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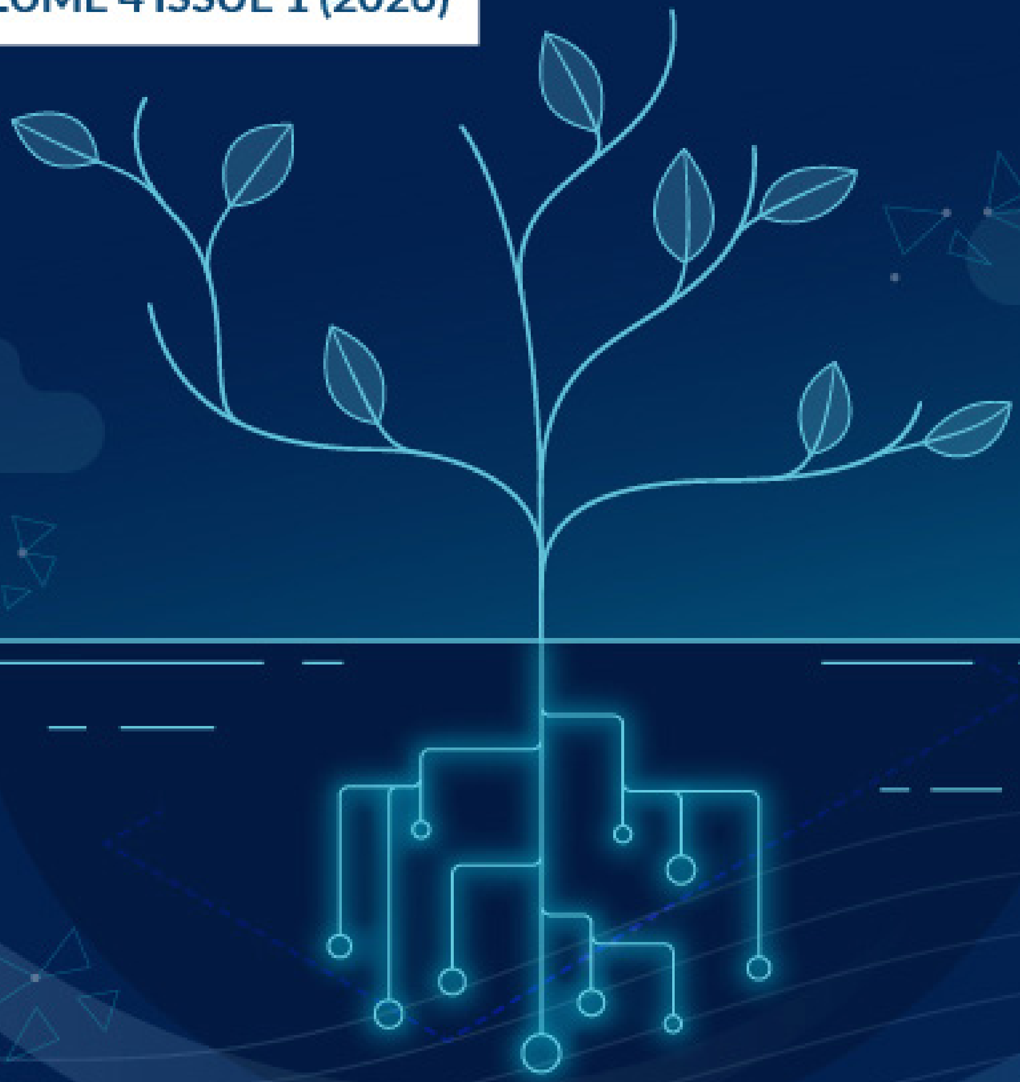

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Global Research Trends and Thematic Evolution in Coffee Production: A Bibliometric Analysis (2000–2025)

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ABSTRACT

Coffee is one of the world's most economically and socially significant agricultural commodities, yet it remains highly vulnerable to climate variability, biotic stress, and sustainability pressures. This study provides a comprehensive bibliometric assessment of global research trends in coffee production using data retrieved from the Lens.org database and analyzed through Biblioshiny (Bibliometrix in R) and VOSviewer. A total of 1,000 peer-reviewed documents published between 2020 and 2025 were examined to evaluate publication growth patterns, collaboration dynamics, thematic evolution, and conceptual structure. Results indicate a marked expansion of scientific output during the early 2020s, driven primarily by research on climate resilience, agroforestry systems, disease management, and sustainability transitions. Thematic mapping identifies "coffee production" and "agroforestry" as motor themes, while sustainability and circular bioeconomy approaches emerge as consolidating priorities. Despite growing interdisciplinarity and collaborative intensity, key gaps persist, including the underrepresentation of Southeast Asia, limited long-term field validation studies, weak integration of extension-oriented research, and insufficient incorporation of microbiome-based productivity enhancement. The findings highlight the evolution of coffee production research toward a systems-oriented framework integrating ecological resilience, genetic improvement, quality differentiation, and resource efficiency. Addressing identified gaps will be critical to strengthening the long-term sustainability and global competitiveness of coffee production systems under intensifying environmental and socio-economic pressures.

INTRODUCTION

Coffee is one of the most economically significant agricultural commodities worldwide, supporting the livelihoods of more than 25 million farming households across tropical regions (International Coffee Organization [ICO], 2023). Global production in recent years has exceeded 170 million 60-kg bags annually, with major producing countries including Brazil, Vietnam, Colombia, and Ethiopia (Food and Agriculture Organization [FAO], 2023; ICO, 2023). The sector contributes substantially to export earnings in many developing economies and plays a central role in rural employment and smallholder income generation. Two species dominate commercial production: Coffea arabica L., accounting for approximately 60–65% of global output, and Coffea canephora Pierre ex A. Froehner (Robusta), comprising the remaining share (ICO, 2023). While Arabica is generally associated with higher market value and specialty markets, Robusta is recognized for its higher yield potential and relative tolerance to environmental stress.

