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Exploring trends and future perspectives in coffee *terroir* investigation

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A B S T R A C T

Coffee is one of the most widely consumed beverages in the world, and its flavor can be influenced by various factors, from cultivation to preparation. Recent studies have intensified the search for understanding how edaphoclimatic characteristics (climate, relief, temperature, and soil type) influence the final product. Therefore, this study aimed to provide an overview of research trends regarding coffee *terroir*, evaluating keywords, authors, countries, institutions, and journals, as well as presenting the main study areas indexed in the Scopus database from 1998 to 2025. The results indicate that research has increased significantly since 2016, with 2025 recording the highest number of publications over the 27 years evaluated. The main trends have evolved toward the determination of geographical origin through statistical models combined with chemical characterization. Furthermore, a notable increase in studies on *Coffea canephora* reflects its growing strategic relevance for resilience to climate change. The study also identifies a technological asymmetry between Global South producers and Global North consumption centers, highlighting the urgent need for autonomous scientific development in producing regions to promote value-added strategies at the origin.

Keywords: Bibliometric analysis, Coffee origin, Geographical indication, Prospects.

Explorando tendências e perspectivas futuras na investigação do *terroir* do café

R E S U M O

O café é uma das bebidas mais consumidas mundialmente, e seu sabor pode ser influenciado por diversos fatores, desde o cultivo até o preparo. Estudos recentes intensificaram a busca pela compreensão de como as características edafoclimáticas (clima, relevo, temperatura e tipo de solo) influenciam o produto final. Portanto, este estudo teve como objetivo fornecer uma visão geral das tendências de pesquisa sobre o *terroir* do café, avaliando palavras-chave, autores, países, instituições e periódicos, além de apresentar as principais áreas de estudo indexadas na base de dados Scopus de 1998 a 2025. Os resultados indicam que a pesquisa aumentou significativamente a partir de 2016, com 2025 registrando o maior número de publicações ao longo dos 27 anos avaliados. As principais tendências evoluíram para a determinação da origem geográfica por meio de modelos estatísticos combinados com a caracterização química. Além disso, um aumento notável nos estudos sobre *Coffea canephora* reflete sua crescente relevância estratégica para a resiliência às mudanças climáticas. O estudo também identifica uma assimetria tecnológica entre os produtores do Sul Global e os centros de consumo do Norte Global, destacando a necessidade urgente de desenvolvimento científico autônomo nas regiões produtoras para promover estratégias de agregação de valor na origem.

Palavras-chave: Análise bibliométrica; Indicação geográfica; Origem do café; Perspectiva.

Introduction

Coffee is the second most traded commodity and comprises one of the most consumed beverages globally. Its popularity can be explained by its distinctive aroma and flavor, which are essential attributes for consumer acceptance. The quality of coffee is linked to its chemical and physicochemical properties, as well as its sensory aspects (body, sweetness, acidity, and aftertaste) (Gomes et al., 2024).

The coffee tree shows that productivity and quality vary, being largely influenced by where it is grown. These characteristics result from integrating the production system's elements, such as topography, management, soil, climate, and genetic aspects of the plant itself (Silva et al., 2014). The combined effect of these factors results in changes in the specific physicochemical composition and, consequently, in the typical sensory characteristics that are perceived in the coffee drink. Therefore, a system of complex interactions between the techniques practiced by producers and the environmental conditions of production results in products with unique characteristics that can be economically exploited, being defined as *terroir* (Tassew et al., 2021; Scholz et al., 2018).

Terroir has been recognized as an important factor in the quality of the grown products. It is related to the understanding of a particular territory, where different local characteristics provide products with different qualities. When under the influence of these factors, products carry with them all the characteristics inherent in the specific elements of the geographical area, thus promoting their differentiation (Filete et al., 2022). The term "*terroir*" was first used in viticulture to explain the hierarchy of quality wines (Agnoletti et al., 2024). The coffee market has significantly changed the way roasters, consumers, and producers visualize coffee-growing areas. The idea of coffee *terroir* has spread beyond the analysis of large production areas to include smaller ones. A more in-depth study of the characteristics of coffee-growing areas and their relationship to the product has suddenly become important and profitable for both coffee producers and buyers (Smith, 2018).

To better understand how these factors can influence the chemical and sensory characteristics of the coffee and thus promote its differentiation, studies aimed at analyzing the characteristics inherent to the place where the coffee is produced are essential. To analyze the available literature on this subject, bibliometric analysis can be useful in the process of analyzing available research.

Bibliometrics is an interdisciplinary technique based on bibliography, computer science, mathematics, and statistics, and can be used to conduct quantitative statistical analysis of existing literature. Therefore, quantitative analysis of literature using scientific statistical methods can provide researchers with a comprehensive reference of the background and trends in the development of a given subject. Compared to traditional literature reviews, bibliometric methods can provide a more comprehensive view of a field of knowledge based on the available literature, in the sense of deciphering and mapping the cumulative and evolving scientific knowledge of well-established fields, making sense of large volumes of unstructured data (Zhang et al., 2023; Donthu et al., 2021).

In this context, grouping studies published in specialized journals using bibliometric analysis can contribute to a comprehensive assessment of the current state of research into the influence of *terroir* on coffee quality. The number of studies related to coffee *terroir* is limited, so there are many promising areas with untapped potential. Therefore, there is a need to comprehensively and systematically understand the past and present research trends, find research gaps, and propose future strategies to disseminate this knowledge. So, this study aimed to conduct a bibliometric survey of global scientific production involving trends related to coffee *terroir*.

Materials and methods

Data collection

The descriptive and exploratory bibliometric analysis developed in this study (Figure 1) was carried out on the Scopus database (https://www.scopus.com/), due to the greater number of articles available related to the topic, using the following keywords with Boolean operator's "*terroir*" OR "geographical origin" AND "coffee" OR "coffea". The selection of these keywords was informed by preliminary literature

screenings and the identification of high-frequency descriptors within the relevant bibliography.

