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CROP PRODUCTION

Trends and findings in the rooting of conilon coffee: a bibliometric review

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ABSTRACT: The structure of the root system of the conilon coffee tree has improved over the years through propagation, genetic, and agronomic studies in response to demands for improvements in plant development, production, and survival of the species. Scientific research plays an important role in generating technologies and the security of applications. However, there is a need to refine the content generated to analyze discoveries and trends on the subject. Therefore, the present study conduct a bibliometric review and analysis on the main contributions of relevant studies, researchers, organizations, and countries in academic research on the rooting of *Coffea canephora* in the Web of Science (WOS) database. Data from the WOS database published between 1982 and 2021 and systematized in the VOSviewer software showed a set of 92 articles, the majority of which originated in Brazil and France, with the main groups being the Brazilian Agricultural Research Corporation, the Federal University of Viçosa, and CIRAD. The study was divided into five areas: genetic diversity, asexual propagation, nematology, tolerance to water stress, and micropropagation. However, in the context of climate changes and its impact on the production and longevity of Brazilian coffee farming, research focused on the root system has increased significantly, integrating it into lines that explore and integrate topics such as climate risk, water management, drought tolerance, and drip irrigation, including reflections on the performance of coffee agronomy.
Key words: adventitious rhizogenesis, indole butyric acid, seedling quality, propagation.

Tendências e descobertas no enraizamento do café Conilon: uma revisão bibliométrica

RESUMO: A estrutura do sistema radicular do cafeeiro Conilon tem sido aprimorada ao longo dos anos por meio de propagação e estudos genéticos e agronômicos em resposta às demandas por melhorias no desenvolvimento vegetal, na produção e na sobrevivência da espécie. Entende-se que a pesquisa científica desempenha um papel importante na geração de tecnologias e também na segurança das aplicações. Porém, há necessidade de refinar o código gerado para descobrir descobertas e tendências sobre o assunto. Nesse sentido, o presente estudo tem como objetivo realizar uma revisão bibliométrica e análise na base de dados Web of Science (WOS) sobre as principais contribuições de estudos, pesquisadores, organizações e países relevantes nas pesquisas acadêmicas sobre o enraizamento de *Coffea canephora*. Dados da base de dados WOS publicados entre 1982 e 2021 e sistematizados no software VOSviewer, mostraram um conjunto de 92 artigos, em que a maioria teve origem no Brasil e na França, tendo como principais grupos a Empresa Brasileira de Pesquisa Agropecuária, a Universidade Federal de Viçosa e o CIRAD. O estudo está dividido em quatro áreas: diversidade genética, propagação assexuada, nematologia, tolerância ao estresse hídrico e micropropagação, porém, destaca-se que no contexto das mudanças climáticas e seu impacto na produção e longevidade da cafeicultura brasileira, podemos ver o surgimento de pesquisas focadas no sistema radicular, integrando-o em linhas que exploram e integram temas como risco climático, gestão hídrica, tolerância à seca e irrigação por gotejamento, incluindo reflexões sobre o desempenho da agronomia cafeeira.
Palavras-chave: rizogênese adventícia, ácido indol butírico, qualidade de mudas, propagação.

INTRODUCTION

Conilon coffee (*Coffea canephora* Pierre ex Fröher) is a commodity with a great impact on the global market, where Brazil is one of the largest producers and exporters of the species, reaching an average export of 3.97 million bags per month in 2021 (OIC, 2022). However, in the context of climate changes, studies involving spatial analysis and modeling indicate that by 2050, areas suitable for coffee growth will be reduced by up to 60% (GOMES et al., 2020). Therefore, studies aimed to obtain plants that are both resistant and adapted to extreme situations are increasing (DAMATTA et al., 2019).

The development of the root system in terms of length, volume, and architecture is essential for the survival of the conilon coffee tree, and the success of production, especially when dealing with crops subjected to water stress (ALVES et al., 2018). This is the reason why it is widely clarified in the literature that functional characteristics of the root system, such as morphological aspects and

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distribution of roots along the soil profile, are related to the strategies of the plant to exploit water and nutrients, and can be manipulated in different ways, including propagation methods (PARTELLI et al., 2014), irrigation management (BONOMO et al., 2017; SOUZA et al., 2018), and mineral nutrition (FLORES et al., 2016; BARROS et al., 2022).

The root system is also the object of studies regarding genetic improvement in experiments that evaluate the genetic variability of the species (SILVA et al., 2020) or in those that evaluate the behavior of different genotypes in response to drought (PINHEIRO et al., 2005; RAMALHO et al., 2018), as well as the mechanisms of tolerance to *Meloidogyne* spp. (LIMA et al., 2015).

Thus, the existence and improvement of important experiments involving root attributes in the conilon coffee tree in different areas and performances are important. However, important questions remain unanswered: What are the research gaps in studies on the rooting of the conilon coffee tree? Which institutions and countries actively contribute to the production of scientific knowledge?

In this scenario, bibliometric analysis is strategic for providing a comprehensive overview of research on rooting in conilon coffee, especially considering that the accumulated knowledge becomes complex as the number of publications expands at increasing rates and in segmented areas and the existence of an intellectual structure can contribute to new findings in scientific research.

