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Research Article

Analysis of Trends in Caffeine Extraction in the Coffee Industry: A Scientometric Review

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ABSTRACT

This scientometric review analyzes the advances and trends in the development of novel methods for extracting bioactive compounds from coffee residues, with a particular focus on caffeine as a secondary metabolite. Despite the growing attention toward the reuse of agricultural byproducts, residues generated during coffee harvesting and processing, such as pulp, mucilage, parchment, and coffee grounds, have received limited attention in scientific literature. Between 2002 and 2024, the number of studies targeting these byproducts has remained low, despite their high content of bioactive compounds of significant relevance to the food, pharmaceutical, and cosmetic industries. This gap in the literature underscores the need to explore innovative and sustainable approaches for the integral use of coffee residues. Furthermore, investigating these methods represents an opportunity to promote a circular economy, reduce environmental pollution, and diversify industrial applications of coffee byproducts, contributing to the sustainable development of the coffee industry.

Keywords: Bioactive Compounds, Caffeine, Coffee residues, Secondary metabolites, Scientometrics, Bibliometrics.

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INTRODUCTION

Coffee stands out for its distinctive flavor and stimulating effects, making it one of the most widely distributed tropical agricultural products worldwide. Its cultivation and commercialization have a significant economic impact, especially in developing countries in Latin America, Africa, and Asia. In 2023, 166 million bags (60-70 kg) of green coffee were produced globally, with Colombia contributing approximately 11.3 million bags, consolidating itself as the third largest producer and exporter of coffee in the world.[1,2] This positioning of Colombian coffee has been linked to the quality of the product offered, which is evaluated from different perspectives using either physical descriptors (e.g. degree of roasting) or sensory descriptors (fragrance, aroma, bitterness, body, among others), which are influenced by multiple parameters such as geographical denomination, genotype, climate, or variations in primary processing or storage.[3] Increased production and improved processes to obtain a product with environmental seals have prompted the search for alternatives to mitigate the environmental impacts associated with coffee processing, primarily water use and solid waste management (0.9 kg per kg of coffee cherries harvested).[4,5]

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According to the Federación Nacional de Cafeteros de Colombia (FNC), the waste generated by coffee processing can potentially be used as a starting material to produce food for humans and animals, organic fertilizers, biofuels, and in the extraction of bioactive compounds such as polyphenols, carotenoids, and caffeine.[1] Therefore, improving the extraction and recovery processes of these bioactives could open new avenues for processing this raw material and propose innovative alternatives for coffee processing.[6,7]

Specifically, caffeine, an alkaloid of the xanthine family, is widely studied for its stimulant effects and applications in different industries.[8-10] Its chemical structure has been extensively characterized; however, its isolation from plant matrices is complex due to the presence of other molecules that hinder the extraction process.[11] Therefore, research has focused on improving extraction and purification methods to overcome the barriers associated with its isolation.[9] Caffeine is not only a highly valuable bioactive compound but also opens new possibilities for sustainable waste reutilization strategies.

In recent years, Centro Nacional de Investigaciones de Café (Cenicafé) and coffee producer associations have joined forces to promote the transformation of coffee waste into value-added by-products.[12] The combination of traditional methodologies, such as solid-liquid extraction, with emerging techniques like Ultrasound-Assisted Extraction (UAE) exemplifies how research in Colombia is turning environmental and economic challenges into opportunities.[13] These advancements strengthen the competitiveness of the agro-industrial sector and open new opportunities in markets for functional products and bioactive extracts, maximizing the economic and social impact on coffee-growing communities.[14]

Research on advanced extraction techniques, such as aqueous solutions of ionic liquids, has demonstrated their effectiveness in improving yield and selectivity compared to conventional methods.[15] For example, caffeine extraction from guarana has reached a yield close to 9% (dry weight) using ionic liquids based on cations such as imidazolium or pyrrolidinium, combined with anions such as chloride, acetate, or tosylate.[16] This approach not only minimizes the use of hazardous solvents and reduces energy demand but also ensures the recyclability and reuse of ionic liquids, promoting a cleaner and more cost-effective process.