For the analysis of frequency indicators, the following aspects were evaluated: the chronological distribution of indexed studies from January 1, 1998, to December 31, 2025 (this timeframe was selected based on the earliest indexed records involving coffee *terroir* or geographic origin); the most cited articles; and the primary countries, organizations, and journals. Furthermore, keyword co-occurrence analysis was conducted (Bamel et al., 2020; Cruz-O'Byrne et al., 2020). The results obtained from the database were exported in table form (Microsoft Excel) and analyzed using VOSviewer software (version 1.6.16) and the "Bibliometrix" package from R software (version 4.5.1) (Aria & Cuccurullo, 2017).

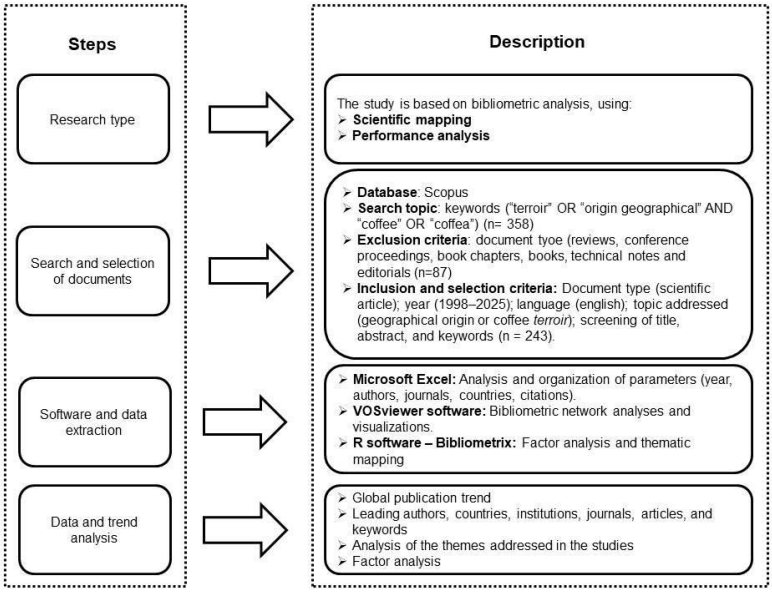

Figure 1. Methodological steps for conducting the bibliometric review on coffee *terroir*.

Results and discussion

Bibliometric analysis

To provide a panoramic view of the scientific production on the topic, Table 1 summarizes the metadata extracted from the Scopus database, covering the period from 1998 to 2025.

Table 1. Main information about data on coffee *terroir* research.

Description	Results
Timespan	1998:2025
Sources (Journals)	119
Documents	243
Annual Growth Rate %	9.16
Document Average Age	7.48
Average citations per document	34.93
Keywords Plus	1775
Author's Keywords	752
Authors	1193
Co-Authors per documents	10.5
International co-authorships %	32.92
Document types (Articles)	243

This section prioritizes the presentation of aggregate metrics and absolute frequencies, establishing the necessary context for the detailed analysis of the analytical categories discussed in the following sections.

Evolution of publications over the years (1998-2025)

In this study, the period was delimited based on information obtained from the Scopus database, from 1998 to 2025, totaling 27 years. A total of 243 original articles were found in this time frame, involving research related to coffee *terroir* (Figure 2). Between 1998 and 2015, 58 articles

were indexed in Scopus, representing 23.86% of the total number of publications. This period can be considered a latency phase in the field of study, characterized by sporadic publications. This trend may be related to the fact that the concept of *terroir* was still incipient or less widespread in coffee production compared to other crops, such as viticulture (Williams et al., 2022).

From 2016 onwards, there has been an increase in the number of publications, especially in 2025 with 32 indexed articles. As the first recorded peak in publications (Figure 2), this behavior coincides with the consolidation of the "Third Wave of Coffee". This movement is characterized by a transition in coffee quality from a commodity to an artisanal and specialty product (Portela et al., 2025; Aydin & Temizkan, 2024), focusing on traceability, brewing methods designed for beverage extraction (Santos et al., 2024), and, fundamentally, the appreciation of the intrinsic characteristics of its origin (Wang et al., 2026; Tassew et al., 2021).

This is possibly due to the intensification of the production and commercialization of Specialty Coffees, which tends to drive the development of research to understand the main factors that may be related to the soil and climate characteristics of a given region (Agnoletti et al., 2024). Furthermore, the observed acceleration suggests a response from the scientific community to the need for adapting coffee production to climate change and the search for new productive frontiers (Filete et al., 2022).

The transition from a residual volume of publications to exponential growth reflects the evolution of *terroir*, moving from a strictly geographic concept to a value-added strategy and a strategic tool for economic resilience.

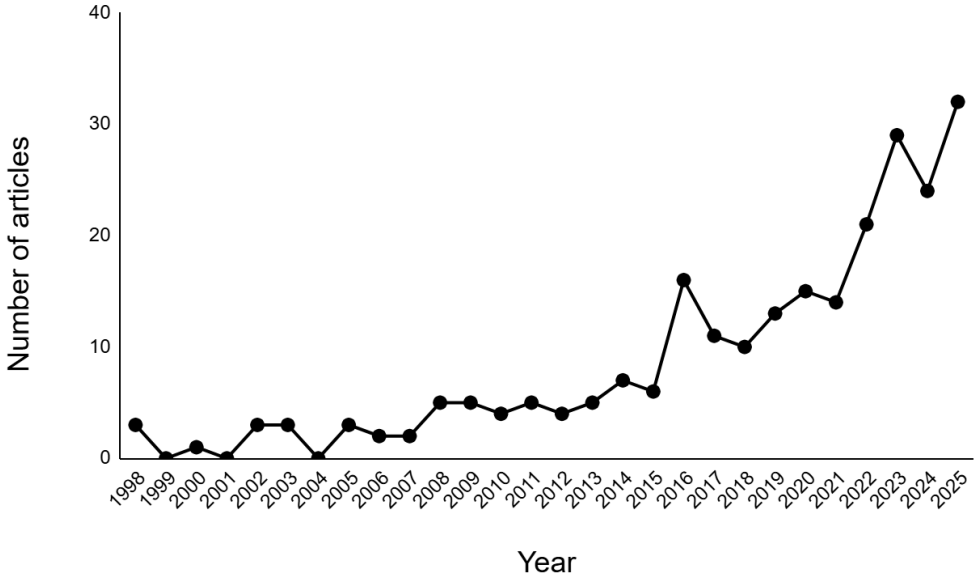

Figure 2. Distribution of coffee *terroir* research publications over 27 years.

