Fronteiras: Journal of Social, Technological and Environmental Science
http://periodicos.unievangelica.edu.br/fronteiras/
ISSN 2238-8869

Brazilian Coffee Cultivation: Regional Productivity, Technological Strategies, and Global Market Perspectives

Luiz Gustavo Alves de Souza[1], Maria do Socorro Mascarenhas[2], Etenaldo Felipe Santiago[3]

[1] Doctoral student in the Natural Resources. Universidade Estadual de Mato Grosso do Sul. ORCID: 0009-0003-4284-8827. Email: lgmatufmt@gmail.com
[2] Doctorate in Natural Resources. Universidade Estadual de Mato Grosso do Sul. ORCID: 0000-0002-5343-4502. Email: maria_mascarenhas@outlook.com
[3] Doctorate in Biological Sciences. Universidade Estadual de Mato Grosso do Sul. ORCID: 0000-0001-6838-1098. Email: felipe@uems.br

ABSTRACT
Brazilian coffee growing, which originated in the 18th century, has consolidated the country as a global leader in coffee production and export, resulting from the combination of favorable edaphoclimatic conditions, fertile soils, and continuous technological advances. Regional diversity enables the cultivation of Coffea arabica and Coffea canephora, expanding sensory profiles, meeting diverse market niches, and strengthening Brazil's strategic position globally. This study aims to assess the main challenges and opportunities of Brazilian coffee production, considering productive, technological, and environmental aspects, relating them to quality, sustainability, and sector competitiveness. A descriptive, exploratory, and analytical review was conducted based on scientific publications and scientometric analysis to map productive trends, technological advances, and the spatial distribution of coffee cultivation between 2015 and 2024. Results show that C. arabica production is predominantly concentrated in the Southeast Region, while the South Region also contributes significantly, favored by high altitudes, fertile soils, and a mild climate, which enhance grain quality. C. canephora production predominates in the North and Northeast Regions, favored by higher temperatures and lower water demand. Despite progress, coffee cultivation still faces major challenges, such as regional technological disparities, high innovation costs, and climate change impacts, requiring adaptive strategies, bioinput use, sustainable management, and development of more tolerant cultivars.
Keywords: coffee varieties, agricultural production, exportation.

RESUMO
A cafeicultura brasileira, originada no século XVIII, consolidou o país como líder mundial em produção e exportação de café, resultado da combinação entre condições edafoclimáticas favoráveis, solos férteis e avanços tecnológicos contínuos. A diversidade regional permite o cultivo de Coffea arabica e Coffea canephora, ampliando os perfis sensoriais, atendendo diferentes nichos de mercado e fortalecendo a posição estratégica do Brasil no cenário global. Este estudo tem como objetivo avaliar os principais desafios e oportunidades da cafeicultura brasileira, considerando aspectos produtivos, tecnológicos e ambientais, relacionando-os à qualidade, sustentabilidade e competitividade do setor. Realizou-se uma revisão descritiva, exploratória e analítica, baseada em publicações científicas e na aplicação de análise cienciométrica para mapear tendências produtivas, avanços tecnológicos e a distribuição espacial da cafeicultura entre 2015 até 2024. Os resultados mostram que a produção de Coffea arabica concentra-se predominantemente na Região Sudeste, enquanto a Região Sul também contribui expressivamente, favorecida por altitudes elevadas, solos férteis e clima ameno, que beneficiam a qualidade do grão. Já a produção de Coffea canephora predomina nas Regiões Norte e Nordeste, favorecidas por temperaturas mais altas e menor exigência hídrica. Apesar dos avanços, a cafeicultura ainda enfrenta desafios, como desigualdade tecnológica regional, altos custos de inovação e impactos das mudanças climáticas, exigindo estratégias adaptativas, uso de bioinsumos, manejo sustentável e desenvolvimento de cultivares mais tolerantes.
Palavras-chave: variedades de café, produção agrícola, exportação.

Submissão: 24/04/2026 Aceite: 19/06/2026 Publicação: 14/11/2026

v.15, n.3, 2026 • p. 235-252. • DOI http://dx.doi.org/10.21664/2238-8869.2026v15i3.8819

© 2021 by the authors. Esta revista oferece acesso livre imediato ao seu conteúdo, seguindo o princípio de que disponibilizar gratuitamente o conhecimento científico ao público proporciona maior democratização mundial do conhecimento. Este manuscrito é distribuído nos termos da licença Creative Commons – Atribuição - NãoComercial 4.0 Internacional (https://creativecommons.org/licenses/by-nc/4.0/legalcode), que permite reproduzir e compartilhar o material licenciado, no todo ou em parte, somente para fim não comercial; e produzir, reproduzir, e compartilhar material adaptado somente para fim não comercial.

Introduction

The history of coffee cultivation in Brazil dates back to the 18th century, with the introduction of the first coffee seedlings into the country. Since then, Brazil has established itself as the world's largest producer of this commodity, a result of the combination of ideal climatic conditions, fertile soils, and the technical advances achieved by producers over time (Araújo, Da Silva & Da Rocha 2023). Currently, the country accounts for about one-third of global coffee production and is notable for its regional diversity, offering unique soil and climate characteristics. This variability enables the cultivation of *Coffea arabica* in the mountains of the Southeast and *Coffea canephora*, predominant in the North, thereby broadening the range of internationally valued flavors and aromas (Nannini & Casimiro 2023). Moreover, continuous investments in research, genetic improvement, technological innovation, and sustainable management reinforce the competitiveness of Brazilian coffee production in the international market, ensuring its leadership in this agribusiness segment (Do Amaral *et al.* 2025).

Coffee production in Brazil encompasses a wide range of practices and products, from natural and pulped beans to diverse sensory profiles, such as more acidic, full-bodied, or aromatic beverages. This diversity meets the demands of both consumer markets and agricultural and economic sectors, highlighting the strategic importance of coffee farming for job creation and the country's socioeconomic development (Volsi *et al.* 2019). As these authors point out, the coffee production chain is complex and involves stages ranging from the cultivation of *Coffea arabica* and *Coffea canephora* to processing, transportation, and marketing. These activities contribute not only to the economic sustainability of producing regions but also to the well-being of local communities, stimulating their economies (Syofya 2023).

Coffee, one of the most consumed beverages in the world, has a strong impact on the Brazilian domestic market, where average annual per capita consumption is approximately 4 kg of roasted coffee, equivalent to about 13% of global demand (De Lima *et al.* 2020). In recent decades, Brazil has experienced significant growth in coffee production, consolidating its position as a major player in the global market. This progress reflects the country's strategic importance, derived from the adoption of advanced management technologies, cultivar diversification, and the expansion of production areas. National production is dominated by *Coffea arabica*, although *Coffea canephora* (Conilon) also plays a major role, contributing to the diversification and stability of Brazilian coffee output (Abdelwahab *et al.* 2024). Furthermore, the broad geographical distribution of crops and the strong participation of smallholders reinforce the sector's socioeconomic relevance, promoting rural development and strengthening the national economy (Vegro & De Almeida 2020).

Technological advances have led to significant gains in productivity, grain quality, and cost efficiency, while reducing environmental impacts and promoting the consolidation of more sustainable agricultural systems (Hegab *et al.* 2023; Vilochani, McAloone & Pigosso 2024). When combined with conservation practices such as terracing, maintaining vegetation cover, and rational irrigation management, these innovations enhance the resilience of production systems and strengthen Brazil's competitiveness in the global market (Ferreira, Biazzin & Hong 2024; Ngure & Watanabe 2024), reaffirming the country's prominent position among the world's leading coffee producers and exporters.

Despite Brazil's relevance and strong performance in coffee production, challenges persist. In certain regions, productivity has been compromised by multiple factors, with climatic variability emerging as the main constraint. Irregular rainfall distribution reduces crop yields, leading to water stress that impairs vegetative growth and diminishes the plant's reproductive capacity (Rakocevic *et al.* 2020; Borgo *et al.* 2024). Water scarcity is among the most critical abiotic stresses in agriculture, as it decreases photosynthetic efficiency by increasing stomatal resistance, limiting CO_2 influx into chloroplasts, causing photoinhibition, and generating reactive oxygen species (Qiao *et al.* 2024; Wang *et al.* 2024). These processes damage thylakoid membranes and compromise the integrity of the photosynthetic apparatus (Nadarajah 2020; Sachdev *et al.* 2021). Furthermore, global climate change, characterized by rising average temperatures and an increasing frequency of extreme weather events, exacerbates these constraints, emphasizing the need for sustainable management, the development of tolerant cultivars, and the adoption of technologies aimed at conserving soil moisture (Swain *et al.* 2020; Ahmed *et al.* 2023; Frimpong *et al.* 2023).