In addition, bibliometric analysis is a validated resource in studies that seek to measure the evolution of publications in various agricultural sectors, exposing in detail the current situation, gaps, and knowledge perspectives, which are important information but not addressed in traditional reviews (VELASCO-MUÑOZ et al., 2018; HUANG et al., 2022; REJEB et al., 2022). Graphic visualization, systematized using this methodology, also enables exploring basic information on the subject, contextualizing how the evidence is connected, what has been researched, and by whom (ROMANELLI et al., 2021).

Given this situation and the understanding of rooting as an important topic in advancing coffee science, the objective of this research was to conduct a bibliometric review and analysis of the Web of Science (WOS) database on the main contributions of studies, researchers, organizations, and relevant countries in academic research on the rooting of *Coffea canephora*, exposing its conceptual evolution and trends.

Analysis methodology

This study used articles indexed in the WOS database, which is considered one of the most complete databases and widely used in the execution of bibliometric analyses and literature reviews of agronomic studies (CAÑAS-GUERRERO et al., 2013; CABRERA et al., 2020; BIRKLE et al., 2020). The articles were selected on January 31, 2022, searching for the terms "*Coffea canephora*" AND "root." The terms were inserted within quotation marks to guarantee greater precision in the records. As the objective of the proposal involved the quantitative analysis of the growth and evolution of the searched terms, a temporal filter was not applied.

A set of 102 articles was downloaded in plain text format, with the "Full record" option for bibliometric analysis, which includes all pieces of authorship information, work title and source, abstract, keywords, cited references, and financing. Next, the titles and abstracts were read to confirm the correspondence of the work with the theme of this experiment, removing duplicated articles or articles from areas that did not evaluate variables related to the roots (for example, post-harvest research and comparison genetics with other species of the Rubiaceae family). The detection of synonyms in the list of keywords was also carried out, and the spelling of the cited references was checked because the name of the same author can be spelled in different ways.

In total, 92 articles remained, organized in .txt format and exported to VOSviewer 1.6.18, a public domain software based on JAVA (ECK et al., 2009), which is a tool to construct and visualize a bibliometric network that characterizes trends in scientific production. Based on this, annual trends in the volume of publications, percentage of publication journals, main research organizations, bibliographic coupling, co-citation networks, and co-authorship networks were analyzed. A global distribution map was constructed using the Biblio-Matrix package in R language (ARIA et al., 2017). An overview of the proposed methodology is presented in figure 1.

Data analysis

Bibliometric analyses revealed 92 articles involving the study of conilon coffee tree roots between 1982 and 2021 (Figure 2). Until 1991, few studies were conducted on *'Coffea canephora'* regarding the evaluation of root characteristics and their reflection on plant growth. According to the WOS database, only one publication was identified per year during this period, until the interval between

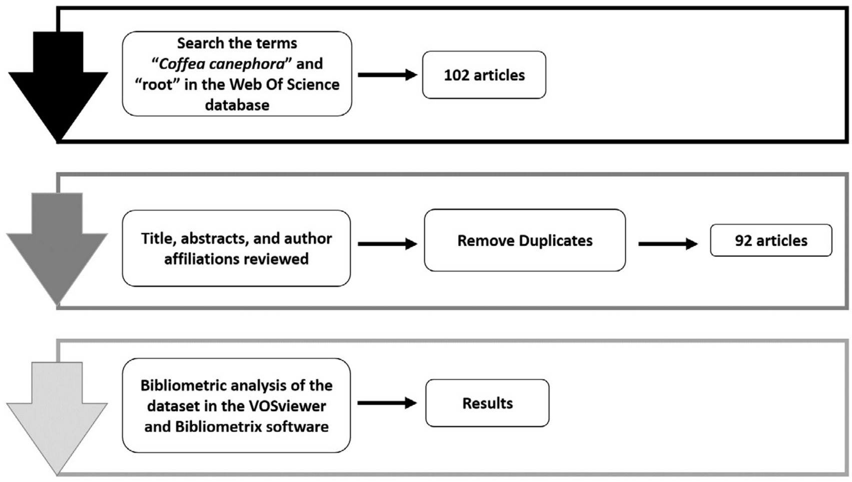

Figure 1 - Flowchart of the methodology used in this study.

1999 and 2001, when investigations into nematode management and in vitro propagation started.

Although, the species *'Coffea canephora*' presents allogamy and, consequently, a high genetic variability (SOUZA et al., 2013; GILLES et al., 2019), the investigation of genotype-dependent responses has focused only on nematodes. The comparison of genotypes has been consolidated since 2005, when differences were identified in the development of the root system of the two clones and, consequently, in drought tolerance (PINHEIRO et al., 2005).