Main authors and Countries participation in coffee terroir research

Based on the analysis of the authors of research related to the study of coffee *terroir*, 1193 authors were observed, of which only 15 co-authors fell within the minimum limit of 5 publications. The most productive authors in the field of research, based on Scopus, are shown in Figure 3 and the co-authorship network between authors based on the year the articles were published in Figure 4. Co-authorship analysis relates to the collaboration of two or more authors on a document and is widely used to understand patterns of cooperation within the academic community (Ampese et al., 2021).

Luciano Navarini, head of research and scientific coordination at illycaffè S.p.A., emerges as a central figure in this field, boasting 16 articles and 403 citations. As illustrated in Figure 3, Navarini presents the most extensive longitudinal contribution among the top authors, with consistent research activity dating back to 2010. His long-

standing expertise is particularly evident in studies investigating the influence of geographical origin on coffee's chemical and sensory profiles. For instance, his work employs complementary non-targeted analytical platforms, such as HS-GC-IMS for rapid origin clustering and GC × GC-MS for high-resolution molecular fingerprinting of volatile organic compounds (VOCs) (Bordiga et al., 2025). Such methodological depth is crucial for illycaffè to ensure the authenticity and quality control of green beans sourced from diverse regions, including Brazil, Ethiopia, and Central America.

When looking at the year the articles were published, the authors represented in cluster yellow and green (Figure 3), Michel Rocha Baqueta, Juliana Azevedo Lima Pallone and Patrícia Valderrama, affiliated with Brazilian institutions/organizations (University of Campinas - UNICAMP), are more active and have more recent research on the subject (2023-2025) (Figure 4) (Baqueta et al., 2023; Baqueta et al., 2024; Moraes-Neto et al., 2025). It is important to emphasize that all the works mentioned have *Coffea Canephora* from the Brazilian *terroir* as their protagonist, produced mainly in the state of Espiríto Santo. Paraná, and Rondônia, which in a way brings prospects for scientific advances for this species, given that for many years it was exclusively destined to produce traditional and soluble coffees.

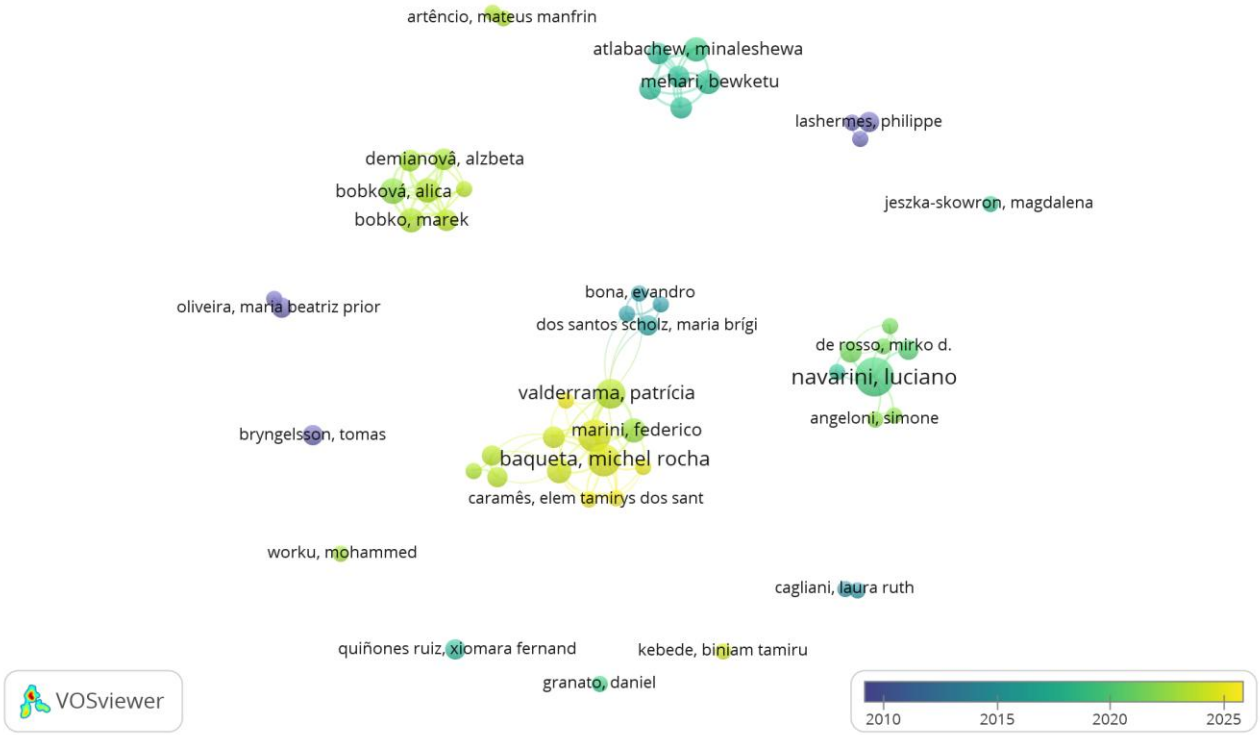

Figure 3. Visualization of the co-authorship network between authors with at least 5 documents about the years of publication.