Although there is extensive literature addressing plants of economic importance, the dynamics of environmental conditions, growing production demands, and adherence to sustainability principles justify continued research to fill existing knowledge gaps. For instance, understanding the effects of stress on photosynthesis,an essential process for plant growth, development, and productivity (Morales *et al.* 2020; Muhammad *et al.* 2021), remains a promising research field with substantial potential for discovery. Moreover, the incidence of pests, diseases, and nutritional deficiencies further intensifies physiological limitations, reducing

metabolic efficiency and plant tolerance to stress. The lack of essential nutrients directly compromises photosynthetic rate, physiological integrity, and ultimately, final productivity (Zenda *et al.* 2021; Khan *et al.* 2023; Lilay *et al.* 2024), constituting key limiting factors for crop performance.

Recent studies have explored the effects of innovative coffee management strategies, including the monitoring of photosynthetic efficiency and detailed analyses of the C3 cycle, with the goal of identifying approaches capable of optimizing plant physiology under conditions of water and nutritional stress (Treves *et al.* 2022; Tian *et al.* 2024). Simultaneously, the development of cultivars with enhanced tolerance to prolonged drought, improved resistance to pests and diseases, and better adaptation to heterogeneous environments represents a promising avenue for maintaining yield stability amid global climate change (Gonzalez Guzman *et al.* 2022). In recent years, several studies have demonstrated that the integration of water and nutrient management technologies has significantly contributed to productivity gains in Brazilian coffee cultivation, particularly in regions vulnerable to water deficits.

In the Cerrado Mineiro region, for instance, irrigated *Coffea arabica* crops achieved an average productivity of 50 bags per hectare, whereas rainfed areas produced 36 bags per hectare, an increase of approximately 38% associated with the adoption of irrigation (Voltolini *et al.* 2025). Freitas *et al.* (2020) evaluated the productivity of coffee intercropped with forest species in comparison with monoculture systems. The authors found that intercropping with African mahogany resulted in the highest cumulative productivity, ranging from 234 to 242 bags ha^{-1}, surpassing the monoculture system, which reached 223.77 bags ha^{-1}. A remarkable increase was observed in 2018, when yields peaked at 125.34 bags ha^{-1}. Intercropping with teak and pink cedar produced intermediate yields of 202–210 bags ha^{-1}, indicating that moderate shading may slightly reduce initial yields but promotes grain stability and quality over time. According to the authors, the overall average of 220.13 bags ha^{-1} demonstrates that intercropping does not compromise productivity and provides additional environmental benefits, such as soil conservation and microclimate regulation.

These results highlight that genetic innovation through the development of more adapted cultivars alone is insufficient. An integrated strategy is essential, one that combines continuous investment in research and innovation, technical training for producers, dissemination of sustainable practices (such as localized irrigation, strategic shading, and soil management enriched with organic matter), and the adoption of advanced agricultural monitoring systems, including remote sensing, drones, and soil moisture sensors. Such integration is crucial to ensuring the sustainability of Brazilian coffee production and meeting the growing global demand for high-quality coffee. Beyond climate and environmental factors, another key element affecting production and global market prospects is government policy. Recently, the United States government, formerly one of Brazil's principal trading partners, imposed tariffs of up to 55% on Brazilian agricultural products entering its market, according to the Office of the United States Trade Representative (USTR 2024). Brazilian coffee is currently among the products affected by these tariffs.

In this context, the adoption of integrated management practices plays a fundamental role in enhancing coffee resilience and mitigating the adverse effects of climate change on production (Fincheira *et al.* 2023; Yadav *et al.* 2023). Moreover, scenario analysis of global trade conditions for Brazilian commodities contributes valuable data for identifying opportunities in the coffee sector. Considering these aspects, this study aims to assess the main challenges and identify potential opportunities for Brazilian coffee farming, by investigating the relationship between productivity and coffee quality and critically discussing the current production scenario and international market dynamics.

Materials And Methods

Study Design

This study is a systematic literature review conducted to identify, synthesize, and critically analyze scientific evidence on Brazilian coffee production, with emphasis on productivity, quality, technological innovation, and sustainability.

The methodological design followed internationally recognized guidelines for systematic reviews, ensuring transparency, reproducibility, and methodological rigor, particularly in the stages of search, selection, and analysis of scientific studies.

Search Strategy

The literature search was conducted in the following databases: Google: Scholar; CAPES Journal Portal; SciELO e Web of Science.

The search covered studies published between 2015 and 2024, aiming to capture recent advances in Brazilian coffee production.

The following descriptors were used in English and Portuguese, combined with Boolean operators (AND, OR): "Brazilian coffee production"; "coffee productivity"; "coffee quality"; "coffee market"; "sustainable coffee production"; "cafeicultura brasileira"; "produtividade do café" e "qualidade do café".

Inclusion and Exclusion Criteria

To ensure consistency and scientific relevance, the following criteria were applied.

Inclusion criteria:

- Peer-reviewed scientific articles
- Studies addressing Brazilian coffee production
- Publications focusing on productivity, quality, sustainability, or technological innovation
- Articles published between 2015 and 2024
- Studies available in English or Portuguese

Exclusion criteria:

- Duplicated studies across databases
- Publications not directly related to the research objective
- Technical reports without peer review
- Abstracts, editorials, dissertations, and theses
- Studies lacking methodological clarity

Study Selection Process

The study selection followed a structured multi-stage process:

Identification: retrieval of studies from selected databases

Screening: removal of duplicates and preliminary reading of titles and abstracts

Eligibility: full-text reading to verify adherence to inclusion criteria

Inclusion: final selection of studies for qualitative and quantitative analysis

This process ensured the selection of relevant and high-quality scientific evidence.

Data Extraction and Organization

The selected studies were systematically analyzed, and the following information was extracted:

- Author(s) and year of publication
- Study objective
- Geographic focus
- Methodological approach
- Main findings related to productivity, quality, and sustainability
- The data were organized into spreadsheets using OriginLab 2024b software, allowing the generation of tables, graphs, and comparative analyses.

Scientometric and Analytical Approach

The scientometric analysis was applied as a complementary methodological approach to identify patterns, trends, and relationships in Brazilian coffee production, with emphasis on productivity, quality, and sustainable management.

This analysis was structured into three interconnected dimensions, temporal, spatial, and integrated analysis, whose procedures, objectives, and analytical steps are summarized in Table 1.

The framework presented in Table 1 guided the organization, processing, and interpretation of the data, allowing a systematic evaluation of production dynamics and their relationship with technological and environmental factors.

Table 1. Procedures for scientometric analysis applied to Brazilian coffee production.

Stage of Analysis	Specific Objectives	Procedures Performed
Temporal Analysis	Assess the historical evolution of Brazilian coffee production between 2014 and 2024.	Compilation of historical series on production, productivity, and certifications. Identification of periods of growth, stability, and decline.
Spatial Analysis	Map the regional distribution of coffee-producing areas in Brazil.	Preparation of maps based on data from CONAB and IBGE. Identification of consolidated production hubs and emerging areas.
Integrated Analysis	Correlate average productivity with coffee quality and market opportunities.	Cross-referencing of data on productivity, sensory attributes, and certifications. Identification of regions with potential for specialty coffees and niche markets.

Source: Prepared by the authors.

The temporal analysis aimed to assess the evolution of Brazilian coffee production between 2014 and 2024, based on historical series of production, productivity, and certification indicators. This step enabled the identification of periods of growth, stability, and decline, supporting the interpretation of production trends in relation to technological and climatic factors. The spatial analysis focused on mapping the regional distribution of coffee production in Brazil, using data from CONAB and IBGE. This stage allowed the identification of consolidated production hubs and emerging regions, highlighting spatial inequalities and regional specificities.

The integrated analysis consisted of cross-referencing productivity data with coffee quality indicators and market dynamics. This step enabled the identification of regions with potential for specialty coffee production and niche markets, as well as the evaluation of strategic opportunities for value aggregation. The adoption of the scientometric approach contributed to a structured interpretation of the data, enabling the identification of trends, gaps, and opportunities in Brazilian coffee production. In addition, this methodological strategy supports the integration of quantitative and qualitative information, strengthening the analytical consistency of the study and its contribution to the understanding of production systems and market dynamics.

The scientometric approach stands out as a strategic tool for understanding the dynamics of scientific knowledge and for identifying patterns of production, collaboration, and impact within academic literature. One of its main advantages lies in its ability to foster critical reflection and generate new insights, allowing the detection of theoretical gaps and unexplored questions that guide the formulation of new research agendas (Mao *et al.* 2018; Do Carmo *et al.* 2023). By enabling a detailed analysis of the evolution of scientific fields, this approach supports the strategic planning of innovative investigations and promotes the generation of relevant discoveries, driving the advancement of knowledge across different disciplines.

According to Batistote, Silva & Mascarenhas (2022), scientometric research makes it possible to quantify and measure qualitative data, in addition to providing an analysis of the state of the art of a given object or phenomenon. Furthermore, this methodology demonstrates broad practical applicability in the formulation, monitoring, and evaluation of public policies related to science, technology, and innovation, as it allows the identification of emerging areas, priority research lines, and global investment trends. This approach thus promotes the rational and efficient allocation of resources, maximizing scientific impact and enhancing the potential for technological innovation (Jeong *et al.* 2021; Capari *et al.* 2022).