Despite its global economic importance, coffee production systems are increasingly challenged by climate variability, land-use change, pest outbreaks, and market volatility. Coffee has been identified as particularly sensitive to rising temperatures and altered precipitation regimes due to its narrow optimal growing conditions (Bunn *et al.*, 2015; DaMatta *et al.*, 2018). Climate projections indicate substantial shifts in suitable cultivation zones, especially for C. arabica, potentially leading to yield instability and geographic redistribution of production (Bunn *et al.*, 2015). Concurrently, major disease outbreaks—most notably coffee leaf rust (Hemileia vastatrix)—have caused severe production losses in Latin America, underscoring the vulnerability of coffee systems to biotic stress and climate–pathogen interactions (Avelino *et al.*, 2015).

In response to these pressures, research has increasingly moved beyond conventional yield optimization toward integrated, systems-oriented approaches emphasizing climate resilience, agroforestry, biodiversity conservation, and sustainable intensification. Shade-grown and agroforestry-based coffee systems have been shown to enhance ecosystem services, buffer microclimatic extremes, and support biodiversity while maintaining productive capacity (Jha *et al.*, 2014; Perfecto *et al.*, 2019). At the same time, advancements in genetic improvement, disease resistance, and postharvest quality management reflect growing demand for both productivity and value-chain differentiation. Coffee quality research has expanded substantially, driven by specialty markets and increasing consumer awareness of traceability, sensory attributes, and bioactive compounds (Farah, 2012; Ludwig *et al.*, 2014).

Moreover, sustainability transitions within the coffee sector increasingly incorporate circular economy

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principles, particularly in the valorization of coffee processing residues such as pulp and spent grounds for bioenergy, soil amendments, and extraction of functional compounds (Mussatto *et al.*, 2011; Janissen & Huynh, 2018). These developments illustrate how coffee production research now intersects with broader global agendas on climate-smart agriculture, resource efficiency, and sustainable commodity governance.

Given the multidimensional nature of coffee production—encompassing agronomy, climate science, plant pathology, genetics, soil management, food chemistry, and socio-economic systems—the volume and complexity of scientific output have expanded considerably in recent years. While numerous empirical and review studies address specific subtopics within coffee research, a comprehensive bibliometric synthesis mapping the intellectual structure, thematic evolution, and research gaps of contemporary coffee production scholarship remains limited. Bibliometric analysis provides a systematic and quantitative framework for examining research growth patterns, collaboration dynamics, and conceptual structures within a field (Aria & Cuccurullo, 2017; Donthu *et al.*, 2021). Science mapping techniques such as keyword co-occurrence and thematic evolution analysis enable the identification of dominant research clusters and emerging knowledge frontiers (Cobo *et al.*, 2011).

Therefore, this study aims to conduct a comprehensive bibliometric assessment of global research trends in coffee production from 2000 to 2025. Specifically, the objectives are to: (i) evaluate publication growth and productivity patterns; (ii) analyze collaboration networks and citation performance; (iii) map the conceptual and thematic structure of the field; and (iv) identify research gaps and future directions to inform sustainable development of coffee production systems. By providing a structured synthesis of the scientific landscape, this study contributes to strategic research planning and supports the advancement of resilient, sustainable, and innovation-driven coffee systems worldwide.

MATERIALS AND METHODS

Data Source and Search Strategy

Bibliographic data were retrieved from the Lens.org database, a comprehensive scholarly and patent indexing platform integrating metadata from multiple sources. Lens was selected due to its broad coverage, open-access accessibility, and export compatibility with bibliometric software. The search query was constructed to capture peer-reviewed literature related to coffee production, including the terms:

"coffee production" OR "coffee cultivation" OR "coffee farming" OR "Coffea arabica" OR "Coffea canephora"

The search was restricted to publications between 2020 and 2025 and limited to English-language journal articles, review articles, and reports. Conference proceedings, editorial materials, and non-scholarly documents were excluded to ensure analytical consistency.

The final dataset consisted of 1,000 documents after screening for duplicates and incomplete records.

Data Processing and Bibliometric Analysis

The retrieved records were exported in BibTeX and CSV formats for analysis. Bibliometric analysis was conducted using Biblioshiny, the web-based interface of the Bibliometrix R package (Aria & Cuccurullo, 2017), and VOSviewer (van Eck & Waltman, 2010).

Two complementary analytical approaches were applied:

Performance Analysis

Descriptive indicators were generated using Biblioshiny, including:

- Annual scientific production
- Source distribution
- Author productivity
- Collaboration metrics
- Citation indicators

These metrics were used to assess research growth patterns, productivity structure, and early impact.

Science Mapping Analysis

Science mapping techniques were employed to examine the intellectual and conceptual structure of the field. Specifically:

- Keyword co-occurrence analysis was conducted to identify thematic clusters and research linkages.
- Thematic mapping (based on centrality and density measures) was applied to classify themes into motor, basic, niche, and emerging categories.
- Network visualization was performed using VOSviewer to generate high-resolution co-occurrence maps, where node size represents keyword frequency and link strength reflects co-occurrence intensity.