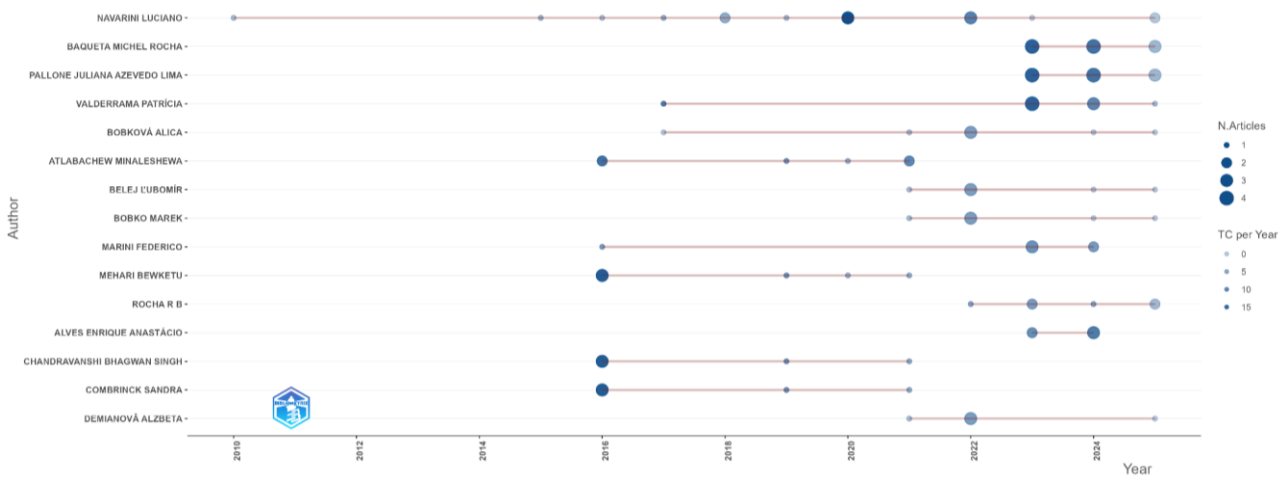

Figure 4. Authors' production over time with the number of articles (N.Articles) and total citations (TC) per year.

The co-authorship analysis between countries consists of evaluating the influence in the field of investigation, as well as the degree of communication between them. The network collaboration between countries with a minimum of 3 publications is shown in Figure 5 and Table 2. Only 22 countries fall within this threshold, and they have been divided into 7 different clusters.

Brazil showed the highest number of collaborations, establishing partnerships with countries across different continents (North America, Asia, and Europe). However, a collaboration network formed exclusively by European countries is clearly visible in the orange cluster. Each node (circle) represents a country, and the union of these circles forms a cluster, which is connected by lines indicating collaboration between them. The thickness and distance between nodes show the strength of collaboration between countries and the similarities among published works (Donthu et al., 2021).

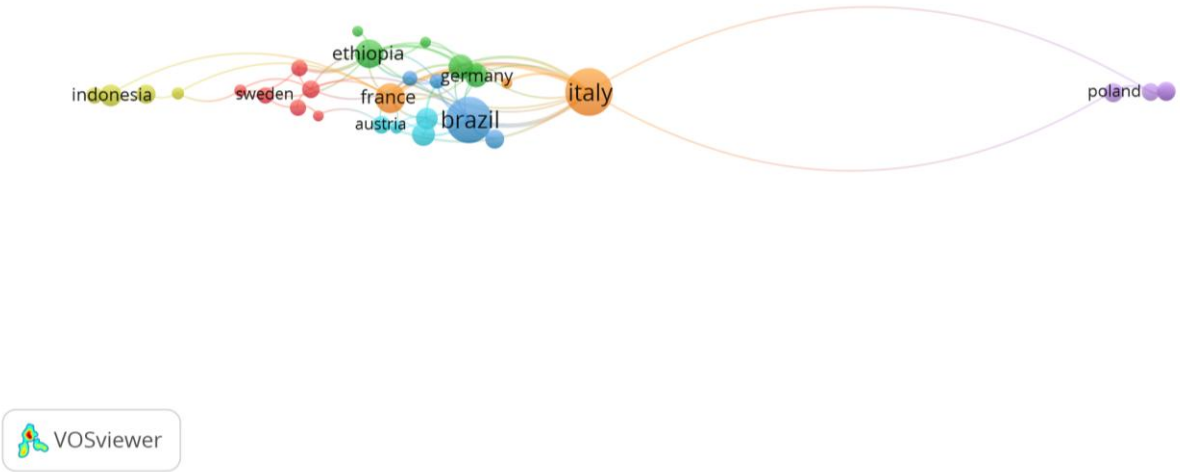

Figure 5. Visualization of the international collaboration network between countries with a minimum of 3 publications.

Table 2. Ranking of countries of origin of publications with total published articles (NP), citations (NC), and average citations per publication (ACPP).

Rank	Country	NP	NC	ACPP
1º	Italy	50	2051	51.51
2º	Brazil	49	1466	56.00
3º	France	21	1159	24.44
4º	Ethiopia	19	529	16.45
5º	United States	14	564	13.89
6º	Portugal	12	594	14.69
7º	Germany	12	392	13.01
8º	Colombia	11	526	9.01
9º	Indonesia	11	188	10.05
10º	Poland	9	499	11.24

It was possible to observe a total of 48 links and total link strength equal to 82 established between all the countries in the collaboration network, with Italy (10), Brazil (10) and Ethiopia (9) standing out in terms of the number of links established with other countries, as well Italy (28), France (22) and Brazil (18) occupying the Top 3 in terms of total link strength. The greater the total link strength, the greater the number of co-authored articles per country.

Despite the relevance of South America in global coffee production, scientific participation is concentrated in a few countries, mainly Brazil and Colombia. Other important South American and Central American producers, such as Peru, Mexico, Honduras, and Guatemala, show incipient or non-existent participation in international collaboration networks (Table 2). This highlights an asymmetry between productive importance and scientific production regarding coffee *terroir*.