Theme of articles involving rooting in C. canephora and most-cited keywords in the studied period

A total of 605 common keywords were identified in 92 articles using data mining. From these, 100 terms with occurrence in at least two works were selected, shaping a network map with temporary visualization (Figure 3) that shows the evolution of

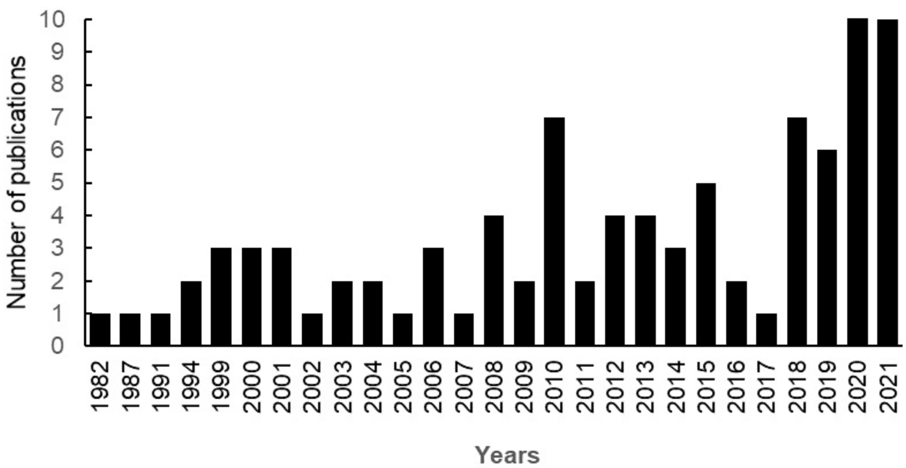

Figure 2 - Number of publications on *Coffea canephora* roots from 1982 to 2021.

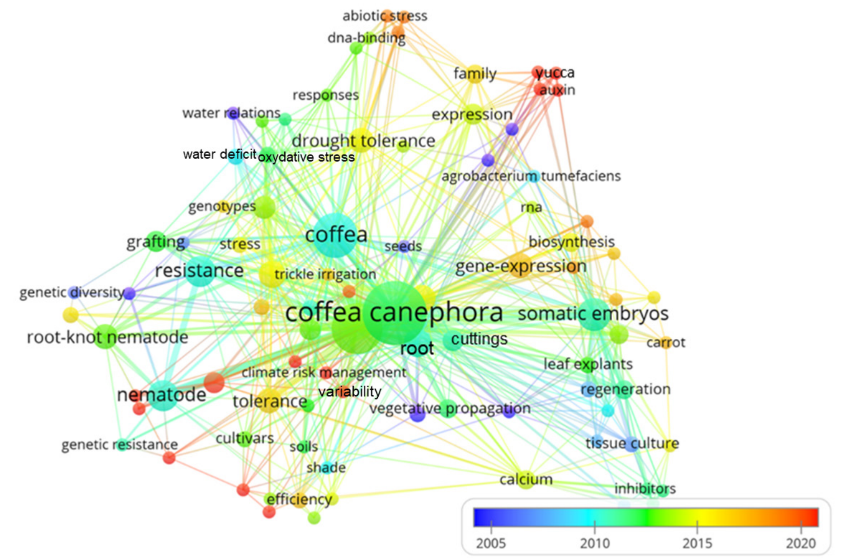

Figure 3 - Overlay visualization map of thematic evolution of articles on rooting in *Coffea canephora*. Different colors indicate the evolution of search keywords based on the average year of publication. The color scale represents the predominant year of a keyword.

the subjects involved in rooting in the conilon coffee tree. Shades of blue indicate that the first surveys of the captured historical series described “genetic diversity, “vegetative propagation,” and “water relations,” evolving to “nematodes,” “tissue culture,” and “graft” (in shades of green), while “drought tolerance,” “auxin,” “abiotic stress,” and “climate risk” had a higher occurrence between 2015 and 2021.

Figure 3 shows that the objective of evaluating the roots of the conilon coffee tree evolved from the characterization of the species and propagation and gained space in matters of interest in genetic improvement, where the expression of attributes that guarantee production is sought, despite adversities, whether of biotic (nematode) or abiotic (drought) origin. This finding corroborates the findings of BERTRAND et al. (2016), who aimed to improve resistance to coffee rust and nematode control and adaptation to drought in coffee trees. This highlighted that modern agriculture tends to deviate from the intense use of pesticides as a solution to problems and that researchers dedicate themselves to searching for resistant plants, integrating the functioning of the genome associated with adaptive responses to combined stresses.

The considerations made by LIMA et al. (2015), who mentioned that genetic improvement of *Coffea canephora* at that time only emphasized the behavior of genotypes concerning drought and rust, and no investigation had been developed around the occurrence of *Meloidogyne* spp, complement this fact. In addition, they showed that ‘Clone 14’ (a drought-resistant genotype) presented chemical and physical barriers in the roots that limit penetration of *Meloidogyne incognita* and *Meloidogyne paranaensis* juveniles and concluded that the integration of drought and nematode resistance mechanisms in the following years should be prioritized mitigating the negative impacts that climate change will have on coffee crops.