Resultados e Discussão

The evolution of the planted area of *Coffea arabica* (A) and *Coffea canephora* (B) in Brazil between 2015 and 2024 reveals contrasting trends between the two species (Figure 1). For *C. arabica*, stability with slight growth is observed, increasing from 1.44 to 1.52 million hectares (Mha) over the period, which represents an approximate 5.56% increase. This constancy reinforces the consolidation of the species as the main coffee variety cultivated in the country, driven by the high added value of its beans, the growing demand for specialty coffees, and the intensive use of sustainable management technologies such as irrigation systems, agricultural mechanization, and genetically improved cultivars. On the other hand, *C. canephora* shows a distinct trajectory,

with a much smaller planted area, ranging from 0.04 to 0.09 Mha between 2015 and 2024, an expressive 125% increase over the period. Despite its smaller share of the total cultivated area, this species plays a strategic role in supplying the instant coffee industry and in the formulation of blends, occupying specific production niches. This expansion is likely associated with the adoption of irrigation technologies, the use of adapted cultivars, and the exploitation of favorable regions such as Espírito Santo, Bahia, and Rondônia, where warm and humid climatic conditions favor productivity.

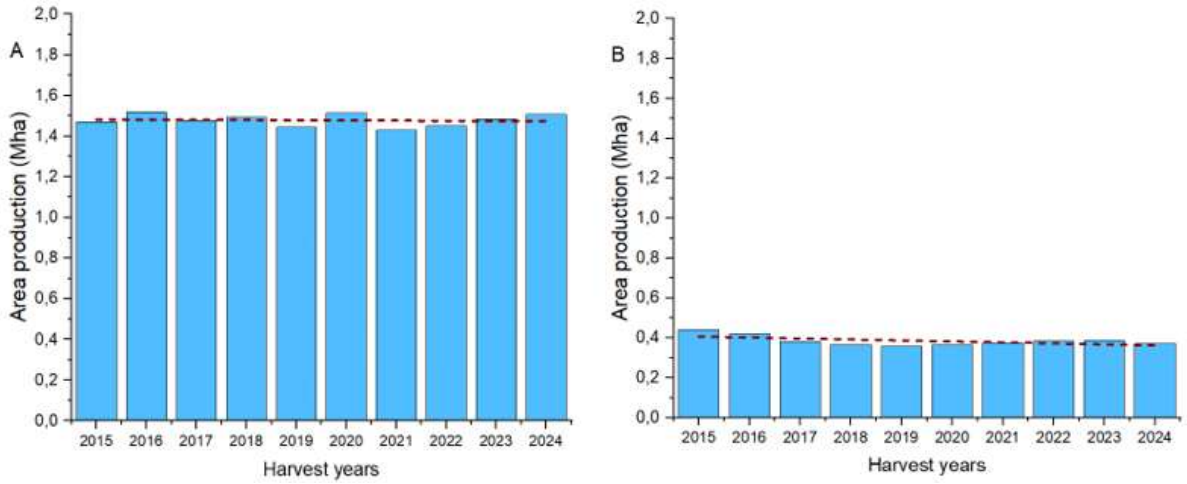


Figure 1. Evolution of the planted area of *Coffea arabica* (A) and *Coffea canephora* (B) in Brazil from 2015 to 2024. Source: Adapted from Conab (2025). Values are expressed in million hectares (Mha). The dashed line indicates the production trend over the evaluated period.

In this context, it is noteworthy that the expansion of Brazilian coffee cultivation is directly related to technological advances achieved through genetic improvement programs, seedling cloning, and irrigation technologies, which have enhanced productivity and crop resilience to climatic variations (Dos Santos *et al.* 2022; Basso *et al.* 2024). Furthermore, there is a consistent predominance of the *Coffea arabica* variety, which has historically represented the largest share of Brazil's coffee production and exports, while *Coffea canephora* accounts for a significantly smaller proportion, although with a clear upward trend in recent years (Vegro & de Almeida 2020).

The analysis of the distribution of *Coffea arabica* (A) and *Coffea canephora* (B) production in Brazil reveals significant regional differences resulting from the combined influence of edaphoclimatic factors, technological management strategies, and local socioeconomic conditions. For *C. arabica*, the Southeast Region accounts for approximately 75% of national production, establishing itself as the main hub of Brazilian coffee cultivation. The South Region contributes around 10%, standing out for its high-quality beans but showing greater climatic vulnerability. The Midwest Region represents about 8%, characterized as a recently expanding coffee-growing area. The Northeast accounts for roughly 5%, showing gradual growth, while the North represents less than 2% of production, reflecting both a limited coffee-growing tradition and the still incipient nature of the activity (Table 2). In contrast, *C. canephora* presents a different scenario: the Southeast Region is responsible for about 70% of the national output. The North occupies the second position, with approximately 15%, favored by warm and humid climatic conditions. The Northeast contributes around 8%, with a trend toward increased production. The Midwest accounts for about 5%, reflecting the expansion of new coffee-growing areas, while the South has virtually no participation due to the poor adaptation of *C. canephora* to milder climates and its higher susceptibility to frost.

Table 2. Percentage distribution of *Coffea arabica* and *Coffea canephora* production by region in Brazil.

Region	***Production of C. arabica (%)***	***Production of C. canephora (%)***
North	2%	15%
Northeast	5%	8%
Midwest	8%	5%
Southeast	75%	70%
South	10%	0%

Source: Adapted from the Brazilian Institute of Geography and Statistics (IBGE 2022).

The cultivation of *Coffea arabica* and *Coffea canephora* is directly related to edaphoclimatic conditions and to the physiological adaptation of the plants to specific regions. *C. arabica* performs best in areas with altitudes between 800 and 1,400 meters and average temperatures ranging from 18 °C to 22 °C, prevailing in mountainous regions and cooler climates (Peñuela-Martínez, Moreno-Riascos & Medina-Rivera 2023). *C. canephora*, in contrast, stands out for its greater hardiness, tolerating higher temperatures (24 °C to 30 °C), lower water requirements, and a shorter production cycle, which allows its cultivation at lower altitudes and in environments with water deficits (Jordaim *et al.* 2015). This adaptive plasticity makes *C. canephora* a strategic species for diversifying Brazil's coffee production, especially in the context of climate change, as it contributes to increasing productive resilience, optimizing the use of natural resources, and promoting the sustainability of the sector, particularly in more vulnerable regions prone to environmental stress.

Despite significant advances, the modernization of coffee farming presents challenges that demand critical analysis. Among these, regional inequality in the adoption of technology stands out. While some regions have achieved high levels of mechanization, use of improved cultivars, and precision irrigation, others, particularly parts of the North and Northeast, still face structural limitations, limited technical assistance, and difficulties accessing rural credit, widening the gap between technologically advanced producers and smallholder coffee farmers (Barreto Peixoto *et al.* 2023; Santos, Ribeiro & Rodrigues 2023). Another major constraint involves the high cost of implementing technologies such as irrigation systems, digital sensors, drones, and management software, which remain inaccessible to many family farmers (Sott *et al.* 2020; Hidalgo *et al.* 2023).

The analysis of the evolution of the planted area of *Coffea arabica* (A) and *Coffea canephora* (B) in Brazil between 2015 and 2024 highlights distinct production dynamics for the two varieties across regions (Figure 2). The results show that *C. arabica* maintains national predominance and relative stability over the years, whereas *C. canephora* demonstrates a gradual expansion trend, though still limited to specific areas. For *C. arabica*, the Southeast Region remains the main cultivation hub, accounting for about 75% of the total planted area, with no significant variations during the analyzed period. This stability is linked to factors such as a long-standing coffee tradition, favorable edaphoclimatic conditions, and the established use of technologies that ensure high productive consistency. The South Region continues to represent around 10%, with slight oscillations related to climatic events, while the Midwest accounts for approximately 8%, showing moderate growth associated with the opening of new coffee-growing areas.

In the Northeast, the average share was 5%, reflecting slow progress, while the North remained below 2% of the total area, characterizing it as a region of low representativeness for the species (Figure 2A). Regarding *C. canephora*, an opposite trend is observed, with a more pronounced increase in planted area, albeit from a smaller base. The Southeast Region concentrates approximately 70% of the cultivated area, showing stable growth, while the North accounts for around 15% and exhibits a continuous expansion trend due to the species' good adaptation to warm and humid climates. The Northeast represents about 8%, consolidating itself as a gradually expanding area, and the Midwest maintains a participation of approximately 5%, reflecting its recent incorporation into coffee cultivation. The South Region, in turn, records virtually no *C. canephora* cultivation, owing to the species' low tolerance to mild temperatures and susceptibility to frost (Figure 2B).