Minimum occurrence thresholds were applied to enhance interpretability of network structures. Thematic quadrants were interpreted following established science mapping frameworks (Cobo *et al.*, 2011).

Methodological Considerations

Recent publication years (particularly 2024–2025) may be subject to indexing lag, potentially influencing growth rate calculations and citation metrics. Citation-based indicators were therefore interpreted with caution due to time-dependent accumulation effects (Wang, 2013). Additionally, variations in author affiliation metadata may affect international collaboration measures.

RESULTS AND DISCUSSION

Descriptive Overview and Bibliometric Characteristics of the Dataset

Bibliometric analysis has become an established quantitative approach for systematically mapping scientific production, identifying research trends, and examining the intellectual structure of a research field (Aria & Cuccurullo, 2017; Donthu *et al.*, 2021). In this study, a dataset comprising 1,000 documents published between 2020 and 2025 was analyzed to characterize the recent trajectory of coffee production research. The five-year timespan ensures that the dataset reflects contemporary research priorities; however, the recency of the corpus necessitates careful interpretation of citation-based indicators, as citation accumulation is inherently time-dependent (Wang, 2013).

Table 1: Summary statistics of the bibliometric dataset used for analysis (2020–2025).

Description	**Results**
MAIN INFORMATION ABOUT DATA	
Timespan	2020:2025
Sources (Journals, Books, etc)	601
Documents	1000
Annual Growth Rate %	-35.15
Document Average Age	4.65
Average citations per doc	8.316
References	16604
DOCUMENT CONTENTS	
Keywords Plus (ID)	3308
Author's Keywords (DE)	3308
AUTHORS	
Authors	3895
Authors of single-authored docs	101
AUTHORS COLLABORATION	
Single-authored docs	106
Co-Authors per Doc	4.46
International co-authorships %	0
DOCUMENT TYPES	
book chapter	10
journal article	988
report	2

The distribution of these 1,000 documents across 601 distinct sources indicates a highly diversified publication landscape. With an average of approximately 1.66 documents per source, the field appears widely dispersed rather than concentrated in a small number of core journals. Such dispersion is often indicative of an interdisciplinary research domain integrating multiple disciplinary perspectives (Porter & Rafols, 2009; Zupic & Čater, 2015). In the context of coffee production, this breadth likely reflects the convergence of agronomy, plant pathology, climate science, soil management, food chemistry, and socio-economic research within a single knowledge system.

The average document age of 4.65 years confirms the contemporary nature of the dataset. The calculated average citation rate of 8.316 citations per document is notable given the relatively short citation window, suggesting that recent publications are gaining scholarly visibility at a meaningful pace. Nevertheless, citation-based metrics must be interpreted cautiously, as recently published works typically require time to accumulate measurable impact (Wang, 2013).

The annual growth rate of –35.15% warrants particular methodological attention. Negative growth within a short and recent timespan is uncommon in actively evolving scientific domains. Bibliometric growth indicators are highly sensitive to database indexing completeness, especially for the most recent publication years (Donthu *et al.*, 2021). It is therefore plausible that incomplete indexing of 2024–2025 publications at the time of data extraction artificially depressed the calculated growth rate. Such indexing lag effects are well documented in bibliometric research and should not be interpreted as a substantive decline in scholarly interest without further year-by-year verification.

The dataset contains 16,604 cited references, corresponding to an average of 16.6 references per document. This citation density reflects cumulative knowledge building and suggests that coffee production research is grounded in a well-established scholarly foundation. Bibliometric scholarship recognizes reference intensity as an indicator of intellectual integration and engagement with prior work (Ellegaard & Wallin, 2015).

From a productivity and collaboration perspective, the dataset includes 3,895 unique authors contributing to 1,000 publications, with an average of 4.46 co-authors per document. Such a collaboration index is consistent with contemporary scientific production patterns, where team-based research increasingly dominates knowledge creation (Wuchty *et al.*, 2007). The interdisciplinary and systems-oriented nature of coffee research—encompassing climate adaptation, disease management, genetic improvement, and sustainability assessment—likely necessitates collaborative expertise across multiple domains. Only 10.6% of the documents are single-authored, further reinforcing the prevalence of collaborative scholarship.

The reported international co-authorship rate of 0% is highly atypical for a globally significant agricultural commodity such as coffee. International collaboration has been consistently associated with increased research visibility and impact (Glänzel & Schubert, 2004). Consequently, the absence of recorded cross-national collaboration likely reflects limitations in affiliation metadata extraction rather than genuine insularity within the research community. Verification of country-level author information is therefore essential to ensure analytical accuracy in subsequent collaboration network analyses.

In terms of document typology, journal articles account for 98.8% of the corpus, with minimal representation of book chapters and reports. The dominance of peer-reviewed journal articles enhances methodological consistency and strengthens the reliability of bibliometric indicators. Furthermore, the dataset includes 3,308 unique Author Keywords and an equivalent number of Keywords Plus entries, providing a rich conceptual vocabulary for subsequent science-mapping analyses. Co-word and network-based approaches, such as those implemented in VOSviewer, are widely recognized as robust tools for uncovering thematic structures and conceptual interconnections within research fields (van Eck & Waltman, 2010; Cobo *et al.*, 2011).

Overall, the dataset represents a recent, diversified, and highly collaborative body of literature characterized by promising early citation performance and strong interdisciplinary engagement. While certain indicators—particularly growth rate and international collaboration—require methodological verification due to potential database constraints, the corpus provides a robust empirical foundation for performance analysis and science mapping of contemporary coffee production research.