It is important to highlight the importance of Ethiopia for coffee studies, as this country is considered the origin and center of genetic diversity of Arabica coffee (*Coffea arabica L.*), as well as the largest producer, exporter and consumer of coffee in Africa and the fifth largest producer in the world. Coffee also plays an important role in the socio-cultural life of the population, for example, the ceremony of drinking coffee after socio-cultural events, such as marriage and the resolution of disputes, is often seen as an endorsement of these events (Worku, 2023).

Furthermore, the significant participation of European countries, such as Italy and France, contrasts with their limited agricultural coffee production, indicating that the technological infrastructure for research in this field is heavily concentrated in scientific centers of the Global North. This scenario suggests that a substantial portion of the scientific knowledge construction regarding coffee *terroir* is conducted outside the producing regions (Global South). In this sense, strengthening technological and scientific investments directly within these regions, while respecting the specific inherent characteristics of each location, is fundamental for sustainable development and the appreciation of the coffee supply chain and, especially, its geographic origin.

Organizations collaboration on coffee terroir research

The main participating organizations in terms of articles, country of origin, number of publications, and citations are illustrated in Table 3. Leading the ranking is the Italian company illycaffè S.p.A., a global leader in high-quality sustainable coffee, responsible for producing a unique blend of 100% Arabica espresso coffee, with beans from 9 of the best Arabica-producing regions in the world, Brazil being the main supplier.

Table 3. Main organizations with articles (NP) and citations (NC) on the study of coffee *terroir*.

Rank	Organization	Country	NP	NC
1º	illycaffè S.p.A	Italy	15	283
2º	Brazilian Agricultural Research Corporation (EMBRAPA)	Brazil	14	225
3º	Federal Technological University of Paraná	Brazil	11	278
4º	State University of Campinas	Brazil	11	115
5º	Tshwane University of Technology	South Africa	10	570
6º	Sapienza University of Rome	Italy	7	131
7º	French Agricultural Research Centre for International Development (CIRAD)	France	5	446
8º	Addis Ababa University	Ethiopia	5	285
9º	French National Research Institute for Sustainable Development (IRD)	France	5	237
10º	University of Gondar	Ethiopia	5	218

One of the studies published in collaboration with the company focused on quantifying quercetin derivatives in roasted *Coffea arabica* from various geographical origins and post-harvest processing methods. This research revealed that Ethiopian roasted coffee exhibited the highest total contents of quercetin derivatives, followed by high levels in Guatemalan and Colombian coffees. Furthermore, the study demonstrated that natural and honey post-harvest processes preserved more of these bioactive compounds compared to the washed method (Santanatoglia et al., 2025). These findings suggest that the interaction between specific coffee origins and processing techniques is a key determinant in increasing flavonoid intake, reinforcing the role of terroir and management in the beverage's functional quality.

With regard to other organizations, Brazilian institutions stand out, such as Brazilian Agricultural Research Corporation (EMBRAPA), the Federal Technological University of Paraná (UTFPR), and the State University of Campinas (UNICAMP) (Table 3). The authors from these three institutions work in partnership, demonstrating a collaborative network in scientific development. One example is the study by Moraes-Neto et al. (2024), which evaluated the authentication of the "Amazonian Robusta" (*Coffea canephora*) Geographical Indication using UV-Vis and NIR spectroscopy combined with chemometrics, involving researchers from UNICAMP and EMBRAPA. Similarly, the work of Baqueta et al. (2024) presented an intelligent digital platform for the authentication and quality inspection of Brazilian indigenous *Coffea canephora* coffees, involving researchers from UNICAMP, EMBRAPA, and UTFPR.

Main journals and research areas of scientific production on coffee terroir

During the study, a total of 119 journals were found with research published on the subject between the years 1998-2025 (Table 1). In general, the identified core journals emphasize the high scientific impact of research on coffee *terroir* (Table 4). The prominence of European-based journals further corroborates the concentration of high-end analytical technology in The Global North, despite coffee production being centered in the Global South.

Leading the ranking, the journals Food Chemistry and Food Research International, with Impact Factors (IF) of 8.8 and 8.1, respectively, concentrate the largest volume of publications, highlighting the focus on the chemical and structural characterization of the product using statistical methods as in studies of Silva et al. (2024), Kim et al. (2025), Belaj et al. (2025) e Tieghi et al. (2024).

Table 4. Main journals found with a minimum of 3 publications and their respective number of publications (NP), number of citations (NC), and impact factor (IF).

Rank	Journal	Country	NP	NC	IF
1º	Food Chemistry	United Kingdom	21	535	8.8
2º	Food Research International	United Kingdom	16	646	8.1
3º	Journal of Agricultural and Food Chemistry	United States	12	1035	6.1
4º	Food Control	Netherlands	10	595	6.0
5º	European Food Research and Technology	Germany	6	382	3.4
6º	Journal of Food Composition and Analysis	United Kingdom	6	209	4.3
7º	Journal of the Science of Food and Agriculture	England	6	197	4.1
8º	Molecules	Switzerland	5	164	4.6
9º	Foods	Switzerland	5	114	5.1
10º	Journal of Mass Spectrometry	United States	5	69	2.0

Furthermore, the Journal of Agricultural and Food Chemistry stands out with the highest number of citations (1,035) (Table 4), indicating its role as a primary reference for the field. This journal follows the same research line as the previously mentioned journals, with the distinction of concentrating pioneering studies, with publications dating back to the early 2000s. This longevity in the field justifies its significant accumulation of citations, consolidating the journal as a seminal reference that established the methodological foundations for the chemical characterization of *terroir*, upon which more recent research is built. Notable examples include the studies by Alonso-Salces et al. (2009), Anderson et al. (2002), and Casal et al. (2000), which are also classified among the most cited articles to be presented in the next section.

The distribution of subject areas categorized by the Scopus database reflects the multidisciplinary nature of coffee *terroir* research (Figure 6).