In addition, caffeine can be used to create ionic liquids due to its chemical structure, which contains functional groups suitable for interacting with other compounds and forming solutions with unique properties.[17-19] Studies on the extraction of caffeine indicate that caffeine obtained from biomass, especially guarana seeds, can interact with cations such as imidazolium or pyrrolidinium and anions like chloride or acetate, forming ionic liquids with specific characteristics.[20,21] Recent studies have successfully synthesized, for the first time, a Deep Eutectic Solvent (DES) composed of various components, including caffeine. When protonated, caffeine enables the formation of N-H bonds in the imidazole ring, allowing it to establish strong interactions with other compounds, such as Ethylene Glycol (EG) and Magnesium Chloride ($ZnCl_2$). The results were complemented with computational simulations, which demonstrated that the coordinative interaction between the components provides remarkable structural stability, highlighting the potential of this novel eutectic solvent for industrial applications, particularly in the extraction of sulfur compounds from fossil fuels.[18] Thus, multiple investigations have developed innovative alternatives that combine sustainability, innovation, and efficiency. However, further analysis is required to scale and optimize processes, offering easy-to-operate and economically viable utilization strategies.

This study examines the evolution of research on the extraction of bioactive compounds from coffee, with a focus on caffeine, considering its scientific, economic, and environmental significance. Although there is growing interest in the valorization of coffee by-products within the framework of sustainability and the circular economy, gaps remain in research that offer a comprehensive scientometric analysis. Accordingly, this research seeks to answer the following question: What are the main trends, gaps, and prospects in research on the extraction of bioactive compounds from coffee, with an emphasis on caffeine, based on a scientometric analysis of scientific production between 2002 and 2024?.

Therefore, the objective of this study is to conduct a scientometric mapping to identify the behavior of research production, predominant countries, journals with the greatest impact, authorship trends in scientific publications, as well as knowledge gaps and future opportunities that can drive the economic development of the coffee sector.

METHODOLOGY

This research used computational algorithms in the RStudio environment, which uses specialized tools and packages such as Bibliometrix.[22] This approach enabled systematic searches of the Scopus and Web of Science (WOS) databases, utilizing criteria defined by title, abstract, and keywords, as well as filters by year, document type, and language. The metadata obtained were subjected to preprocessing and normalization, generating CSV or RIS files in data frame type data structures within the R environment, using functions such as readfiles() and convert2df().[23] This procedure facilitated the organization, refinement, and quantitative analysis of bibliographic information.

Database and Search Strategy

This review was conducted in accordance with the guidelines established in two previous studies on the subject. The search was carried out in the Scopus and WoS databases, which are considered the primary and most comprehensive sources of publication metadata and impact indicators.[24,25] The search was conducted using the keywords "extraction," "caffeine," and "coffee" in the title, abstract, and keyword fields. The selection was restricted to articles published since 2002, written in English, and classified as research articles in scientific journals. Studies addressing coffee byproducts, such as beans, pulp, parchment, silverskin, or outer skin, were also included. Selected studies focused on the bioactive properties of coffee extracts, excluding those reporting only total phenolic content without assessing bioactive activities.[26,27]

Study Selection and Data Extraction

The reference list retrieved from the Tree of Science (ToS) platform was managed using a reference organizer to remove duplicates. The ToS algorithm is based on the metaphor of "The Tree of Science", which aims to guide the researcher to think about the contribution to the scientific community (forest) and then its practical application (tree).[28] From this analogy, the algorithm identifies the articles that are located at the root and trunk, using a metric called SPA (Scientific Production Adjustment).[8,24]

The selection process was divided into two phases: initially, articles considered irrelevant were excluded by reviewing their titles and abstracts; subsequently, a comprehensive review of the full texts was conducted to ensure they met the inclusion criteria and contained sufficient information. Data were collected from the primary articles and, when necessary, from supplementary materials. The extracted data included details about the studies (authors, publication year), the types of samples (coffee by-products), the processing techniques (pre-treatment and extraction), and the reported results (such as antioxidant activity).

RESULTS

Scientometric Analysis

Study Eligibility Results

After executing the search queries and identifying the relevant articles, the next step involved downloading the full information of each document, which included the title, authors, abstract, keywords, cross-references, and DOI.