Temporal Evolution and Growth Dynamics of Coffee Production Research

The temporal distribution of publications reveals a marked expansion in scholarly output on coffee production during the early 2020s, culminating in a peak around 2021 (Figure 1). Annual output increased from approximately 280 documents in 2020 to more than 330 in 2021, indicating an accelerated growth phase in global research activity. This expansion reflects broader structural transformations in agricultural research priorities, particularly in climate-sensitive perennial crops. Coffee has increasingly been characterized as a climate-vulnerable commodity due to its narrow agroecological requirements and sensitivity to temperature increases and rainfall variability (Bunn *et al.*, 2015; DaMatta *et al.*, 2018). Modeling studies have projected significant shifts in suitable cultivation zones for Coffea arabica, reinforcing global scientific attention toward adaptation strategies and resilience planning (Bunn *et al.*, 2015).

The surge in publication output during this period is also consistent with the intensification of sustainability-oriented research agendas. Global policy frameworks emphasizing sustainable intensification, biodiversity conservation, and climate-smart agriculture have stimulated interdisciplinary investigations integrating agronomy, agroforestry, carbon dynamics, and socio-economic resilience (Perfecto *et al.*, 2019; Phalan *et al.*, 2011). Coffee systems, particularly shaded and agroforestry-based production models, have become focal case studies for examining trade-offs between productivity, ecosystem services, and farmer livelihoods. The integration of environmental sustainability and value-chain governance has thus expanded the conceptual boundaries of coffee research beyond yield optimization toward systems-based analysis.

In parallel, recurring biotic stresses have reinforced research urgency. The resurgence of coffee leaf rust (Hemileia vastatrix) across Latin America during the past decade resulted in substantial production losses and prompted renewed investment in breeding for resistance, integrated pest management, and adaptive farm-level strategies (Avelino *et al.*, 2015). Disease outbreaks of this magnitude often act as catalytic events, accelerating research output and international collaboration in affected commodities. The intersection of climate stress and pathogen dynamics has further amplified the need for resilient cultivars and improved crop management frameworks (DaMatta *et al.*, 2018).

The apparent decline in publication counts from 2022 onward should be interpreted with methodological caution. Bibliometric indicators are highly sensitive to database indexing completeness, particularly for the most recent publication years (Donthu *et al.*, 2021). Articles published in late 2024 or 2025 may remain in press or incompletely indexed at the time of data extraction, artificially depressing annual output counts. Citation accumulation also follows a temporal lag structure, meaning that recent publications are systematically underrepresented in performance metrics (Wang, 2013). Consequently, the observed contraction in the final years of the dataset is more plausibly attributed to indexing lag rather than a substantive decline in scholarly interest.

When these structural limitations are considered, the broader trajectory indicates sustained and intensifying global engagement with coffee production research over the past decade. The publication growth pattern underscores the strategic importance of coffee within contemporary agricultural research, particularly at the

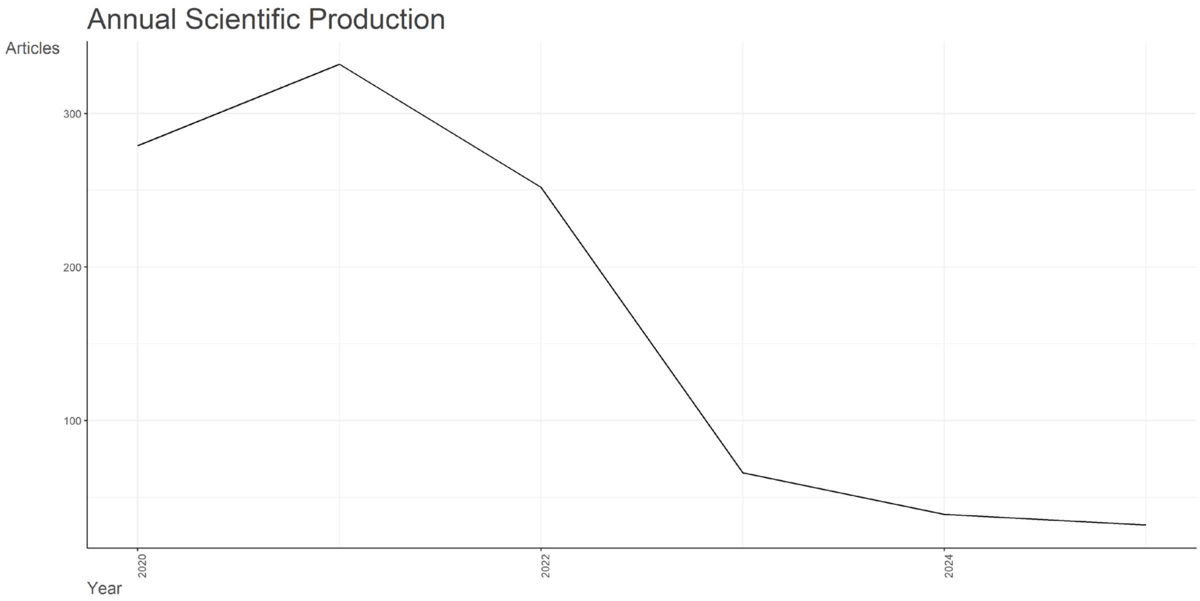

Figure 1: Annual publication trend in coffee production research (2000–2025).

nexus of climate resilience, sustainable production systems, biodiversity conservation, and global value-chain transformation. As climate variability intensifies and sustainability governance becomes increasingly embedded in commodity markets, coffee is likely to remain a central model system for interdisciplinary agricultural research.