Although, most experiments were linked to resistance to nematodes, it was possible to divide the research topics into eight main clusters through the observation of the graph of keywords without temporal visualization (Figure 4). The first group (in red) characterizes the improvement of coffee rooting through in vitro propagation; the second group (in green) relates drought tolerance with responses to abiotic stress, including genotypic and hormonal parameters (auxin), between the green and red clusters. The turquoise blue cluster grouped studies involving gene expression, biosynthesis, and *Agrobacterium tumefaciens*. This last keyword is directly related to transgenic initiatives in *C. canephora*, where researchers have proposed protocols for the direct regeneration of embryos using leaf explants (HATANAKA et al., 1999) and

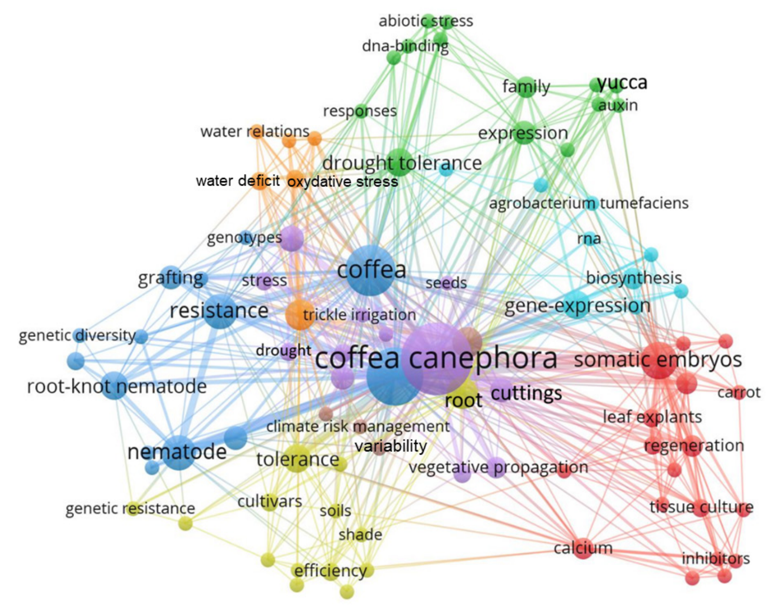

Figure 4 - The network visualization map of the co-occurrence of keywords was repeated at least twice in articles published during the 1987–2021 period. Different colors represent the diversity of thematic clusters and associated keywords.

hypocotyl segments (SRIDEVI, 2010; KUMA et al., 2006) through infection with *Agrobacterium tumefaciens*.

The fourth cluster (in blue) dominated the graphic space and shows a strong connection (expressed by the increased line thickness) of research on root formation and structure through genetic diversity and grafting in the management of nematodes in *Coffea canephora*. The fifth cluster (in yellow), whose main term was “tolerance” (identified by the diameter of the label), grouped studies involving genetic diversity, shading, and water use efficiency.

The sixth cluster (lilac) combined the central word “*Coffea canephora”* with recurrent terms in works that evaluated the relationship between roots and water availability, including drought, propagation methods (cuttings and seeds), and drip irrigation. The orange cluster, which is strongly related to the green cluster, gathered words usually cited in studies involving abiotic stress, where oxidative stress, water relations, and water deficit were measured.

The last cluster (in brown) included the terms “climatic risk,” “management,” and “variability.” The short distance between this cluster and the central words (*Coffea canephora* and root) is remarkable, exposing again that the interest in the root system evolved from focus on the genetic characterization and propagation of plants to studies with the aim of improving the response and survival of coffee plants in adverse environments, especially through the development of resistant crops and diversification in the cultivation pattern, as a path suggested in systematic reviews (DAMATTA et al., 2019; PHAM et al., 2019).

Global distribution of scientific production: countries, institutions and authors

Regarding the geographical distribution of research on conilon coffee, 87 articles (94.5% of publications) originated from five countries (Figure 5). Brazil has the largest number of documents (41 articles), followed by France (20 articles), Vietnam (10 articles), and Costa Rica and India (8 articles each). France’s ranking is interesting as the country is among the main importers of coffee, while Brazil, Vietnam, and Colombia occupy the production ranking (MAPA, 2022) and, therefore, a considerable number of researches in these territories would be foreseeable.

The 92 articles that addressed the rooting of the conilon coffee tree were published in 65 journals, with an average of 1.41 articles per journal. Figure 6A shows that 16 journals had at least two publications on the researched theme with the highest percentage of publications, being

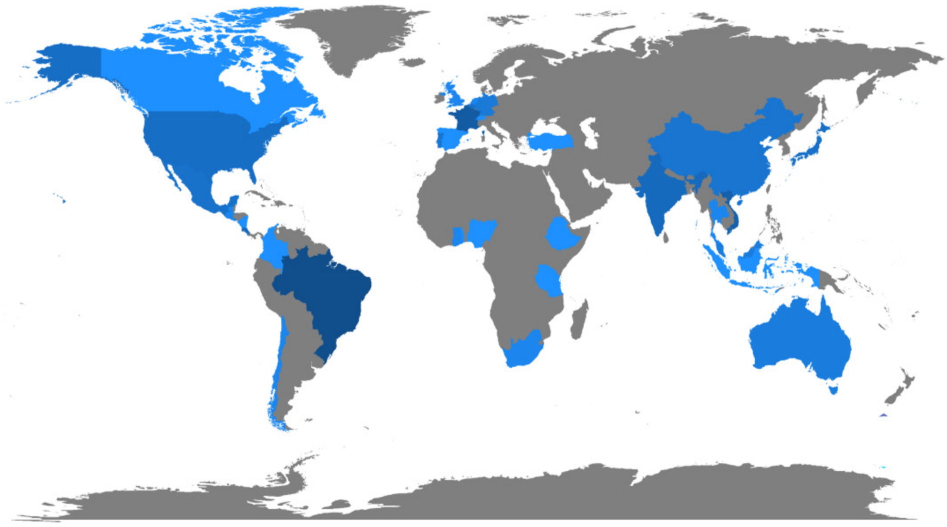

Figure 5 - Global distribution of scientific production involving the rooting of *Coffea canephora* rooting Darker blue shades indicate a greater number of published papers.