The temporal analysis between 2015 and 2024 makes it possible to identify trends of stability, expansion, and regional adaptation, providing valuable insights for strategic planning and sustainable management of Brazilian coffee cultivation. While *C. arabica* maintains historical predominance and stability in cultivated area, consolidating itself as the main Brazilian variety aimed at the production of specialty coffees, *C. canephora* shows proportionally faster growth, associated with its adaptation to warm and humid regions and the growing demand for instant coffees and blends (CONAB 2025). Understanding these differences is essential for guiding public policies, sectoral investments, and agricultural management strategies, as the spatial distribution of cultivated areas reflects both the edaphoclimatic potential and the socioeconomic impacts of the activity. Recent studies highlight that Brazil accounts for about 35% of global coffee production, and monitoring the evolution of cultivated areas is crucial to maintaining international competitiveness and ensuring production sustainability (EMBRAPA 2023).

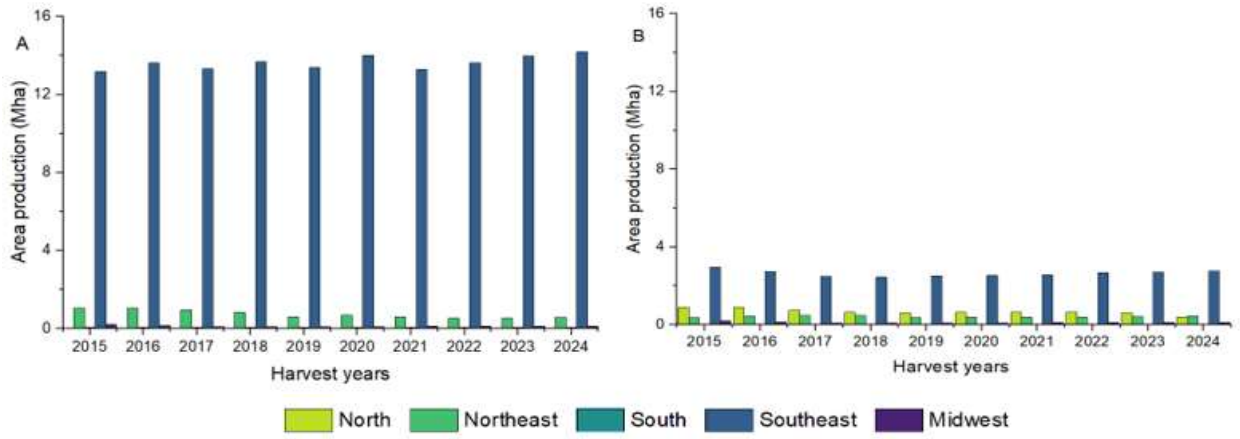


Figure 2. Analysis of the evolution of the planted area of *Coffea arabica* (A) and *Coffea canephora* (B) by region in Brazil. Source: Adapted from Conab (2025). Values are expressed in million hectares (Mha).

The assessment of average productivity, expressed in 60-kg bags per hectare, for *Coffea arabica* (A) and *Coffea canephora* (B) in Brazil between 2015 and 2024 reveals regional differences that reflect the environmental and technological diversity of national coffee cultivation. *C. arabica* in the Southeast Region maintains absolute leadership in productivity, resulting from the combination of a long-standing tradition, consolidated infrastructure, and a high level of mechanization, along with the increasing use of precision management technologies. The South Region exhibits intermediate performance but experiences sharp fluctuations caused by climatic variability and the higher incidence of frosts, which directly affect production. The Midwest shows gradual growth in productivity indices, driven by the expansion of coffee-growing areas and the adoption of more modern agricultural systems. In the Northeast, productivity gains are more modest, limited by edaphoclimatic constraints and prolonged droughts, while the North displays the lowest average values, reflecting low technological investment and the still incipient nature of coffee production in the region (Figure 3A).

For *C. canephora*, the scenario is substantially different. The species records the highest productivity levels in the North and Northeast Regions, favored by its strong adaptation to warm and humid environments and by the intensive use of irrigation, genetic improvement programs, and technologies aimed at increasing production efficiency. The Southeast Region also achieves good results, though on a smaller scale, mainly supported by irrigated systems and the use of adapted cultivars. The Midwest follows a continuous growth trend, in line with the opening of new agricultural areas and the implementation of innovative production practices. The South, in turn, exhibits low productivity, a result of *C. canephora*'s limited tolerance to milder climates and its susceptibility to frost (Figure 3B).

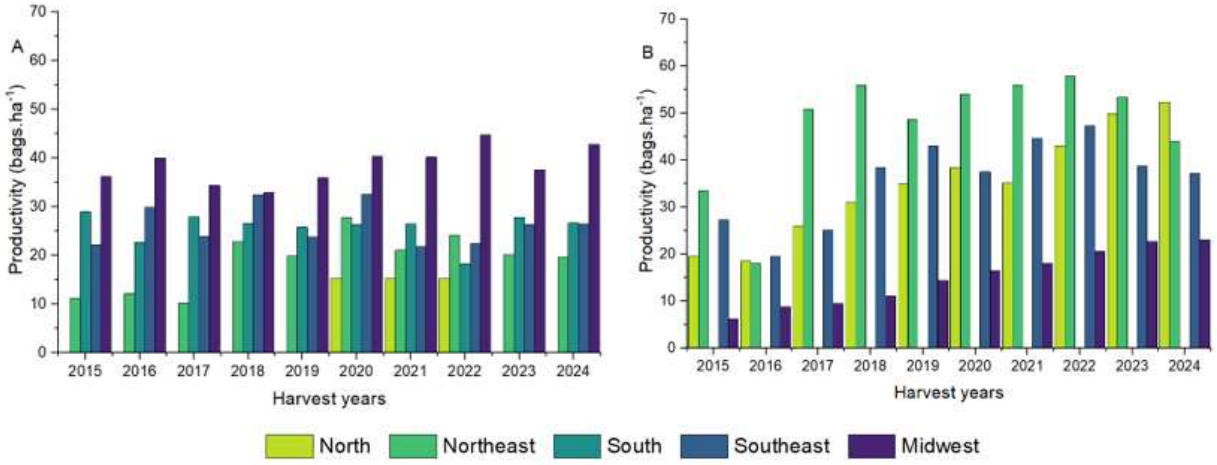


Figure 3 – Average productivity of *Coffea arabica* (A) and *Coffea canephora* (B) in different regions of Brazil. Source: Adapted from Conab (2025). Values are expressed as productivity in bags per hectare (bags ha^{-1}).

The observed patterns reinforce the importance of adopting technological, environmental, and structural factors in determining coffee productivity in Brazil. The leadership of the Southeast in *C. arabica* production is associated with the intensive use of technology, genetic improvement programs, and sustainable management practices, highlighting the direct impact of innovation on regional competitiveness (CONAB 2024). For *C. canephora*, the high yields in the North and Northeast demonstrate the efficiency of varietal adaptation and investments in irrigation and management (EMBRAPA CAFÉ 2023). In this context, public policies and state initiatives aimed at modernizing the sector have played a central role in reducing production disparities and strengthening Brazilian coffee cultivation, consolidating the country as a global leader in both diversity and production volume (IBGE 2024).

The evolution of Brazilian exports of *Coffea arabica* and *Coffea canephora*, expressed in 60 kg bags between 2020 and 2024 (Figure 4), highlights important transformations in the dynamics of the national coffee sector, reflecting the interaction among productive, environmental, technological, and market-related factors. From the temporal perspective adopted in this study, variations in export volumes represent not only annual fluctuations in production but also the responses of the Brazilian coffee sector to climate change, international market demands, and adaptation strategies implemented throughout the production chain. In the case of *Coffea arabica*, exports remained close to 30 million bags at the beginning of the analyzed period, demonstrating relative stability following the high-yield cycle observed in 2019. This behavior is consistent with the historical importance of arabica coffee in Brazil's export portfolio, as the species accounts for the largest share of national production destined for specialty and premium coffee markets. However, between 2021 and 2022, a decline in export volumes was recorded, which may be associated with the combination of adverse climatic factors and physiological characteristics inherent to the crop. During this period, major coffee-producing regions in southeastern Brazil experienced extreme weather events, including prolonged droughts and severe frosts, which negatively affected vegetative development, flowering, and fruit formation. Furthermore, the negative biennial bearing characteristic of arabica coffee contributed to reduced productivity, limiting the availability of beans for export (Medda, Fadda & Mulas, 2022).