Table 1 illustrates the general process, from the initial search results to the final data analysis. To harmonize the datasets (Scopus and Wos databases), it was necessary to employ a combination of text mining and web scraping techniques. These methods allowed the extraction of the required information and standardization of references across both databases. The subsequent data analysis was divided into two main sections: (i) a traditional scientometric analysis, using advanced techniques as referenced in recent studies, and (ii) the ToS metaphor was applied to delve into the connections between the different research fields, as shown in Figure 1.

The research on caffeine extraction can be visualized as a hierarchical structure enriched by bibliometric analysis, highlighting key trends and thematic areas within this field. At the roots, foundational findings and methodologies such as solvent extraction, Soxhlet, and Ultrasound-Assisted Extraction (UAE) establish the principles of caffeine isolation. These initial studies form the trunk, representing seminal works exploring caffeine extraction across diverse matrices like coffee beans, tea leaves, and agricultural residues. These studies not only set the baseline for assessing efficiency and yield but also provide the methodological foundation for subsequent advancements.

From this trunk rise the three branches, each reflecting distinct research directions. First, food science optimizes extraction methods to enhance sensory properties and recover bioactive compounds. Second, caffeine chemistry delves into molecular aspects, chemical extraction processes, and the analysis of antioxidants and phenolic acids. Lastly, bioactive applications and sustainability investigate the repurposing of coffee by-products, such as grounds and pulp, into sustainable innovations, including biofuels, fertilizers, and biodegradable materials.

Figure 1 illustrates the PRISMA flowchart, which highlights that data preprocessing was a crucial stage in this work. This process was rigorous due to the structural differences between the formats exported by Web of Science (.txt) and Scopus (.csv). Thus, the preprocessing procedures reported by Saurith[26] were implemented, which include the Bibliometrix packages in R-Studio to integrate and clean the obtained metadata. The VOSviewer software allowed bibliometric mapping and visualization; the maps built the association-strength normalization. Fractional counting methodology was used for author networks, which reduces the bias of highly productive authors. The full counting method was also used to analyze the keywords, applying a minimum threshold of 5 for keywords and 3 publications for authors.[26,29] Clustering was performed using the VOS algorithm, configured with a resolution parameter of 1.0, to maintain a balance between the number of clusters generated and their interpretability within the thematic network.[30] Gephi 0.10.1 software and the ForceAtlas2 algorithm were used for the final visualization and spatial analysis of the network (scaling=2.0, gravity=0.1, edge weight influence=1.0, prevent overlap=on, and executed until stabilization).[26,31] Network metrics (degree, betweenness, and modularity class) were calculated in Gephi, and minimum link filters were applied to improve readability. The result was a robust Excel file with structured and refined information, ready for analysis and graph generation.

Scientific production

In Figure 2, the scientific output from two databases, Scopus and WoS, is shown for the period between 2003 and 2024. The graph reflected a peak of publications recorded in 2021, which stands out compared to previous years. This increase is related to the surge in research focused on recovering active compounds from coffee, thereby promoting the circular economy in the coffee industry.

Latin America has implemented policies aimed at mitigating the environmental pollution caused by the coffee industry to transition toward sustainable energy. In this context, coffee industry waste has become a key element in innovation, driving ongoing research to develop viable short-, medium-, and long-term solutions for proper waste management. These residues not only pose a challenge to the sustainability of the coffee sector but also have the potential to negatively impact human health and the environment if not managed efficiently.

Table 1: Search parameters used in both databases.

Parameter	WOS	Scopus
Range	2002 - 2024	
Date	October 29, 2024	
Document Type	Paper, book, chapter, reviews	
Words	TITLE-ABS-KEY (extraction AND caffeine AND coffee) AND PUBYEAR>2002 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))	
Results	496	440
Total (WOS+Scopus)		734

Country Analysis

Table 2 and Figure 3 show that Brazil is one of the Latin American countries most focused on coffee research, particularly on the extraction of caffeine and other bioactive compounds found in both the bean and its residues. This is closely linked to its position as the world's leading coffee producer and exporter, which drives the optimization of its processes within the framework of a circular economy. These studies have been published in various scientific journals, with a higher concentration in high-impact publications classified in the Q1 quartile.