Conceptual Structure of Coffee Production Research

The author keyword co-occurrence network provides a structured visualization of the intellectual and conceptual architecture underpinning global research on coffee production (Figure 2). Co-word analysis is widely recognized as a robust science-mapping approach for identifying thematic clusters and knowledge structures within a research field (Cobo *et al.*, 2011; van Eck & Waltman, 2010). The high centrality of the term "coffee" reflects its integrative role across agronomic, ecological, biochemical, and socio-economic domains, confirming that contemporary scholarship conceptualizes coffee not merely as a crop commodity but as a complex socio-ecological production system embedded within environmental constraints and global market dynamics. The density of interconnections among nodes indicates a mature and highly networked research field characterized by thematic convergence rather than fragmentation.

A major thematic cluster is anchored on production systems and climate-related variables, including "production," "agroforestry," "climate variability," "temperature," "smallholders," and "biodiversity." This configuration reflects a paradigmatic shift from conventional yield-maximization paradigms toward climate-resilient and ecologically integrated production models. Coffee has been repeatedly identified as highly sensitive to rising temperatures and shifting precipitation regimes, with projections indicating substantial alterations in suitable growing zones under climate change scenarios (Bunn *et al.*, 2015; DaMatta *et al.*, 2018). The strong linkage between agroforestry and climate-related keywords supports growing evidence that shaded coffee systems buffer microclimatic extremes, enhance biodiversity, and contribute to ecosystem service provision (Perfecto *et al.*, 2019; Jha *et al.*, 2014). The presence of "smallholders" further emphasizes the socio-economic dimension of coffee systems, recognizing that the majority of global coffee production is undertaken by small-scale farmers whose livelihoods are particularly vulnerable to climatic and market volatility (Avelino *et al.*, 2015). This cluster thus illustrates the integration of ecological resilience and rural development within contemporary coffee research.

A second prominent cluster centers on species-specific and genetic research, particularly "Coffea arabica," "Coffea canephora," "coffee leaf rust," "genetic diversity," and disease-management terms. The persistence of these keywords underscores the enduring influence of biotic stress on research priorities. The global resurgence of coffee leaf rust (Hemileia vastatrix) during the past decade caused widespread yield losses and renewed emphasis on resistant cultivars and integrated disease management strategies (Avelino *et al.*, 2015). The integration of genetic diversity within this cluster reflects the recognition that breeding and germplasm conservation are central to long-term adaptation strategies under both climatic and pathogenic pressures (DaMatta *et al.*, 2018). The close proximity of Coffea arabica to disease-related terms in the network highlights its well-documented susceptibility and the corresponding research intensity directed toward enhancing genetic resilience.

Another distinct cluster encompasses quality attributes and biochemical components, including "caffeine," "chlorogenic acid," "polyphenols," "lipids," and "coffee

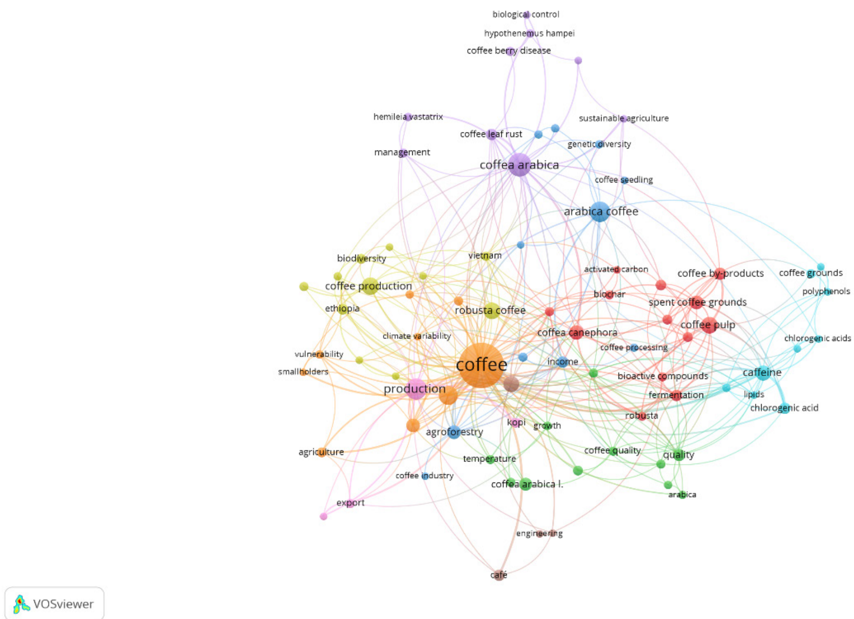

Figure 2: Conceptual structure of coffee production research based on author keyword co-occurrence (2000–2025).

quality." This thematic concentration signals the expansion of coffee research beyond primary production into postharvest science, food chemistry, and functional food research. Coffee is a major dietary source of bioactive compounds with recognized antioxidant and physiological properties, which has stimulated growing scientific interest in its chemical composition and health-related attributes (Farah, 2012; Ludwig *et al.*, 2014). The interconnection between quality-related and production-related terms suggests that agronomic practices are increasingly evaluated for their effects on bean biochemical composition and sensory characteristics, reflecting the rise of specialty coffee markets and traceability standards (Toledo *et al.*, 2016). This shift demonstrates how production research is increasingly integrated with market-driven quality differentiation and value-chain considerations.