"Pesquisa Agropecuária Brasileira," which is a monthly journal edited by Embrapa Technological Information and aims to disseminate the pioneering results produced by researchers from EMBRAPA itself (Empresa Brasileira de Pesquisa Agropecuária) and from other national or international institutions.

The themes published in the "Pesquisa Agropecuária Brasileira" evaluated factors that affect root distribution, citing as a source of variation, the species, irrigation system, and propagation method. In contrast, two other journals with high numbers of publications, "Plant Cell Reports" and "Plant Cell Tissue and Organ Culture," focused on tissue culture, the first of which covers all aspects of plant cell science, plant genetics, and molecular biology, while the second emphasizes technologies and discoveries in plant biology, biotechnology, and molecular controls involved in the morphogenesis of plant cells and tissues.

Figure 6B shows the 16 most relevant journals in studies on *C. canephora* rooting, with a minimum of 20 citations. The two journals with the highest number of citations elaborated on protocols that are still important in the study of coffee tree rooting. The article of PINHEIRO et al. (2005) was published in the "Annals of Botany," in which researchers evaluated water stress in the crop, characterizing the behavior of contrasting genotypes concerning sensitivity to water stress, integrating biometric responses (especially the root system depth and biomass), stomatal conductance, and carbon isotope ratio. Plant Cell Reports have published articles that validated the protocol for micropropagation (HATANAKA et al., 1999; KUMAR et al., 2006; PRIYONO et al., 2010).

Figure 7 depicts the connections between the organizations involved in the research of conilon coffee, where approximately 127 organizations were grouped into five clusters. In this network, CIRAD is centrally arranged, and despite being a French organization, the material produced has links with public research institutions, both the Brazilian Agricultural Research Corporation (Embrapa) and the Capixaba Research Institute, Assistance Technique and Rural Extension of Espírito Santo (INCAPER). Adjacent these institutions is the cluster of universities (in blue) located in Espírito Santo, Minas Gerais, and Rio de Janeiro. The other clusters grouped international institutions that conduct similar lines of research but in a reduced number, and the institutions of Ghent University and the Vietnam Academy of Science and Technology are grouped more distantly from the others (green cluster).

Table 1 shows the influence of research agencies and the predominance of Brazil and France over the institutions involved in the scientific production of coffee rooting. The Federal University of Viçosa led the ranking of citations and, together with the other five Brazilian universities, highlights