In contrast, Italy and the United States, despite having a lower output compared to Brasil, stand out in terms of appointments. This indicates that the research from these countries has garnered considerable attention within the scientific community. This difference in citations highlights an important distinction between the quantity and quality of research. While Brazil leads in article production, other countries manage to generate research that has a greater impact on the academic community, reflecting a more selective and in-depth approach to researching specific processes. The landscape of caffeine extraction research highlights the active contribution of both coffee-producing and coffee-consuming countries. Coffee-producing nations focus on improving extraction methods to optimize the yield and quality of bioactive compounds, like caffeine. Meanwhile, coffee-consuming countries contribute by developing innovative technologies for more efficient extraction, particularly from coffee by-products

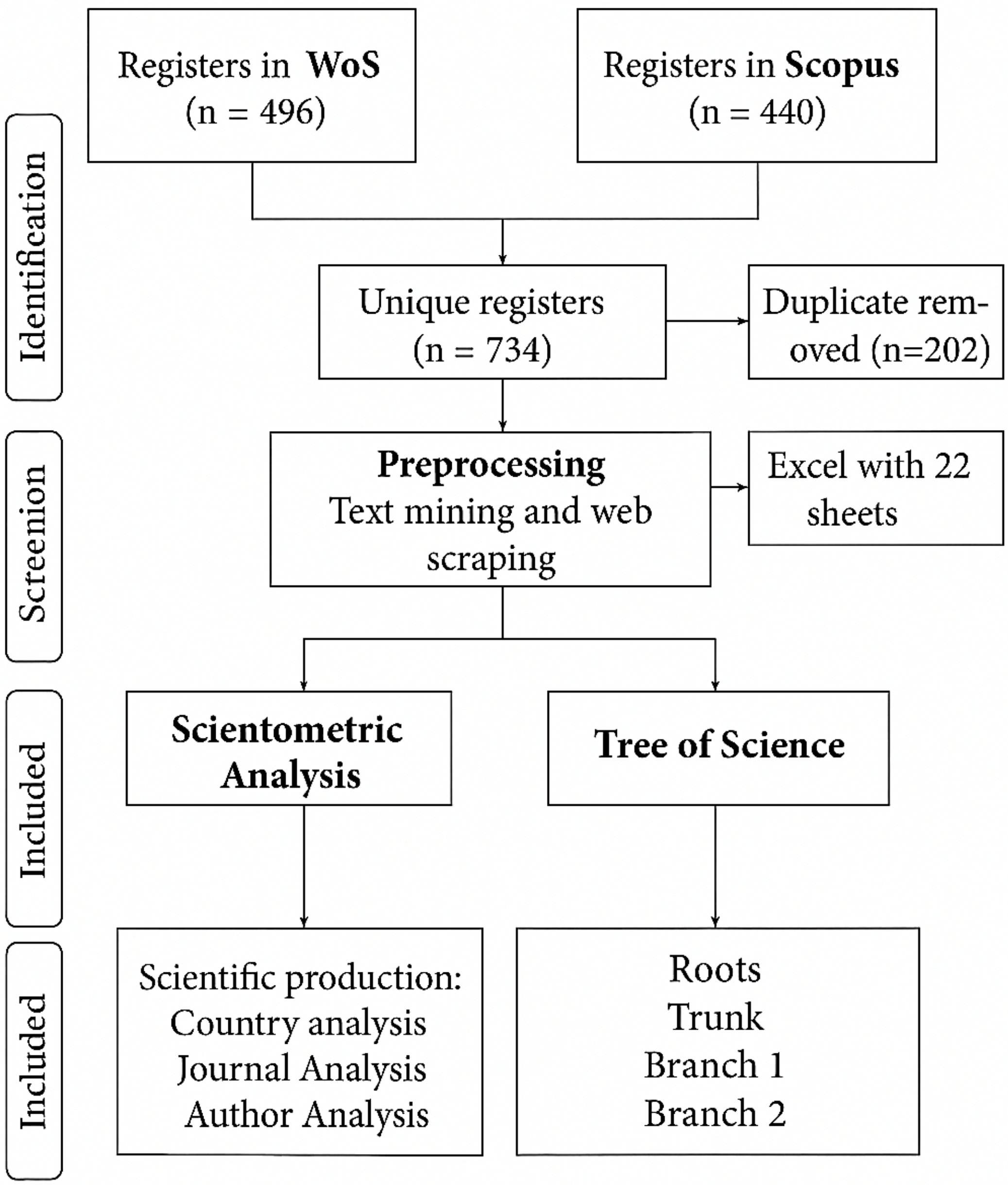

Figure 1: PRISMA diagram for preprocessing data.

like mucilage and pulp, emphasizing sustainability and waste valorization.