Emerging prominently within the network is a cluster associated with "coffee by-products," "coffee pulp," "spent coffee grounds," "biochar," and "bioactive compounds." The structural positioning of this cluster—linked to both production and biochemical themes—indicates the consolidation of circular economy and waste valorization research within the coffee sector. Coffee processing generates substantial quantities of organic residues, and recent studies have explored their potential for bioenergy production, soil amendments, nutraceutical extraction, and biochar development (Mussatto *et al.*, 2011; Janissen & Huynh, 2018). This reflects a broader sustainability discourse aimed at minimizing environmental externalities while enhancing economic efficiency across the value chain. The integration of by-product utilization within the conceptual network suggests a transition from linear production models toward more resource-efficient and regenerative production frameworks.

Emerging research also highlights the importance of postharvest technological innovation in strengthening quality preservation and energy efficiency within coffee systems. Controlled-environment drying systems, particularly energy-efficient hot air recirculation technologies, have demonstrated potential to improve dehydration uniformity and reduce postharvest losses while optimizing energy use in parchment coffee processing (Rodríguez Robles *et al.*, 2018). The integration of drying system innovation within sustainability-oriented coffee production reflects a broader transition toward resource-efficient processing infrastructures. Such technological interventions bridge primary production and quality differentiation, reinforcing the multidimensional nature of contemporary coffee research.

Overall, the network topology reveals a clear evolution of coffee production research from narrowly defined agronomic productivity studies toward a multidimensional systems framework. Contemporary scholarship increasingly integrates climate adaptation, genetic resilience, biodiversity conservation, quality optimization, and circular bioeconomy strategies within a single interconnected knowledge landscape. Such thematic convergence aligns with broader trends in agricultural research emphasizing systems thinking and transdisciplinary integration (Perfecto *et al.*, 2019). The high degree of interlinkage among clusters suggests that future research will likely continue to bridge field-level production ecology with postharvest innovation, sustainability governance, and value-chain transformation. This integrative trajectory is critical for ensuring the long-term viability and resilience of global coffee systems under intensifying environmental and socio-economic pressures.

Thematic Evolution and Strategic Positioning of Coffee Production Research

The thematic map (Figure 3) provides a strategic diagram of the intellectual structure of coffee production research by positioning themes according to their centrality (relevance within the field) and density (degree of internal development). Thematic mapping is widely applied in science mapping studies to identify motor, basic, niche, and emerging themes, thereby revealing the maturity and structural organization of a research domain (Cobo *et al.*, 2011; Aria & Cuccurullo, 2017). The configuration observed in this study suggests a field that is both consolidated around core production concerns and simultaneously diversifying into sustainability, biochemical quality, and technological innovation.

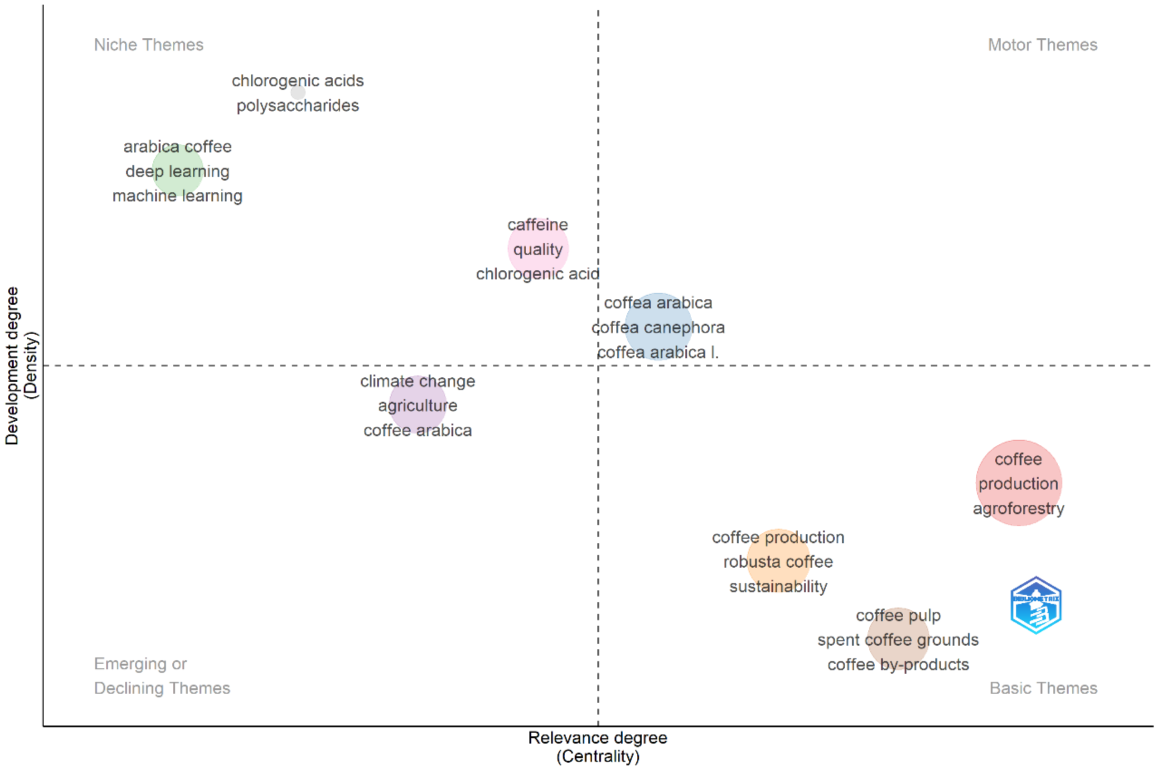

Figure 3: Thematic map of global coffee production research based on keyword co-occurrence analysis (2000–2025).