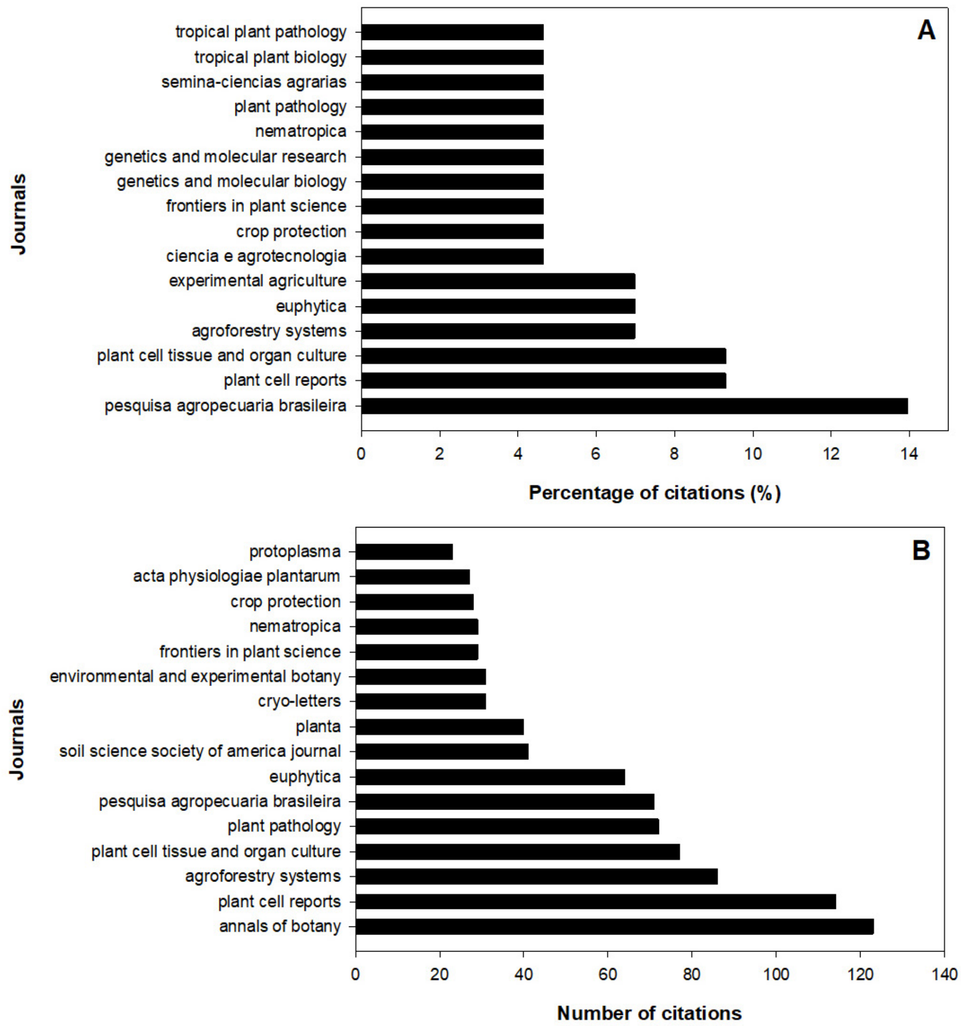

Figure 6 - The 16 most influential scientific journals in the study of conilon coffee tree rooting (A) and percentage of publications on the subject (B).

the importance of integrating teaching and research in the scientific and technological production of coffee. In addition, Embrapa, representing Brazilian research institutions, led scientific production, with the highest number of studies published on coffee rooting, followed by CIRAD, an institution where researcher Benoit Bertrand initiated and deepened investigations of nematodes in the crop and the influence of the root system on resistance to the pathogen, resulting in the institution being recognized as a world reference in the subject.

Figure 8 shows the bibliographic coupling of the 92 documents and the formation of eight large clusters, of which four red-shaded centers represent the documents with the greatest impact on the research of the roots in the conilon coffee tree. The largest grouping refers to studies dedicated to the mechanisms of pathogen resistance, led by NOIR et al. (2003) and BERTRAND et al. (2016).

The second cluster highlighted in the figure above reinforces the relevance of the work developed by PINHEIRO et al. (2005) and its impact on investigating root characteristics in optimizing coffee plantations, given its recurrence in new studies. Also noteworthy in this cluster is the evolution of works by researcher Fábio Luiz Partelli, who explored the root development of ‘conilon’ coffee trees propagated by cuttings and seeds and the effects on productivity

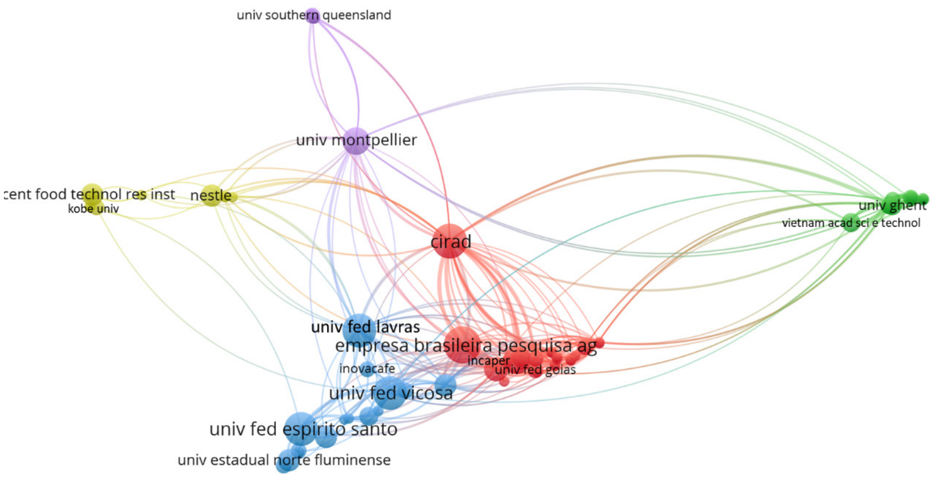

Figure 7 - Co-authorship network for agronomic research on the rooting of conilon coffee trees at the organizational level.

between 2006 and 2014, as well as the contribution of the model of a study proposed by SILVA et al. (2018), who, highlighted that tolerant genotypes tend to increase the concentration of abscisic acid both in the root and in the shoot during exposure to drought when exploring reciprocal grafting between *Coffea canephora* clones with contrasting drought tolerances.

The third experimental trend guided by the bibliographic connection concerns the search for solutions to optimize the root system of the conilon coffee tree through micropropagation technologies. The work of HATANAKA et al. (1991), a pioneer in this type of investigation, is a replicable model with results that help understand new investigations.

The articles selected for this bibliometric study cite their structure, comprising 2,503 authors. Applying the option to select authors with a minimum of five citations, 81 authors remained for displaying the co-citation density. Relationships and relevance among researchers who created certain sub-areas in the intellectual base on the roots of *Coffea canephora*

Table 1 - The 15 organizations relevant in coffee agronomic research in terms of number of articles (NP) and number of citations (NC).