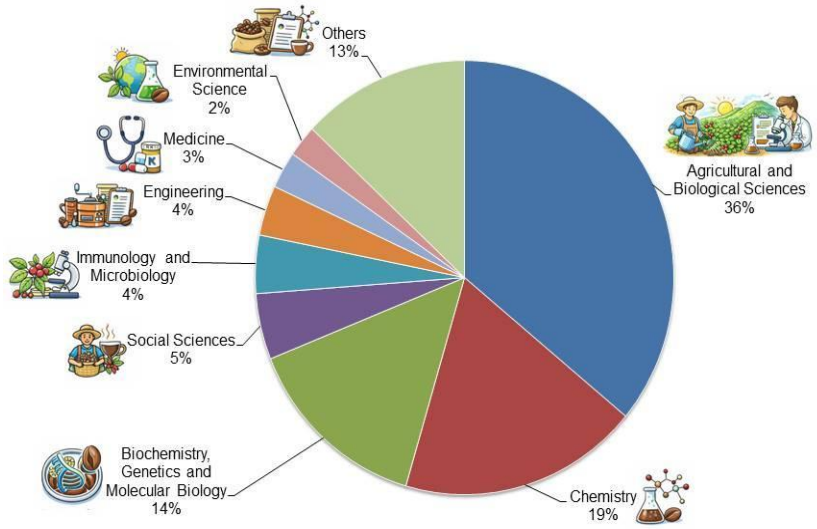

Figure 6. Distribution of scientific production on coffee *terroir* by Scopus subject areas (1998-2025).

The predominance of Agricultural and Biological Sciences (36%) and Chemistry (19%) confirms that *terroir* validation is strongly aligned with field productivity and the chemical characterization of coffee beans, as observed in the

studies by Oliveira et al. (2025), Ledezma et al. (2025) and Kim et al. (2025). In these works, the authors utilize analytical and statistical methods to demonstrate how environmental variables, including soil fertility at the subsurface and relief, influence the final composition and beverage typicity of the coffee.

The area of Biochemistry, Genetics and Molecular Biology (14%) indicates a consolidated research trend toward metabolomics, aimed at identifying chemical markers that can act as a fingerprint of geographic origin (Wei et al., 2012; Dharmawan et al., 2023; Urugo et al., 2024).

Additionally, "Others" encompasses areas such as Multidisciplinary, Chemical Engineering, Pharmacology, Toxicology and Pharmaceutics, Neuroscience, and Economics, Econometrics and Finance, which together represent 13%. Despite the smaller quantity of studies, the Social Sciences area reflects the evolution of the *terroir* concept beyond laboratory analysis and statistical methods, covering aspects related to Geographical Indications (GI), regional development, and the role of coffee producers (Belletti et al., 2018; Rosenberg, 2023; Ashardiono & Trihartono, 2024). This diversity of areas indicates that coffee *terroir* should not be limited strictly to geographical factors, given its complexity that integrates environmental, chemical, and human factors.

Most cited articles

It is generally observed that more recent scientific research tends to have a higher number of citations, which is related to the availability of more recent information (Gonçalves et al., 2019). However, this is not what is observed in the information compiled in Table 5, in which older articles (2000-2012) hold around 80% of the total number of citations in the ranking compared to more recent articles (2018-2019).

The most cited article (247 mentions) (Table 5), published in the journal Food Research International, the authors aimed to understand the wide range and variability of volatile compounds present in individually roasted coffee beans using solid-phase microextraction combined with gas chromatography/mass spectrometry (SPME-GC-MS) of both Arabica and Robusta species from 13 countries (Caporaso et al., 2018).

The authors found that the compounds with the greatest variability were 2,3-butanediol, 3-ethylpyridine and hexanal, compounds known to be potent odorants, and these findings could help standardize the final aroma of coffee. It was also possible to develop classification models based on the geographical origin and type of coffee beans using Linear Discriminant Analysis (LDA) and Neural Networks (NN). It is important to note that this is the first published study of aromatic compounds formed in individual coffee beans using the SPME-GC-MS technique. In addition, the authors emphasize that, in addition to the degree of roasting, the content of volatile compounds can be influenced by factors such as the composition of the raw bean, which is strongly influenced by the species, the geographical origin, the stage of ripeness and the types of processing used throughout the coffee production chain.

The second most cited article (228 citations) was written by Jeszka-Skowron et al. (2016), in which the authors compared the chlorogenic acid and caffeine content in raw Arabica and Robusta coffee extracts, based on their origin and preparation (decaffeinated and steamed coffee beans). It was observed that Robusta coffee extracts contained twice as much caffeine as Arabica extracts, and their content ranged from 3.41% by dry mass in Arabica from Laos or Rwanda to 8.16% in Robusta coffee from Indonesia. The highest concentration of 5-O-caffeoylquinic acid (5-CQA) was obtained in both Ugandan coffees. The decaffeination process does not affect the concentration of this main chlorogenic acid, but steaming the coffee beans with hot water produced a significant decrease in the level of 5-CQA. The extracts from Vietnamese green coffee beans had the highest antioxidant activity in both tests. *Coffea* species and geographical origin, as well as different preparation processes, influence the content of the main compounds in the raw coffee extract, as well as its determined antioxidant activity.

Table 5. Ranking of the most cited articles on coffee *terroir* research in the last 27 years (1998-2024).

