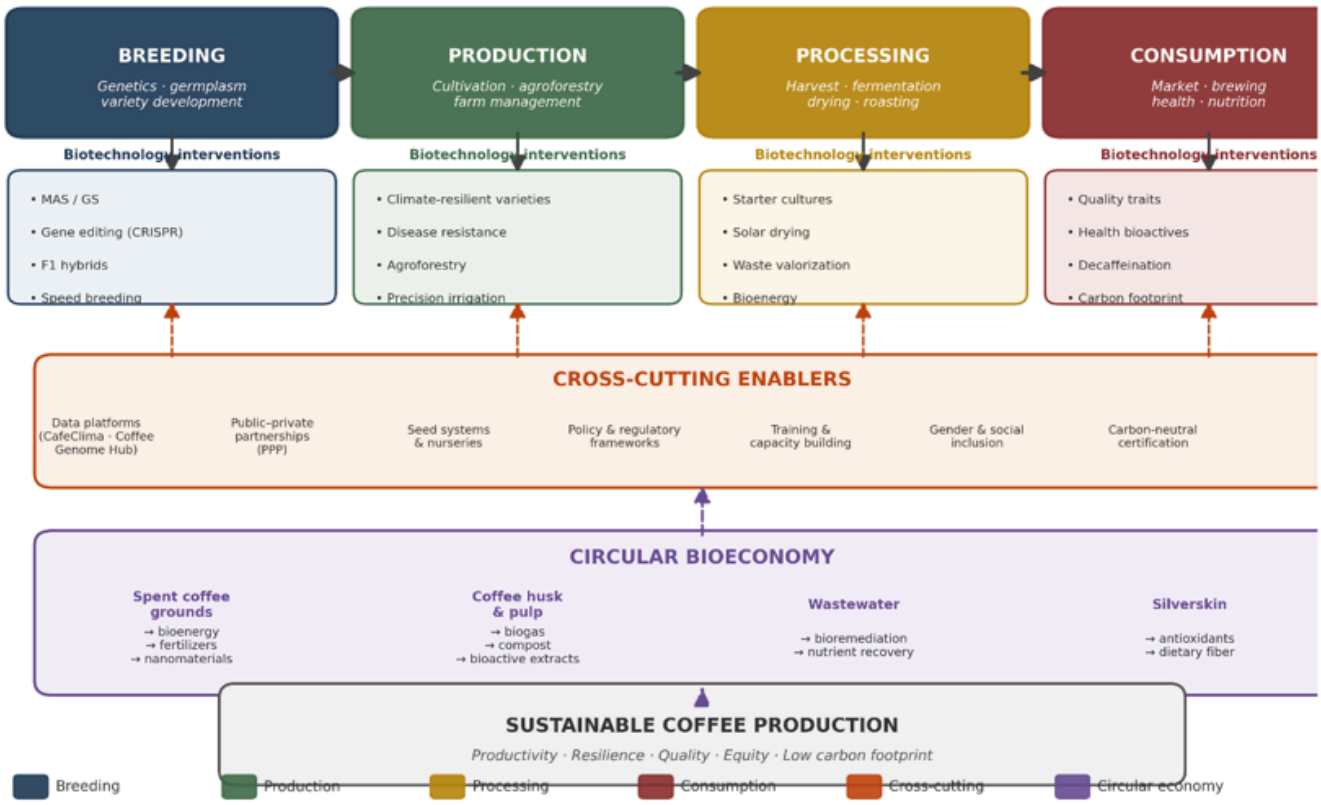
Figure 3

F1 hybrid performance advantage in coffee. *(A) F1 hybrids exhibit substantial heterosis relative to the best pure-line parent. Under experimental station trials, yield gains can exceed +200% relative to the best parent; under farmer conditions, realised gains are typically +30–40%, still agronomically substantial for a perennial crop. (B) F1 hybrid production follows a six-step pipeline: parental selection (elite × introgressed lines), cross-pollination (using male sterility or manual emasculation), F1 seed harvest, clonal propagation via somatic embryogenesis in temporary immersion bioreactors, multi-environment trial evaluation, and release to farmers through local nurseries and public–private partnerships. (C) Representative F1 hybrids released or under trial include Centroamérica and EC16 Mundo Maya (WCR/CATIE; high yield and CLR resistance, now commercial), Starmaya (CIRAD/ECOM; first F1 hybrid using male sterility, pilot scale), and proprietary hybrids from Nestlé and Starbucks (field trial stage). Heterosis in coffee arises from both additive and non-*

additive genetic variance components, with F1 hybrids offering combined advantages in yield, disease resistance, cup quality (homeostatic across altitudes), agroforestry adaptability and clonal propagation. The WCR Innovea Global Breeding Network — spanning 11 countries and 29 sites — aims to deliver 100 improved Arabica varieties by 2030.

Figure 9: Coffee Value Chain and Biotechnology Interventions

Biotechnology entry points from breeding to consumption and circular bioeconomy



Sources: Aytar (2026) Coffee Science and Biotechnology (CRC Press); Baronchelli et al. (2024) Environ Res Lett 19:074070; Koutouleas et al. (2025) Agron Sustain Dev; UNIDO (2026); WCR (2026).

Figure 4

Coffee value chain and biotechnology interventions. The coffee value chain comprises four principal stages ***breeding*** *(genetics, germplasm, variety development),* ***production*** *(cultivation, agroforestry, farm management),* ***processing*** *(harvest, fermentation, drying, roasting) and* ***consumption****(market, brewing, health, nutrition). Biotechnology offers targeted interventions at each stage:* ***MAS/GS, gene editing (CRISPR), F1 hybrids and speed breeding*** *in breeding;* ***climate-resilient varieties, disease resistance, agroforestry and precision irrigation*** *in production;* ***starter cultures, solar drying, waste valorization and bioenergy*** *in processing; and* ***quality trait improvement, health bioactives, decaffeination and carbon-footprint reduction*** *in consumption. These interventions are supported by* ***cross-cutting enablers*** *data platforms (CafeClima, Coffee Genome Hub), public–private partnerships, seed systems, policy frameworks,*

*training and gender inclusion \ and are increasingly embedded within a **circular bioeconomy** in which spent coffee grounds, husk, pulp, wastewater and silverskin are valorized into bioenergy, fertilizers, nanomaterials, antioxidants and dietary fiber. The ultimate outcome is **sustainable coffee production** combining productivity, resilience, quality, equity and a low carbon footprint. Cultivation dominates the carbon footprint (~70%), followed by consumption (~12%), underscoring the importance of climate-smart agricultural practices and post-harvest innovation*

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