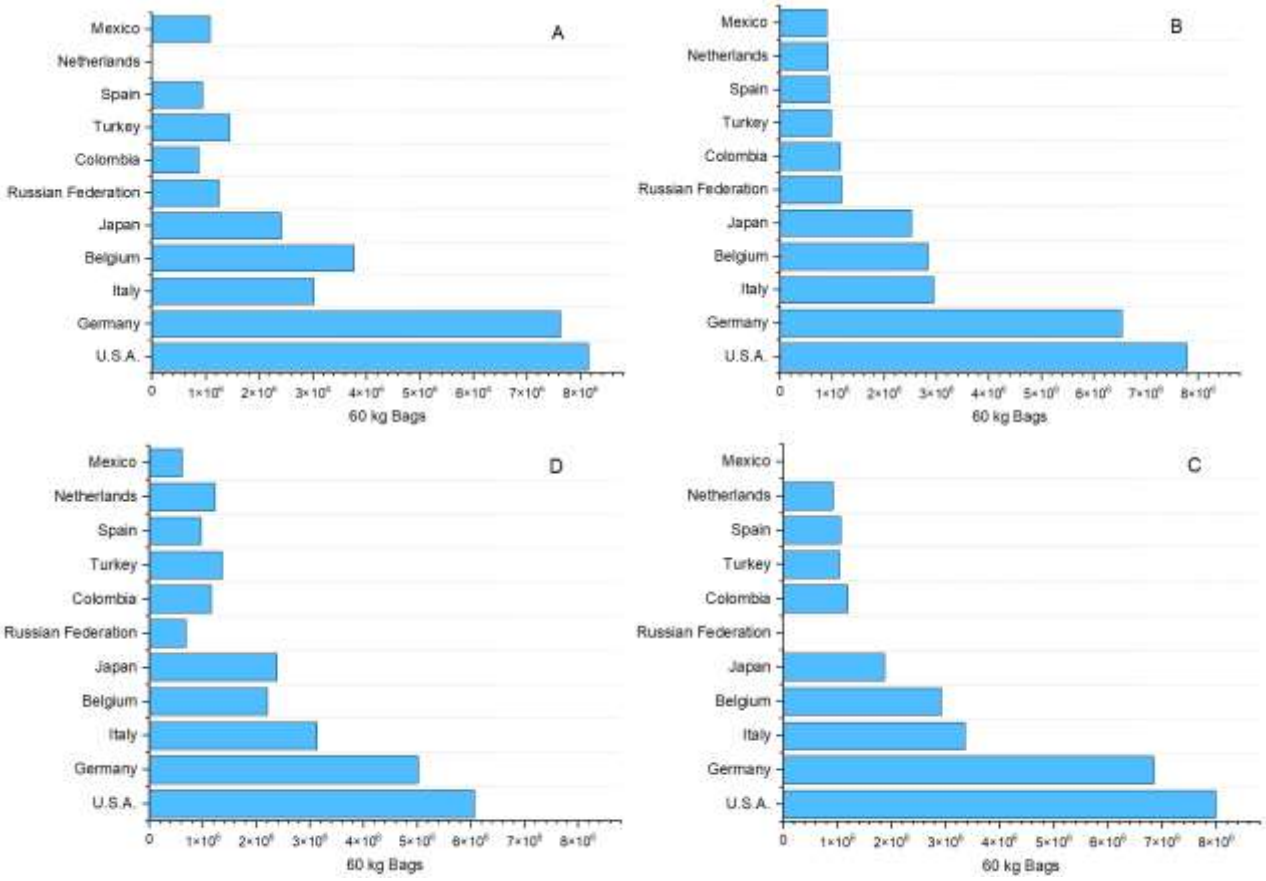
The decline observed between 2021 and 2022 highlights the high sensitivity of arabica coffee to climatic variability, an issue that has been widely discussed in the literature due to the impacts of climate change on tropical agricultural systems. This scenario reinforces the need for continuous investments in adaptation technologies, including breeding programs, conservation-oriented soil management, efficient irrigation systems, and climate-risk mitigation strategies. Therefore, the observed results demonstrate that the competitiveness of Brazilian coffee production is increasingly associated with its capacity to respond to extreme climatic events and maintain supply stability in a highly competitive global market. From 2023 onward, a gradual recovery in *C. arabica* exports was observed, culminating in volumes exceeding 35 million bags in 2024. This growth coincided with the recovery of productive capacity following previous climatic impacts and with more favorable weather conditions in major producing regions. Additionally, increasing international demand for specialty, certified, and sustainably produced coffees contributed to strengthening the competitiveness of Brazilian products. The appreciation of arabica coffee prices in international markets also played an important role in this process, stimulating exports and reinforcing Brazil's position as the world's leading coffee supplier (Maya Chacon, 2023). From this perspective, the recovery observed after 2022 does not merely represent a cyclical rebound but also reflects structural processes of productive modernization and strategic repositioning of Brazilian coffee farming in response to evolving global consumer demands.

In contrast, *Coffea canephora* exhibited a different pattern throughout the analyzed period. Until 2022, export volumes remained relatively modest, ranging between 2 and 5 million bags annually. However, between 2023 and 2024, a substantial expansion occurred, with exports surpassing 10 million bags, representing one of the most significant changes observed during the study period. This growth can be interpreted as the result of structural transformations in both coffee production and global consumption patterns. From a market perspective, the growing demand for instant coffee products increased the need for robusta and conilon beans, which are predominantly used by the soluble coffee industry due to their physicochemical characteristics and lower production costs (Brando et al., 2022). Simultaneously, the intensification of climate change has increased interest in species that are more tolerant to high temperatures and water deficits. In this context, *C. canephora* offers important agronomic advantages, including greater hardiness and production stability, characteristics that have favored its expansion across different producing regions.

Furthermore, recent advances in breeding programs and agronomic management have significantly improved the sensory quality of Brazilian conilon and robusta coffees. As a result, the species has gained access to market segments traditionally dominated by arabica coffees, expanding its participation in exports and adding value to national production (Ngure & Watanabe, 2024). This process demonstrates that the expansion of

canephora should not be interpreted merely as a quantitative increase in exports, but rather as part of a broader strategy of productive diversification and enhanced resilience within the Brazilian coffee sector. From the spatial dimension of the analysis, the expansion of exports is associated with regional production specialization. While arabica coffee remains concentrated mainly in the states of Minas Gerais, São Paulo, and Bahia, the growth of canephora production has been driven by Espírito Santo, Rondônia, and emerging agricultural areas with favorable edaphoclimatic conditions for robusta cultivation. This regional complementarity contributes to reducing production risks, enhancing supply stability, and strengthening Brazil's competitiveness across different segments of the international coffee market.

The integrated analysis of the results suggests that the simultaneous recovery of arabica exports and the rapid expansion of canephora exports represent an important adaptation mechanism of Brazilian coffee farming to global environmental and economic transformations. Diversification between species reduces dependence on a single production system, increasing the sector's ability to respond to climatic fluctuations, changes in consumption patterns, and volatility in international prices. In the context of international trade, coffee remains one of the most important commodities in Brazilian agribusiness, accounting for approximately 7.6% of the country's total exports in 2021 (Syofya, 2023). Its production chain encompasses agricultural production, roasting, grinding, instant coffee manufacturing, and commercialization activities. Beyond its economic significance, coffee farming also plays an important social role, generating direct and indirect employment in thousands of farms and municipalities whose economies depend heavily on the sector (Vegro & De Almeida, 2020).



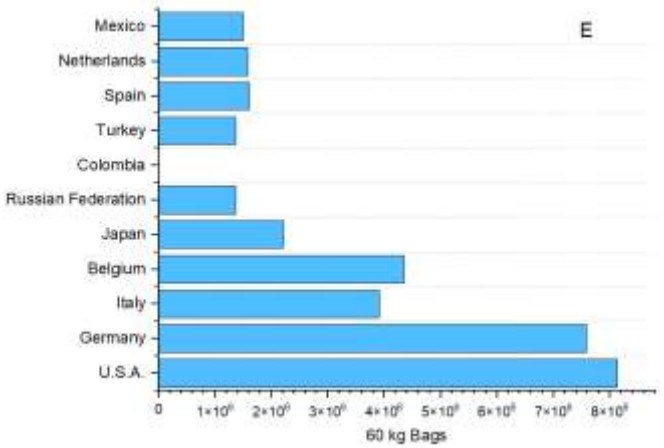


Figure 4. Representation of the coffee export volume (in 60 kg bags) to the main importing countries in the years 2020 (A), 2021 (B), 2022 (C), 2023 (D), and 2024 (E). Source: Adapted from Consórcio Pesquisa Café (2025).

Regarding consumer markets, the United States remained the primary destination for Brazilian coffee exports throughout the analyzed period, followed by Germany, Belgium, Italy, and Japan (Figure 4). This distribution reflects the consolidation of Brazil's commercial relationships with traditional coffee-consuming countries and the growing demand for high-quality coffee products. However, the increasing complexity of the international geopolitical landscape has introduced new challenges to global trade. Tariff policies implemented during the administration of President Donald Trump contributed to increased uncertainty in international markets, affecting several export-oriented production chains (Mudoi & Tamuli, 2024). Although Brazil initially benefited from trade realignments associated with the United States–China trade dispute (Kumar, 2025), the increase in tariffs applied to Brazilian products from 2025 onward became a potential limiting factor for future export expansion. Finally, the results demonstrate that the evolution of Brazilian coffee exports between 2020 and 2024 is the outcome of a complex interaction among climatic, technological, productive, economic, and geopolitical factors.