Rank	Authors	Title	Journal	Year	IF	NC
1º	Caporaso et al.	Variability of single bean coffee volatile compounds of Arabica and robusta roasted coffees analyzed by SPME-GC-MS	Food Research International	2018	8.1	247
2º	Jeszka-Skowron et al.	Chlorogenic acids, caffeine content and antioxidant properties of green coffee extracts: influence of green coffee bean preparation	European Food Research and Technology	2016	3.4	228
3º	Belletti; Marescotti;Touzard	Geographical Indications, Public Goods, and Sustainable Development: The Roles of Actors' Strategies and Public Policies	World Development	2017	6.9	218
4º	Toledo et al.	Relationship Between the Different Aspects Related to Coffee Quality and Their Volatile Compounds	Comprehensive Reviews in Food Science and Food Safety	2016	14.1	217
5º	Alonso-Salces et al.	Botanical and Geographical Characterization of Green Coffee (*Coffea arabica* and *Coffea canephora*): Chemometric Evaluation of Phenolic and Methylxanthine Contents	Journal of Agricultural and Food Chemistry	2009	6.1	200
6º	Anderson et al.	Chemical Profiling To Differentiate Geographic Growing Origins of Coffee	Journal of Agricultural and Food Chemistry	2002	6.1	174
7º	Giraudo et al.	Determination of the geographical origin of green coffee beans using NIR spectroscopy and multivariate data analysis	Food Control	2019	6.0	151
8º	Risticevic et al.	Headspace solid-phase microextraction–gas chromatographic–time-of-flight mass spectrometric methodology for geographical origin verification of coffee	Analytica Chimica Acta	2008	6.2	139
9º	Wei et al.	^{13}C NMR-Based Metabolomics for the Classification of Green Coffee Beans According to Variety and Origin	Journal of Agricultural and Food Chemistry	2012	6.1	115
10º	Casal et al.	Discriminate Analysis of Roasted Coffee Varieties for Trigonelline, Nicotinic Acid, and Caffeine Content	Journal of Agricultural and Food Chemistry	2000	6.1	121

IF- Impact factor; NC- Number of citations.

Co-occurrence of keywords used by authors

Keyword co-occurrence analysis is a tool capable of evaluating terms/keywords used by authors that occur simultaneously in documents, allowing an understanding of the main subjects covered and research trends (Argumendo-Garcia et al., 2021). Of the 756 keywords, only 33 met the pre-established threshold of at least 5 occurrences (Figure 7).

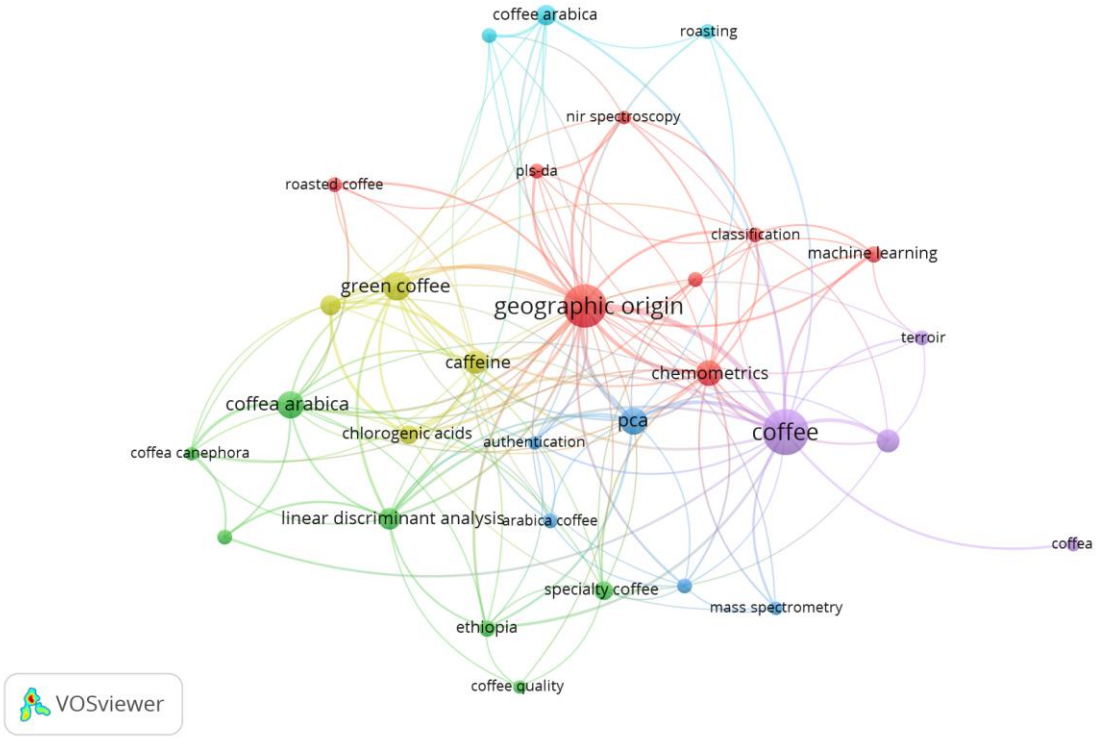

Figure 7. Network of keywords used by authors with a minimum of 5 occurrences in publications concerning coffee *terroir* research. Different colors represent the diversity of thematic clusters found and associated keywords: red (cluster I), green (cluster II), dark blue (cluster III), yellow (cluster IV), purple (cluster V) and light blue (cluster VI).

From this analysis, it's possible to observe the development of research aimed at different areas/techniques or even the use of statistical analyses involving the study of coffee *terroir*. Figure 7 shows the distribution of keywords in the 6 different clusters based on their relevance and similarity, and Table 6 presents the articles related to the terms of each group. According to the terms grouped in cluster I (red), mention should be made of the study carried out by Gines et al. (2025), In the face of the need for reliable methods to verify the geographical origin of single-origin coffee and prevent fraud, they proposed a rapid, cost-effective approach combining energy-dispersive X-ray fluorescence (EDXRF) elemental profiling with chemometric and machine learning techniques to ensure authenticity and traceability.

About cluster II (green), one of the articles related to the keywords in this group is the work by Candeias et al. (2025), which presented an innovative approach to authenticate the geographical origin of instant coffee from southern Bahia using vibrational spectral data combined with Data-Driven Smooth Independent Class Analogy Modeling (DD-SIMCA). MIR spectroscopy allowed for detailed analysis of chemical composition, while the portable NIR spectrometer provided cost-effective in situ capabilities. The proposed methodology offers a robust solution for quality control in the coffee

industry and has potential for broader applications in related areas.