Motor Themes: Production and Agroforestry

In the upper-right quadrant (high centrality and high density), the cluster dominated by "coffee," "production," and "agroforestry" represents the motor theme of the field. Motor themes are well-developed and central to the research domain, serving as driving forces of scholarly activity (Cobo *et al.*, 2011). The prominence of agroforestry alongside production indicates that contemporary coffee research increasingly situates yield and productivity within ecologically integrated systems. Shade-grown coffee systems have been widely recognized for their capacity to buffer microclimatic extremes, enhance biodiversity, and provide ecosystem services, thereby contributing to climate resilience (Jha *et al.*, 2014; Perfecto *et al.*, 2019). The consolidation of agroforestry within the motor quadrant suggests that sustainability is no longer peripheral but embedded within the mainstream discourse of coffee production.

Basic Themes: Sustainability and By-Product Utilization

The lower-right quadrant (high centrality but lower density) contains "coffee production," "robusta coffee," "sustainability," and clusters associated with "coffee pulp," "spent coffee grounds," and "coffee by-products." Basic themes are important for the field but remain underdeveloped relative to motor themes (Cobo *et al.*, 2011). The positioning of sustainability indicates that while it is central to coffee research, its theoretical and methodological consolidation is still evolving. This aligns with broader agricultural transitions toward sustainable intensification and climate-smart agriculture (Pretty *et al.*, 2018).

The inclusion of by-product-related keywords within this quadrant highlights the growing emphasis on circular economy approaches in the coffee sector. Coffee processing generates substantial organic residues, and increasing research attention has been directed toward valorization strategies such as biochar production, composting, bioenergy conversion, and extraction of bioactive compounds (Mussatto *et al.*, 2011; Janissen & Huynh, 2018). Their classification as basic themes suggests that waste valorization is strategically important but continues to develop in conceptual coherence and technological integration.

Beyond agronomic and ecological considerations, recent scholarship increasingly emphasizes the role of market dynamics, consumer perception, and digital engagement in shaping coffee value chains. Enterprise-level analyses demonstrate that social media engagement significantly influences purchase intention and consumer loyalty within local coffee markets (Madrid *et al.*, 2025b). These findings suggest that digital visibility and branding strategies are becoming integral components of coffee system competitiveness, particularly in emerging regional markets. The integration of marketing analytics into coffee research reflects an expanding systems perspective that incorporates both production ecology and consumer behavior within a unified sustainability framework.

Niche Themes: Biochemical Components and Emerging Technologies

In the upper-left quadrant (high density but low centrality), niche themes include "chlorogenic acids," "polysaccharides," "arabica coffee," and technological terms such as "deep learning" and "machine learning." Niche themes are internally well-developed but peripheral to the broader research network (Cobo *et al.*, 2011). The clustering of biochemical compounds reflects sustained interest in coffee chemistry and functional properties, particularly given coffee's status as a major source of dietary antioxidants and bioactive molecules (Farah, 2012; Ludwig *et al.*, 2014). However, their lower centrality indicates that while quality and chemical profiling are advanced areas, they remain somewhat specialized relative to system-level production research.

The presence of artificial intelligence-related terms suggests the early incorporation of digital technologies into coffee research, including applications in disease detection, yield prediction, and quality grading. Digital agriculture and machine learning are increasingly applied across crop systems (Kamilaris & Prenafeta-Boldú, 2018), and their niche positioning implies a technically developed but still emerging integration within mainstream coffee production studies.

Emerging or Declining Themes: Climate Change and Agricultural Transitions

The lower-left quadrant (low centrality and low density) includes "climate change," "agriculture," and "coffee arabica." Themes in this quadrant are classified as emerging or declining (Cobo *et al.*, 2011). Given the broader literature, it is unlikely that climate change represents a declining topic; rather, its placement may reflect conceptual diffusion across multiple clusters rather than isolation within a single thematic core. Coffee has been consistently identified as highly vulnerable to climate variability, with projections indicating shifts in suitable cultivation areas and increasing disease pressure under warming scenarios (Bunn *et al.*, 2015; DaMatta *et al.*, 2018). The relative dispersion of climate-related terms may indicate that adaptation research is increasingly embedded within agroforestry, sustainability, and genetic resilience themes rather than functioning as an isolated topic.

Structural Interpretation

Overall, the thematic configuration reveals a research field transitioning from commodity-focused agronomic studies toward an integrated socio-ecological systems framework. Production and agroforestry function as the structural backbone of the field, while sustainability and circular economy themes are consolidating as strategic priorities. Biochemical and technological innovations represent specialized but advancing domains, and climate-related concerns are increasingly diffused across interconnected research clusters. Such structural integration is consistent with contemporary agricultural research paradigms emphasizing resilience, biodiversity conservation, and value-chain sustainability (Perfecto *et al.*, 2019; Pretty *et al.*, 2018).

The map therefore reflects a mature yet evolving research landscape in which traditional productivity concerns coexist with emerging priorities in environmental governance, resource efficiency, and technological modernization. This convergence suggests that future coffee research will continue to adopt transdisciplinary approaches linking field-level production ecology, genetic adaptation, digital innovation, and circular bioeconomy strategies to ensure long-term system resilience.

Research Gaps and Future Directions

The thematic and conceptual analyses reveal a dynamic and increasingly interdisciplinary research landscape in coffee production. However, several structural gaps remain evident and represent important directions for future scholarship.