The recovery of *Coffea arabica* exports and the accelerated growth of *Coffea canephora* exports highlight the adaptive capacity of Brazilian coffee farming in the face of challenging scenarios, reinforcing the importance of technological innovation, productive diversification, and sustainability as key pillars for maintaining Brazil's leadership in the global coffee market. In addition to the economic benefits associated with export growth, the results also have important socioeconomic and environmental implications. The expansion of the coffee sector contributes to employment generation, income creation, and regional development in several producing areas of the country, while simultaneously promoting investments in more sustainable and efficient technologies.

The increasing demand from international markets for traceability, socio-environmental certification, and carbon footprint reduction has encouraged the adoption of agricultural practices aligned with sustainability principles. Therefore, the future competitiveness of Brazilian coffee farming will depend not only on productivity gains but also on its ability to reconcile economic growth, environmental conservation, and social inclusion, thereby strengthening its position in increasingly demanding markets guided by sustainability criteria. In this scenario of uncertainty, the Brazilian government has sought to negotiate fairer trade margins with the United States, given that the U.S. maintained a goods trade surplus with Brazil of approximately US$ 6.8 billion in 2024 (U.S. Trade Representative 2025). Furthermore, considering the relative elasticity of Brazilian agricultural exports, the pursuit of new markets and the consolidation of stronger trade partnerships with other countries have proven to be the most reliable alternatives for Brazil's agricultural products, according to the Organization for Economic Co-operation and Development (OECD 2024).

From an economic perspective, Arabica coffee represents approximately 74% of national production and stands out in the international market, especially in the specialty coffee segment, due to the high sensory quality of its beans (CONAB 2023). Conilon, responsible for about 26% of total production, has historically supplied the domestic market and the instant coffee industry, but it has been expanding its share in exports according to the United States Department of Agriculture (USDA 2024). This progress is driven not only by the growing global demand for high-quality blends but also by commercial strategies aimed at market diversification and value addition. In this context, the states of Bahia and Rondônia have emerged as important production hubs, contributing to regional diversification and strengthening the sector's competitiveness, consolidating Brazil's

position as a global leader in coffee production and exports, both in volume and in product diversity (Conceição *et al.* 2020; Volsi *et al.* 2019).

The comparative performance between the two species highlights the dominant role of *Coffea arabica* in Brazilian coffee production, especially in the export market, where the beverage's sensory quality and a long-standing reputation sustain its leadership (Bozzola *et al.* 2021). However, the growth observed in *Coffea canephora* suggests a strategic diversification of exports, reducing excessive dependence on arabica and expanding Brazil's competitiveness in specific segments of the global value chain. Overall, the analysis of the 2015–2024 period shows that, although Brazil remains firmly established as the world's largest exporter of arabica coffee, there is a clear trend toward the strengthening of canephora in international trade, a development that may positively impact both trade balance stability and the resilience of the national coffee sector amid climate change and emerging market demands (Ngure & Watanabe 2024).

The analysis of Brazil's coffee export revenues highlights recent dynamics between 2020 and 2024. During this period, *Coffea arabica* remained the predominant variety, accounting for more than 80% of the total exported volume. Exports increased from 35.6 million bags in 2020 to 36.9 million in 2024, demonstrating production stability and the sector's capacity to respond to fluctuations in the international market. Conversely, *Coffea canephora* experienced significant growth, expanding its export volume from 4.9 million bags in 2020 to 9.3 million in 2024, an increase of nearly 90%. This advancement reflects a market diversification strategy driven by the rising global demand for blends and higher-quality instant coffees. In terms of export revenue, there was a marked upward trend. In 2020, Brazil recorded approximately US$ 5.65 billion in coffee export revenues, remaining relatively stable through 2021 (US$ 6.17 billion). Starting in 2022, revenues rose sharply, surpassing US$ 9.24 billion, reflecting arabica's appreciation in international markets and increased demand for specialty coffees. Although 2023 showed a slight decline (US$ 8.05 billion) due to falling global prices and the replenishment of international stocks, 2024 marked a historic record, reaching US$ 12.51 billion, an accumulated growth of more than 120% over the five-year period analyzed (Table 3).

Table 3. Brazilian coffee exports by variety and economic performance (2020–2024).

Year	Coffea arabica (bags)	Coffea canephora (bags)	Total exported (bags)	Export revenue (US$ thousand)
2020	35,624,383	4,927,184	44,707,485	5,658,238.6
2021	32,208,424	3,755,163	40,042,658	6,174,423.4
2022	34,112,232	1,508,798	39,411,102	9,244,014.2
2023	30,845,111	4,727,317	39,245,773	8,051,062.8
2024	36,946,011	9,355,618	50,443,037	12,514,639.7

Source: Brazilian Coffee Exporters Council – Cecafé (2025).

These results highlight not only the dominant role of arabica but also the structural strengthening of canephora, whose contribution to the trade balance has become increasingly significant. The expansion of robusta indicates a strategic diversification of exports, reducing exclusive dependence on arabica and enhancing Brazil's competitiveness across different segments of the global value chain.

The analysis of the evolution of foreign exchange revenue from *Coffea arabica* and *Coffea canephora* exports in Brazil highlights the strategic relevance of monitoring the economic performance of these varieties within both national and international contexts. Overall, *C. arabica* maintains absolute leadership, consolidating itself as the country's main variety and confirming its historical and competitive importance in the global coffee market (Samper, Giovannucci & Vieira 2017). This predominance can be explained by the international recognition of the quality of Brazilian beans, the growing appreciation of specialty coffees, and the adverse climatic conditions in competing producing regions which, in certain years, affected global supply and consequently enhanced Brazil's competitiveness (Ali & Tufa 2024).

On the other hand, *C. canephora* shows a more modest performance but with a continuous upward trend in recent years, demonstrating its growing potential in the international market (Sseremba *et al.* 2021). This expansion is associated with the consolidation of robusta/conilon as a strategic raw material for the instant coffee and capsule industries, sectors that have been experiencing strong growth. Furthermore, significant advances in crop management, post-harvest processing, and cultivar selection have contributed to improving beverage quality, increasing its acceptance and integration into international markets (Gandia *et al.* 2018; Zanin, Yeretzian & Smrke 2025).

The comparison between the two species shows that although *Coffea arabica* remains the main source of foreign exchange for Brazil, the growth of *Coffea canephora* represents an important step toward diversifying the

export portfolio, providing greater resilience to the national coffee sector in the face of market fluctuations and climatic adversities (Mihai *et al.* 2024). In addition, the increase in foreign exchange revenue from *canephora* may contribute to the economic valorization of producing regions traditionally less represented in international coffee trade, strengthening regional inclusion and enhancing the country's global competitiveness. Thus, the results demonstrate that Brazil's coffee export revenues no longer rely exclusively on arabica but increasingly benefit from the growing participation of c*anephora*. This complementarity between species reinforces the importance of policies that promote technological innovation, quality improvement, and market diversification to ensure the long-term economic and social sustainability of coffee production (Bager & Lambin 2020).

Final Considerations

Brazilian coffee cultivation reflects a complex interaction among edaphoclimatic conditions, species adaptability, technological development, and market dynamics. The results indicate that *Coffea arabica* remains the dominant species in Brazil, particularly in the Southeast Region, where favorable altitude, mild temperatures, consolidated infrastructure, and greater technological adoption support higher productivity and stronger participation in exports. In contrast, *Coffea canephora* has expanded its strategic relevance, especially in regions such as Espírito Santo, Rondônia, and Bahia, due to its greater rusticity, adaptation to warmer environments, and increasing use in instant coffee, blends, and diversified market segments.

The temporal and spatial analyses suggest that Brazilian coffee production is undergoing a gradual process of productive diversification. While arabica continues to sustain Brazil's historical leadership in quality, productivity, and foreign exchange revenue, the recent expansion of canephora should not be interpreted merely as quantitative growth. Rather, it represents a strategic response to climate variability, changing global demand, and the need to reduce excessive dependence on a single species. This trend may strengthen the resilience of the Brazilian coffee sector, particularly under scenarios of increasing climatic instability.

However, the results also reveal structural limitations that require critical attention. Technological inequality, restricted access to credit, insufficient technical assistance, and uneven regional infrastructure continue to limit the productive potential of small and medium-sized producers. Therefore, the modernization of Brazilian coffee cultivation cannot be evaluated only through productivity gains or export performance; it must also be analyzed in terms of regional inclusion, environmental sustainability, and the capacity to reduce asymmetries within the production chain.

From an economic perspective, the growth of export revenues between 2020 and 2024 reinforces the importance of coffee as a strategic commodity for Brazilian agribusiness. Nevertheless, the increasing participation of *C. canephora* demonstrates that the sector's competitiveness increasingly depends on diversification, value aggregation, quality improvement, and adaptation to new international market demands. In this sense, public policies, technological innovation, genetic improvement, sustainable management practices, and producer training are essential to consolidate a more resilient and inclusive coffee production model.

Thus, this study contributes to the understanding of Brazilian coffee cultivation by integrating productive, regional, technological, and market dimensions. The future of the sector will depend not only on maintaining Brazil's global leadership in coffee production and exports, but also on its ability to promote sustainable, regionally balanced, and socially inclusive strategies capable of responding to climate change and global market transformations.