Organization	-------------NP-------------	-------------NC-------------
Empresa Brasileira de Pesquisa Agropecuária	11	78
Cirad	10	179
Universidade Federal de Viçosa	9	218
Universidade Federal de Lavras	9	75
Universidade Federal do Espírito Santo	9	42
Institut de recherche pour le développement	6	169
Universidade de montpellier	6	69
Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural	5	53
Central Food Technological Research Institute	4	96
Nestle	4	67
Empresa de pesquisa agropecuária de Minas Gerais	4	52
Universidade de São Paulo	4	32
Universidade Estadual Norte Fluminense Darcy Ribeiro	4	24
Universidade de Brasília	3	33
Universidade de Ghent	3	27

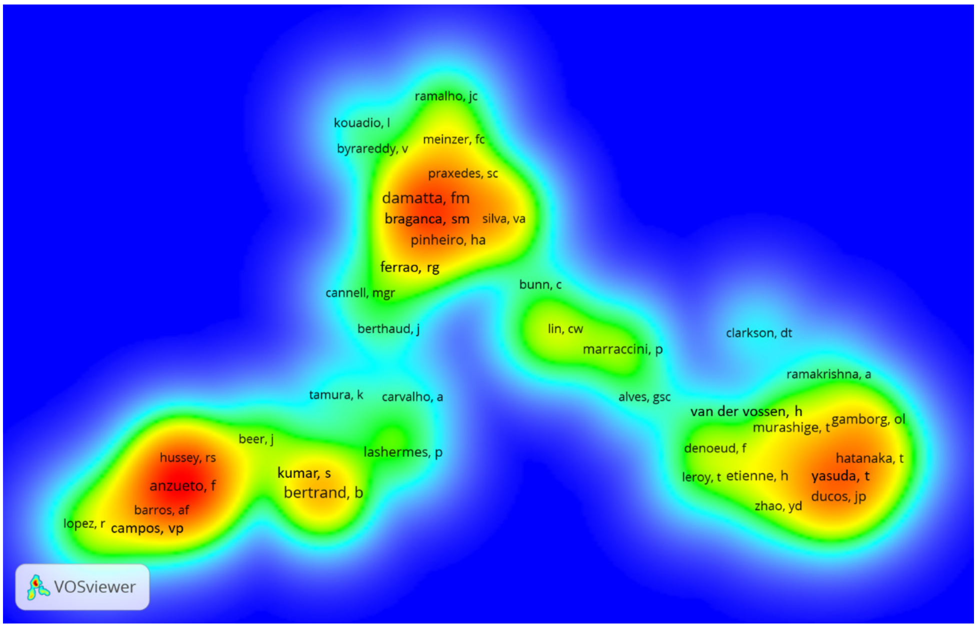

Figure 8 - Scientific map of the bibliographic coupling of works involving the rooting of *Coffea canephora*.

were observed using this analysis, again highlighting the occurrence of authors concentrated in three main clusters (Figure 9).

Figure 9 showed that the central group was mostly Brazilian researchers, mainly from INCAPER (FERRÃO, R. G.; BRAGANÇA, S. M.) and the Universidade Federal de Viçosa (DAMATTA, F. M.; PINHEIRO, H. A.; PRAXEDES, S. C.) who conducted experiments on genetic improvement of clones and stress physiology, respectively. In the cluster on the

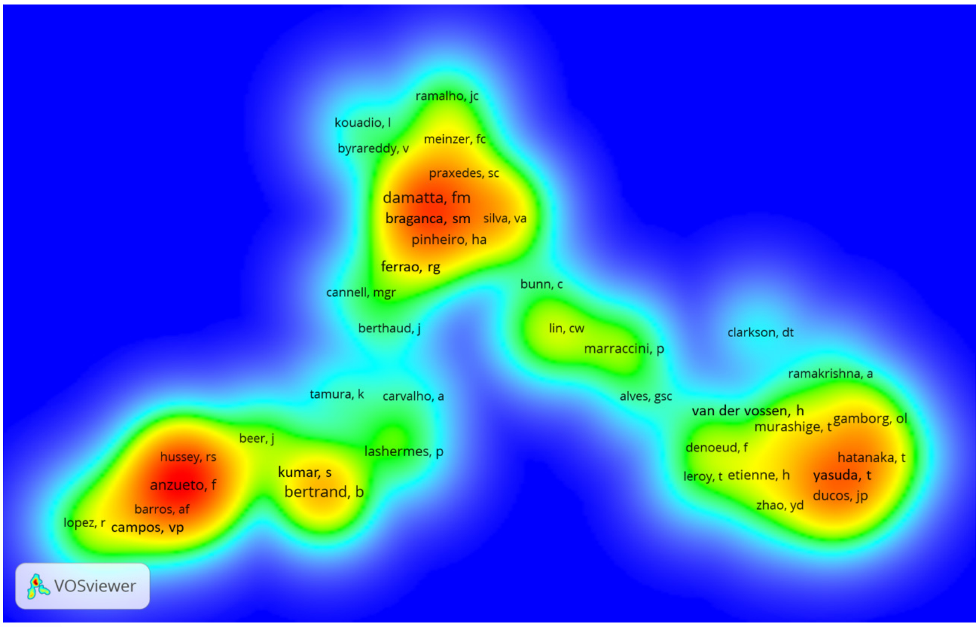

Figure 9 - Scientific map of the cocitation of the most relevant authors in *Coffea canephora* rooting research.

left, Vicente Paulo Campos and Aline Ferreira Barros are the only Brazilian researchers who stand out in coffee plant nematology, which are dominated by professionals from France.