In cluster III (dark blue), according to the terms present in this group, can be related to the article by Urugo et al. (2024) in which the volatile aromatic compounds of raw Arabica coffee beans from different regions of Ethiopia were identified using headspace solid-phase microextraction combined with gas chromatography and mass spectroscopy (HS-SPME-GC-MS) and a chemometric approach. The variations in volatile compounds observed were attributed to differences in coffee growing altitude, annual precipitation, and average daily temperatures. Thus, Ethiopian green Arabica coffee beans from different regions of the country can be differentiated using volatile metabolite profiles, which are highly related to their quality and can be applied as an intellectual property tool to protect and authenticate Ethiopian green beans.

Table 6. Distribution of keywords used by the authors in the clusters and related articles.

Cluster	Color	Keywords	Related articles
I	Red	Chemometrics, classification, coffee beans, geographic origin, machine learning, nir spectroscopy, pls-da and roasted coffee	Giraudo et al. (2019); Gines et al. (2025); Yang et al. (2021)
II	Green	Coffea arabica, coffea canephora, coffee quality, Ethiopia, linear discriminant analysis, pattern recognition and speciality coffee	Candeias et al. (2025); Mehari et al. (2016); Woldegebriel. (2025)
III	Dark blue	Arabica coffee, authentication, mass spectrometry, metabolomics and pca	Dharmawan et al. (2023); Urugo et al. (2024); Voica et al. (2016)
IV	Yellow	Antioxidant activity, caffeine, chlorogenic acids and green coffee	Atlabachew et al. (2021); Demianovâ et al. (2021); Worku et al. (2023)
V	Purple	Coffee, geographical indication and *terroir*	Artêncio et al. (2022); Suksomboon (2023); Zinsli (2023)
VI	Light blue	Coffee arabica, roasting and robusta	Caporaso et al. (2018); Vivo et al. (2023); Górnaś et al. (2016)

Cluster IV (yellow) features keywords such as antioxidant activity caffeine, trigonelline, and chlorogenic acid. As an example of an article related to these terms, we can mention the research carried out by Atlanachew et al. (2021) which used a simple, cheap, and fast method for the simultaneous determination of trigonelline, caffeine, and chlorogenic acid in raw coffee bean extract based on salting-assisted liquid-liquid extraction, with a view to quality control and traceability of the geographical origin of coffee samples.

Based on some of the terms present in cluster V (purple) such as coffee, geographical indication, and *terroir*, we can mention the work of Suksomboon (2023) which conducted a coffee tasting experiment based on brain responses to information about the origin of 40 participants, grouped equally by gender and level of involvement, were collected by electroencephalography to verify: the impact of GI indication on four brain waves (alpha, beta, delta, and theta) and two brain lobes (frontal and temporal); preference; gender and involvement moderations. The results show that women showed differences in power in both hemispheres, more channels/waves, indicating greater sensitivity to the indication of origin. Men showed differences in power in fewer channels/waves. It is observed that involvement has a slight moderating effect when compared to gender. Regarding preference, the analysis of delta and theta waves indicated that men preferred coffee with geographical indication (GI), while women preferred coffee without GI, although most of them indicated the opposite when asked verbally at the end of the tasting session.

Finally, cluster VI (light blue), which grouped terms related to *Coffee arabica* origin, roasting and robusta, relates to the article by de Vivo et al. (2023) which characterized samples of Arabica coffee from Peru, Colombia, and Brazil, Robusta coffee from India, Vietnam, and Uganda, and espresso coffee (EC) with different degrees of roasting (light, medium, and dark) and analyzed them using SHS-GC/MS analysis, with the aim of discriminating the samples according to their geographical origin. Linear discriminant analysis (LDA), performed based on data from the chemical classes of volatile organic compounds (VOCs), correctly identified 97.53% of the samples tested through cross-validation. Thus, the quantitative distribution of volatile compounds proved to be a useful tool for discriminating samples by geographical origin.

Accordingly, the recurrence of spectroscopic techniques used for geographic origin validation is strongly associated with multivariate analysis, highlighting the role of statistics as a structural axis of the field. Despite the diversity of techniques employed, it is observed that studies representing the clusters are concentrated in a few producing countries, indicating that emerging coffee regions remain underrepresented in the keyword occurrence analysis. On the other hand, these characteristics present opportunities for expanding multidisciplinary studies that consider the complexity of the *terroir* system, including environmental, territorial, and productive parameters, as well as the chemical and sensory characteristics of the coffee.

Conclusions

Research related to coffee *terroir* has increased significantly since 2017, with 2025 having the highest number of publications over the 27 years evaluated in this study. Overall, the study provides a comprehensive overview of the growth and development of research related to coffee *terroir*, as well as the forms of interaction and collaboration between authors, countries, and institutions, and can thus assist other researchers in future research aimed at analyzing the influence of geographical origin on coffee quality and authenticity.

Future perspectives point toward the development of studies focused on determining the *terroir* of coffee-producing micro-regions, aiming to identify the influences inherent to the practices adopted by producers, as well as the microorganisms present in the soil and coffee fruit, and how these factors affect the final cup quality. Furthermore, there is a highlighted need for studies relating geographical, environmental, and cultural factors to the edaphic, chemical, functional, and sensory characteristics of coffee, allowing for a broad understanding of regional typicity and *terroir* expression throughout the coffee supply chain.

Additionally, a notable increase was observed in studies conducted on *Coffea canephora* and the use of statistical methods to determine the authenticity, typicity, and geographical origin of coffee. This movement highlights the growing relevance of this species within the context of contemporary coffee production, especially in the face of climate change, as *C. canephora* coffees show greater adaptation to adverse conditions, reinforcing their strategic potential for the sustainability and resilience of coffee production.

As a limitation, the reduced participation of small producers and emerging regions in global scientific production is highlighted. In this context, there is an evident need to increase the representation of these territories by strengthening international collaborations, especially among Global South countries. Although countries like Brazil and Colombia lead physical production, there is still a technological asymmetry compared to consumption centers such as Italy and France. Therefore, fostering autonomous technological and scientific development in these regions is fundamental to reducing dependence on external technologies and promoting value-added strategies at the origin. This approach allows knowledge about *terroir* to be transformed into economic assets and resilience for the local supply chain.

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