Acknowledgments

To Universidade Estadual de Mato Grosso do Sul/UEMS; Programa de Pós-Graduação em Recursos Naturais/PGRN; Programa Institucional de Bolsas aos Alunos de Pós-Graduação/PIBAP; Fundação de Apoio ao Desenvolvimento do Ensino, Ciência e Tecnologia do Estado de Mato Grosso do Sul/FUNDECT; Conselho Nacional de Desenvolvimento Científico e Tecnológico/CNPq; Financiadora de Inovação e Pesquisa/FINEP e Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil/CAPES – Código 001 a LGAS e a MSM.

References

Abdelwahab, S. I., Taha, M. M. E., Jerah, A. A., Aljahdali, I. A., Oraibi, B., Alfaifi, H. A., ... & Farasani, A. (2024). Coffee arabica research (1932–2023): Performance, thematic evolution and mapping, global landscape, and emerging trends. Heliyon, 10(16).

Ahmed, Z., Gui, D., Murtaza, G., Yunfei, L., & Ali, S. (2023). An overview of smart irrigation management for improving water productivity under climate change in drylands. Agronomy, 13(8), 2113.

Ali, U., & Tufa, A. (2024). Current status of specialty coffee production and market in Ethiopia: a review. Journal of Agriculture, Food and Natural Resources, 2(1), 79-91.

Araújo, M. D. R. P., da Silva, P. L., & da Rocha, A. P. S. (2023). Cafeicultura: Evolução do café no Brasil, Minas Gerais e no município de João Pinheiro–MG. Revista Contemporânea, 3(11), 21683-21706.

Bager, S. L., & Lambin, E. F. (2020). Sustainability strategies by companies in the global coffee sector. Business Strategy and the Environment, 29(8), 3555-3570.

Barreto Peixoto, J. A., Silva, J. F., Oliveira, M. B. P., & Alves, R. C. (2023). Sustainability issues along the coffee chain: From the field to the cup. Comprehensive Reviews in Food Science and Food Safety, 22(1), 287-332.

Basso, M. F., Neves, M. F., & Grossi-de-Sa, M. F. (2024). Agriculture evolution, sustainability and trends, focusing on Brazilian agribusiness: a review. Frontiers in Sustainable Food Systems, 7, 1296337.

Batistote, M., Silva Fasioli, R., & Mascarenhas, M. D. S. (2022). A utilização das biomassas como fonte de energia sustentável. In BIOMASSA: RECURSOS, APLICAÇÕES E TECNOLOGIAS EM PESQUISAS (Vol. 1, pp. 22-32). Editora Científica Digital.

Borgo, L., Rabêlo, F. H. S., Marchiori, P. E. R., Guilherme, L. R. G., Guerra-Guimarães, L., & Resende, M. L. V. D. (2024). Impact of drought, heat, excess light, and salinity on coffee production: strategies for mitigating stress through plant breeding and nutrition. Agriculture, 15(1), 9.

Bozzola, M., Charles, S., Ferretti, T., Gerakari, E., Manson, H., Rosser, N., & von der Goltz, P. (2021). *The Coffee Guide. International Trade Centre*.

Brando, C. H., Regio, G., Pohlan, H. J., Janssens, M. J., Centeno, D. J. S., Torrico-Albino, J. C., ... & Ronchi, C. P. (2022). Climate-smart production of coffee: Improving social and environmental sustainability (Vol. 111). Burleigh Dodds Science Publishing.

Capari L, Wilfing H, Exner A, Höflehner T, & Haluza D 2022. Cooling the city? A scientometric study on urban green and blue infrastructure and climate change induced public health effects. Sustainability 14(9): 4929.

CONAB - Companhia Nacional de Abastecimento. (2023, 18 de maio). *Levantamento da Conab estima produção de café em 54,74 milhões de sacas na safra 2023*. Retrieved on September 6, 2025 of https://www.gov.br/conab/pt-br/assuntos/noticias/levantamento-da-conab-estima-producao-de-cafe-em-54-74-milhoes-de-sacas-na-safra-2023

CONAB - Companhia Nacional de Abastecimento. (2025). *Acompanhamento da safra brasileira de café: Safra 2025*. Brasília: CONAB. Retrieved on September 6, 2025 of https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/safra-de-cafe/3o-levantamento-de-cafe-safra-2025/boletim-cafe-setembro-2025

Conceição, R. L. C. D., Macedo, R. D., Gomes, A. D. S., Pires, M. D. M., Lisboa, G. J., & Santo, M. M. D. E. (2020). Specialization and competitiveness: analysis of Brazilian exports of cocoa beans and products. Revista Mexicana de Ciencias Agrícolas, 11(6), 1207-1219.

Cecafé - Conselho dos Exportadores de Café do Brasil**.** (2025, julho 16). *Exportação de café do Brasil tem receita recorde de US$ 14,7 bilhões na safra 2024/25* [Notícia]. Cecafé. Retrieved on September 6, 2025 of https://www.cecafe.com.br/publicacoes/noticias/cecafe-exportacao-safra-2024-25-20250716/.

Consórcio Pesquisa Café. (n.d.). *[Institutional page]*. Embrapa Café. Retrieved October 17, 2025, from http://www.consorciopesquisacafe.com.br/index.php/2016-07-18-14-42-22.

De Lima, L. M., de Pellegrini Elias, L., e Silva, M. M. C. D., da Silva, K. V., & Pacheco, A. S. V. (2020). Behavioral aspects of the coffee consumer in different countries: The case of Brazil. In Coffee Consumption and Industry Strategies in Brazil (pp. 321-341). Woodhead Publishing.

Do Amaral, F. M., Costa, N. L., Pinto, N. G. M., & Velho, J. P. (2025). Inovação da cafeicultura brasileira: a transformação do café como commodity. OBSERVATÓRIO DE LA ECONOMÍA LATINOAMERICANA, 23(6), e10371-e10371.

Do Carmo G, Felizardo LF, de Castro Alcântara V, da Silva CA, & do Prado JW 2023. The impact of Jürgen Habermas's scientific production: a scientometric review. Scientometrics, 128(3): 1853- 1875.

Dos Santos, T. B., Da Silva Ferreira, M. F., Marques, I., Oliveira, S. C., Zaidan, I. R., Oliveira, M. G., ... & Partelli, F. L. (2022). Current challenges and genomic advances towards the development resilient coffee genotypes to abiotic stresses. Genomic designing for abiotic stress resistant technical crops, 41-69.

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. (2023). *Sistemas de produção de café no Brasil*. Brasília. Retrieved October 17, 2025, from https://www.embrapa.br/cafe

Ferreira, F. C. M., Biazzin, C., & Hong, P. C. (2024). Transition paths of Brazil from an agricultural economy to a regional powerhouse: A global supply chain perspective. Sustainability, 16(7), 2872.

Fincheira, P., Hoffmann, N., Tortella, G., Ruiz, A., Cornejo, P., Diez, M. C., ... & Rubilar, O. (2023). Eco-efficient systems based on nanocarriers for the controlled release of fertilizers and pesticides: Toward smart agriculture. Nanomaterials, 13(13), 1978.

Freitas, A. F. D., Nadaleti, D. H. S., Silveira, H. R. D. O., Carvalho, G. R., Venturin, R. P., & Silva, V. A. (2020). Productivity and beverage sensory quality of arabica coffee intercropped with timber species. *Pesquisa Agropecuária Brasileira*, *55*, e02240.

Frimpong, F., Asante, M. D., Peprah, C. O., Amankwaa-Yeboah, P., Danquah, E. O., Ribeiro, P. F., ... & Botey, H. M. (2023). Water-smart farming: Review of strategies, technologies, and practices for sustainable agricultural water management in a changing climate in West Africa. Frontiers in Sustainable Food Systems, 7, 1110179.

Gandia, R. M., de Andrade Ferreira, C., Guimarães, E. R., Sugano, J. Y., & de Rezende, D. C. (2018). The coffee capsules consumption practice. Revista Pensamento Contemporâneo em Administração, 12(2), 31-42.

Gonzalez Guzman, M., Cellini, F., Fotopoulos, V., Balestrini, R., & Arbona, V. (2022). New approaches to improve crop tolerance to biotic and abiotic stresses. Physiologia plantarum, 174(1), e13547.

Hegab, H., Shaban, I., Jamil, M., & Khanna, N. (2023). Toward sustainable future: Strategies, indicators, and challenges for implementing sustainable production systems. Sustainable Materials and Technologies, 36, e00617.

Hidalgo, F., Quiñones-Ruiz, X. F., Birkenberg, A., Daum, T., Bosch, C., Hirsch, P., & Birner, R. (2023). Digitalization, sustainability, and coffee. Opportunities and challenges for agricultural development. Agricultural Systems, 208, 103660.

IBGE - Instituto Brasileiro de Geografia e Estatística (2022). *Café arábica e canephora – 2017*. In *Atlas Geográfico Escolar: Espaço econômico – Agricultura: culturas permanentes*. Rio de Janeiro: IBGE. Retrieved in June 2022, from https://sidra.ibge.gov.br/tabela/6955.