The 92 articles selected for this study were written by 401 authors, and when selecting the occurrence in at least two publications, it resulted in a network of 62, in which only 26 were connected to a set of four clusters (Figure 10). This co-authorship analysis can be complemented with information on the number of documents and citations in table 2, showing that Benoit Bertrand, a CIRAD researcher, has the highest number of publications, with eight articles cited 201 times in papers indexed on the WOS platform (intense red cluster).

Next, Fábio Luiz Partelli, Ph.D. in plant physiology from UENF and Associate Professor at UFES, is the second author in terms of the number of published research, with a total of six articles and 56 citations. The third and fourth places in the number of published works are occupied by Herve Etienne and Pierre Marracini, who conducted joint research in the molecular and micropropagation areas.

CONCLUSION

A bibliometric review of 92 articles published in the WOS database, involving the rooting of "*Coffea canephora*," revealed that the research is concentrated in four main areas: genetic diversity and asexual propagation, nematology, tolerance to water stress, and micropropagation, with this order reflecting the temporal evolution of the research subject over 39 years.

Close to the central terms "*Coffea canephora*" and "root," words such as climate risk, management, tolerance, drought, and drip irrigation were identified, indicating a trend in scientific production where the root system plays a fundamental role in the adaptation and survival of conilon coffee in the face of future constraints.

Brazil stands out among the countries with the highest number of papers in the research area, with Embrapa having the highest number of documents and the Universidade Federal de Viçosa having the highest number of citations in the database. The terms searched in this review had a higher percentage of publications in the journals Pesquisa Agropecuária Brasileira and Plant Cell Reports, with the latter ranking second among the most cited scientific journals.

This bibliometric approach presented itself as a quantitative and updated methodology for predicting trends in the field of conilon coffee rooting research. This provides support for future researchers to gain a comprehensive understanding of the

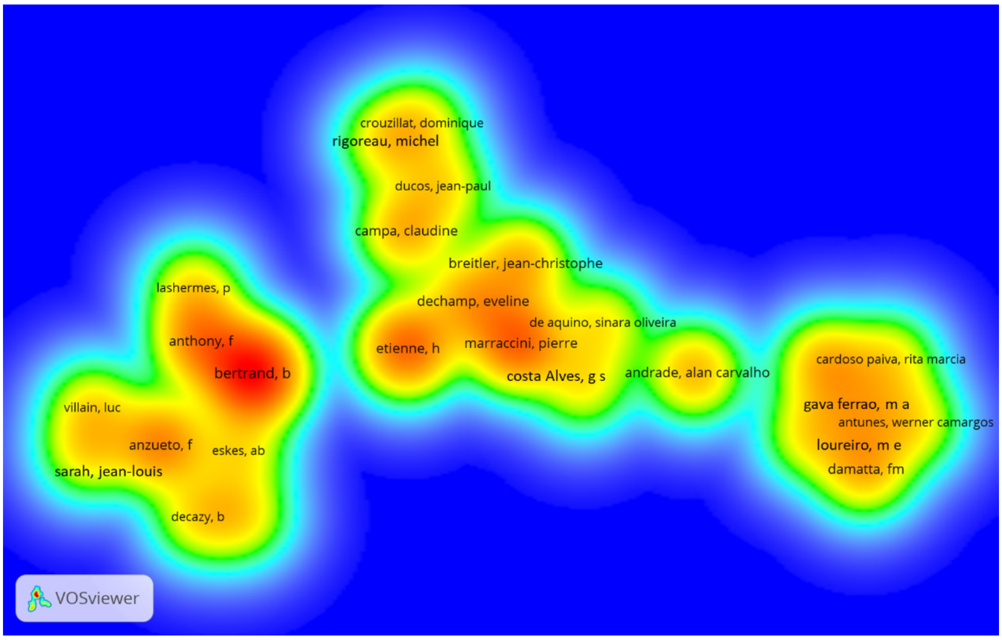

Figure 10 - Scientific map of the co-authorship of research on the rooting of conilon coffee trees.

Table 2 - The top 10 co-authors of conilon rooting research in terms of the number of papers (NP), number of citations (NC), calculated mean of citations per publication (NC/NP), and total link strength (TLS).

Author (a)	-----------NP----------	-----------NC----------	--------NC/NP--------	-----------TLS---------
Benoit Bertrand	8	201	25	14
Fábio Luiz Partelli	6	56	9	3
Heve Etienne	5	102	20	17
Pierre Marraccini	5	66	13	14
Francois Anthony	4	117	29	6
Francisco Anzueto	4	84	21	5
Alan Carvalho Andrade	3	26	9	7
Jean-Christophe Breitler	3	56	19	13
Claudine Campa	3	87	29	9
André Monzoli Covre	3	30	10	3
Fabio Murilo DaMatta	3	154	51	3
Eveline Dechamp	3	56	19	13

subject, identify gaps and opportunities in different lines of research, and potentially include information from other databases, such as SCOPUS, to broaden knowledge on the topic.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS' CONTRIBUTIONS

VPS, LOA and SDA conceived and designed experiments. VPS and SDA performed the data acquisition. LOA and JMSL performed statistical analyses of experimental data. All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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