Underrepresentation of Southeast Asia

Despite Southeast Asia being one of the major global coffee-producing regions—particularly for Coffea canephora (Robusta)—the bibliometric patterns suggest comparatively limited scholarly visibility relative to Latin America and parts of Africa. Vietnam and Indonesia are among the world's leading producers, yet research output from these regions appears underrepresented in high-impact indexed literature. This imbalance may reflect disparities in research funding, publication access, or indexing bias toward Global North institutions. Strengthening regional research capacity and enhancing international collaboration in Southeast Asia would provide more geographically balanced insights into climate adaptation, pest dynamics, and sustainable intensification strategies specific to tropical lowland systems. Given that climate vulnerability and production systems vary significantly across agroecological zones (Bunn *et al.*, 2015), greater regional representation is essential for generating context-specific solutions.

Limited Long-Term Field Validation Studies

A second gap concerns the scarcity of long-term, field-based validation of proposed adaptation and sustainability strategies. While numerous studies model climate impacts or evaluate short-term interventions, relatively few longitudinal experiments assess multi-year performance of agroforestry systems, improved cultivars, or soil management practices under variable climatic conditions. Long-term trials are critical for understanding cumulative ecological effects, yield stability, pest pressure dynamics, and soil health trajectories (DaMatta *et al.*, 2018). Without sustained field validation, the scalability and resilience of recommended practices remain uncertain. Future research should prioritize multi-season trials integrating agronomic, ecological, and socio-economic indicators to strengthen the evidence base for policy and farm-level implementation.

Weak Integration of Extension and Farmer-Centered Research

Although smallholders dominate global coffee production, extension-oriented and participatory research frameworks remain comparatively underrepresented in the bibliometric structure. Many studies focus on technical innovations—such as varietal improvement, disease resistance, or quality enhancement—without systematically evaluating adoption pathways, farmer perceptions, or institutional support mechanisms. Given the socio-economic vulnerability of smallholder producers, research that integrates participatory approaches, knowledge co-creation, and training needs assessment is essential to ensure effective technology transfer (Avelino *et al.*, 2015). Bridging the gap between experimental research and extension systems would enhance the practical impact of scientific advancements and support inclusive value-chain transformation.

Despite Southeast Asia being one of the largest global producers of Coffea canephora (Robusta), bibliometric patterns suggest comparatively limited representation in high-impact indexed literature relative to Latin America and parts of Africa. Vietnam and Indonesia rank among the world's top coffee exporters, yet regional research outputs are often underrepresented in mainstream citation databases. Emerging regional studies published in developing-country journals illustrate growing scholarly engagement in areas such as coffee marketing behavior, pricing strategies, and processing innovation (Madrid *et al.*, 2025a; Madrid *et al.*, 2025b; Rodríguez Robles *et al.*, 2018). However, these contributions remain insufficiently integrated into global research syntheses.

This imbalance may reflect disparities in research funding, indexing visibility, and publication access rather than actual research inactivity. Strengthening international collaboration networks and improving indexing inclusion of Southeast Asian journals would enhance geographic balance in coffee scholarship. Given the region's dominance in Robusta production and vulnerability to climate stressors, greater regional representation is essential for developing context-specific adaptation and sustainability strategies.

Economic sustainability at the enterprise level also warrants greater analytical integration. Studies examining pricing strategies and customer satisfaction in emerging coffee markets highlight the importance of aligning value perception with pricing structures to maintain competitiveness (Madrid *et al.*, 2025a). Such enterprise-level analyses remain peripheral in global coffee production discourse yet are critical for translating agronomic gains into viable market returns for producers and entrepreneurs.

Insufficient Integration of Microbiome Research and Productivity Outcomes

Emerging advances in plant–microbiome interactions and soil microbial ecology are reshaping agricultural sciences, yet their integration within coffee production research remains relatively limited. While soil fertility, disease management, and biofertilizer applications appear in scattered clusters, comprehensive investigations linking microbial community dynamics to coffee productivity, resilience, and quality parameters are still nascent. Increasing evidence from other cropping systems demonstrates that plant growth–promoting rhizobacteria (PGPR) and beneficial microbial consortia can enhance nutrient uptake, stress tolerance, and disease suppression (Compant *et al.*, 2010). Integrating microbiome research into coffee systems—particularly under climate stress scenarios—represents a promising frontier that could bridge productivity enhancement with sustainability objectives. Future interdisciplinary research combining molecular ecology, field agronomy, and crop physiology is warranted to advance this domain.

CONCLUSION

This bibliometric analysis provides a comprehensive synthesis of global research trends in coffee production from 2000 to 2025, revealing a field that has evolved from predominantly agronomic yield-focused studies toward a multidimensional systems-oriented framework. Thematic mapping demonstrates that production and agroforestry function as motor themes, while sustainability, circular economy approaches, and species-specific resilience strategies continue to consolidate as strategic priorities. Simultaneously, niche developments in biochemical profiling and digital agriculture indicate ongoing technological diversification within the field.

The temporal growth trajectory highlights intensified research activity driven by climate change concerns, disease outbreaks, and sustainability transitions. Despite this progress, important structural gaps persist, including geographic imbalances in research representation, limited long-term field validation, insufficient integration of extension systems, and underdeveloped microbiome-focused productivity research.

Addressing these gaps will require transdisciplinary collaboration, stronger regional research networks, and integration of ecological, genetic, socio-economic, and technological dimensions. As climate variability intensifies and sustainability governance increasingly shapes global commodity markets, coffee production research must continue to move beyond isolated disciplinary approaches toward holistic, resilience-oriented frameworks.

Strengthening this integrative trajectory will be critical to ensuring the long-term viability, productivity, and sustainability of global coffee systems.

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