Jeong Y, Jang H, & Yoon B 2021. Developing a risk - adaptive technology roadmap using a Bayesian network and topic modeling under deep uncertainty. Scientometrics, 126: 3697 - 3722.

Jordaim, R. B., Colodetti, T. V., Rodrigues, W. N., Salles, R. A. D., Amaral, J. F. T. D., Maciel, L. S., ... & Tomaz, M. A. (2025). Genotypic Performance of Coffea canephora at Transitional Altitudes for Climate-Resilient Coffee Cultivation. Horticulturae, 11(6), 595.

Khan, F., Siddique, A. B., Shabala, S., Zhou, M., & Zhao, C. (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. Plants, 12(15), 2861.

Kumar, C. (2025). Complexity of US-China trade war: associated threats and realities. International Journal of Services Technology and Management, 30(1), 58-89.

Lilay, G. H., Thiébaut, N., du Mee, D., Assunção, A. G., Schjoerring, J. K., Husted, S., & Persson, D. P. (2024). Linking the key physiological functions of essential micronutrients to their deficiency symptoms in plants. New Phytologist, 242(3), 881-902.

Mao G, Huang N, Chen L, & Wang H 2018. Research on biomass energy and environment from the past to the future: A bibliometric analysis. Sci. Total Environ. 635: 1081- 1090.

Maya Chacon, J. D. (2023). The coffee: Overview of the global market, the performance and the business strategies in Colombia.

Medda, S., Fadda, A., & Mulas, M. (2022). Influence of climate change on metabolism and biological characteristics in perennial woody fruit crops in the Mediterranean environment. Horticulturae, 8(4), 273.

Mihai, R. A., Ortiz-Pillajo, D. C., Iturralde-Proaño, K. M., Vinueza-Pullotasig, M. Y., Sisa-Tolagasí, L. A., Villares-Ledesma, M. L., ... & Catana, R. D. (2024). Comprehensive assessment of coffee varieties (Coffea arabica L.; Coffea canephora L.) from Coastal, Andean, and Amazonian Regions of Ecuador; a holistic evaluation of metabolism, antioxidant capacity and sensory attributes. Horticulturae, 10(3), 200.

Morales, F., Ancín, M., Fakhet, D., González-Torralba, J., Gámez, A. L., Seminario, A., ... & Aranjuelo, I. (2020). Photosynthetic metabolism under stressful growth conditions as a bases for crop breeding and yield improvement. Plants, 9(1), 88.

Mudoi, D. K., & Tamuli, D. (2025). Trade Turbulence: India's Economic Journey Under US Tariff Influence. *American Journal of Economics and Business Management*, *8*(5), 2136-2147.

Muhammad, I., Shalmani, A., Ali, M., Yang, Q. H., Ahmad, H., & Li, F. B. (2021). Mechanisms regulating the dynamics of photosynthesis under abiotic stresses. Frontiers in plant science, 11, 615942.

Nadarajah, K. K. (2020). ROS homeostasis in abiotic stress tolerance in plants. International journal of molecular sciences, 21(15), 5208.

Nannini, W. T., & Casimiro, F. H. C. (2023). Cooperativismo e territorialização do agronegócio do café no sul de Minas Gerais. PEGADA-A Revista da Geografia do Trabalho, 24(1), 1-30.

Ngure, G. M., & Watanabe, K. N. (2024). Coffee sustainability: leveraging collaborative breeding for variety improvement. Frontiers in Sustainable Food Systems, 8, 1431849.

OECD - Organization for Economic Co-operation and Development. (2024). *Price and volume elasticities of Brazilian foreign trade*. OECD Publishing. Retrieved October 17, 2025 https://www.oecd.org/en/publications/price-and-volume-elasticities-of-brazilian-foreign-trade_223388731464.html.

Peñuela-Martínez, A. E., Moreno-Riascos, S., & Medina-Rivera, R. (2023). Influence of temperature-controlled fermentation on the quality of mild coffee (Coffea arabica L.) cultivated at different elevations. Agriculture, 13(6), 1132.

Qiao, M., Hong, C., Jiao, Y., Hou, S., & Gao, H. (2024). Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. Plants, 13(13), 1808.

Rakocevic, M., Braga, K. S. M., Batista, E. R., Maia, A. H. N., Scholz, M. B. S., & Filizola, H. F. (2020). The vegetative growth assists to reproductive responses of Arabic coffee trees in a long-term FACE experiment. Plant growth regulation, 91(2), 305-316.

Sachdev, S., Ansari, S. A., Ansari, M. I., Fujita, M., & Hasanuzzaman, M. (2021). Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms. Antioxidants, 10(2), 277.

Samper, L. F., Giovannucci, D., & Vieira, L. M. (2017). The powerful role of intangibles in the coffee value chain (Vol. 39). WIPO.

Santos, V. P., Ribeiro, P. C. C., & Rodrigues, L. B. (2023). Sustainability assessment of coffee production in Brazil. Environmental Science and Pollution Research, 30(4), 11099-11118.

Sott, M. K., Furstenau, L. B., Kipper, L. M., Giraldo, F. D., Lopez-Robles, J. R., Cobo, M. J., ... & Imran, M. A. (2020). Precision techniques and agriculture 4.0 technologies to promote sustainability in the coffee sector: state of the art, challenges and future trends. Ieee Access, 8, 149854-149867.

Sseremba, G., Kagezi, G. H., Kobusinge, J., Akodi, D., Olango, N., Mulindwa, J., ... & Arinaitwe, G. (2021). Early morphological growth response and incidence of key pests under two spacing regimes of *Coffea canephora*. Pelita Perkeb, 37, 107-125.

Swain, D. L., Singh, D., Touma, D., & Diffenbaugh, N. S. (2020). Attributing extreme events to climate change: a new frontier in a warming world. One Earth, 2(6), 522-527.

Syofya, H. (2023). The Effect of Environmental Sustainabiity and Value Chain Concept in the Context of Local Economy on Value Added of Coffee Commodities in Kerinci. West Science Business and Management, 1(03), 107-117.

Tian, W., Su, C., Zhang, N., Zhao, Y., & Tang, L. (2024). Simulation of the physiological and photosynthetic characteristics of C3 and C4 plants under elevated temperature and CO2 concentration. Ecological Modelling, 495, 110805.

Treves, H., Küken, A., Arrivault, S., Ishihara, H., Hoppe, I., Erban, A., ... & Stitt, M. (2022). Carbon flux through photosynthesis and central carbon metabolism shows distinct patterns between algae, C3 and C4 plants. Nature plants, 8(1), 78-91.

USTR - Office of the United States Trade Representative. (2024). 2024 National Trade Estimate Report on Foreign Trade Barriers. Retrieved October 17, 2025, from https://ustr.gov/sites/default/files/2024%20NTE%20Report.pdf.

USTR - Trade Representative. (2025). *Brazil trade summary*. Office of the United States Trade Representative. Retrieved October 17, 2025, from https://ustr.gov/countries-regions/americas/brazil.

Vegro, C. L. R., & de Almeida, L. F. (2020). Global coffee market: Socio-economic and cultural dynamics. In *Coffee consumption and industry strategies in Brazil* (pp. 3-19). Woodhead Publishing.

Vilochani, S., McAloone, T. C., & Pigosso, D. C. (2024). Consolidation of management practices for Sustainable Product Development: A systematic literature review. Sustainable Production and Consumption, 45, 115-125.

Volsi, B., Telles, T. S., Caldarelli, C. E., & Camara, M. R. G. D. (2019). The dynamics of coffee production in Brazil. PloS one, 14(7), e0219742.

Voltolini, G. B., Carvalho, G. R., Andrade, V. T., Ferreira, A. D., Raposo, F. V., Carvalho, J. P. F., ... & Pereira, A. A. (2025). Agronomic performance of irrigated and rainfed Arabica coffee cultivars in the Cerrado Mineiro region. *Agronomy*, *15*(1), 222.

Wang, P., Liu, W. C., Han, C., Wang, S., Bai, M. Y., & Song, C. P. (2024). Reactive oxygen species: multidimensional regulators of plant adaptation to abiotic stress and development. Journal of Integrative Plant Biology, 66(3), 330-367.

Yadav, M. R., Kumar, S., Lal, M. K., Kumar, D., Kumar, R., Yadav, R. K., ... & Rajput, V. D. (2023). Mechanistic understanding of leakage and consequences and recent technological advances in improving nitrogen use efficiency in cereals. Agronomy, 13(2), 527.

Zanin, R. C., Yeretzian, C., & Smrke, S. (2025). The aroma of instant coffee: Its release and modulation by encapsulation. In Coffee in Health and Disease Prevention (pp. 175-187). Academic Press.

Zenda, T., Liu, S., Dong, A., & Duan, H. (2021). Revisiting sulphur—The once neglected nutrient: It's roles in plant growth, metabolism, stress tolerance and crop production. Agriculture, 11(7), 626.