As seen in Figure 3, there is a relationship between different countries that share information over time, driven by the need to address global challenges and develop solutions to optimize the extraction processes of caffeine and other bioactive compounds present in coffee residues. These dynamics foster knowledge transfer, establishing cooperation patterns that strengthen research and promote progress toward more efficient and sustainable strategies.

Journal Analysis

Table 3 outlines the leading journals in coffee-related research, highlighting metrics such as publication count, country of origin, impact factor, quartile ranking, and H-index, offering insights into their academic relevance. Most of the journals are in the top quartile (Q1), with five in this category, indicating strong academic impact. Moreover, a comparative analysis revealed that journals classified in the first quartile (Q1) exhibit an average H-index nearly four times higher than those in lower quartiles (Q3-Q4). The Field-Weighted Citation Impact (FWCI) values of Food Chemistry and Journal of Agricultural and Food Chemistry exceed 1.5, indicating that papers published in these outlets are cited 50-70% more than the global average for comparable research areas. This metric, which normalizes citation performance across disciplines, provides a standardized way to assess global impact; consequently, values above 1.0 reflect higher-than-average international influence.[32] These normalized indicators reinforce the leadership of Q1 journals in disseminating high-impact research on coffee and caffeine extraction.[33] Geographically, the journals are predominantly based in countries such as the Netherlands, Switzerland, the United States, and the United Kingdom. This distribution reflects the concentration of advanced research infrastructure and funding in these regions, which facilitates high-quality academic output and drives global collaboration in the field.

In addition to publication and citation trends, this study also analyzed the h-index (a quantitative bibliometric indicator). The cumulative H-index for research on caffeine extraction increased from 9 to 68 between 2005 and 2024. Over the past five years, scientific research on coffee by-products has increased by 6.18%, driven primarily by global interest in sustainability and the valorization of waste generated by the coffee industry.[34] The average Field-Weighted Citation Impact (FWCI) across all documents was 1.43, suggesting that publications in this area are cited approximately 43% more than the global average in similar research fields.[32] This behavior aligns with the high values of the H index and impact factors observed in first-quartile (Q1) journals, such as *Food Chemistry, Foods*, and *Journal of Agricultural and Food Chemistry* (Table 3), whose FWCI values exceed 1.5, demonstrating sustained leadership in the dissemination of high-impact research. Furthermore, an average of 37.4 citations per document suggests not only high visibility but also the consolidation of this line of research as a benchmark in the sustainable valorization of coffee byproducts.[34] This citation level reflects the growing interest of the scientific community in integrating circular economy approaches and applied biotechnology in the study of bioactive compounds.[35,36]

Building upon these quantitative insights, the analysis of the thematic network in caffeine extraction studies (Figure 4) provides a complementary perspective on how research areas are interconnected and evolving. Central journals act as connecting nodes, facilitating the dissemination of knowledge. The temporal evolution of the network shows sustained growth and increased interconnection among studies, reflecting the expansion of research. This information is valuable for researchers seeking to identify emerging areas, establish international collaborations, and optimize their research strategies.

Author Collaboration Network

Table 4 highlights the authors with the highest number of publications on coffee research. The top five authors in the caffeine

Table 2: Country contributions to caffeine extraction research: production, citation, and quartile distribution.

Country	Production		Citation		Q1	Q2	Q3	Q4
	Count percentage		Count percentage					
Brasil	90	11.67%	2735	14.09%	46	20	9	3
Italy	82	10.64%	2111	10.88%	53	12	8	0
USA	48	6.23%	1361	7.01%	27	7	0	0
China	39	5.06%	595	3.07%	25	10	0	2
Germany	32	4.15%	1133	5.84%	23	3	0	0
Spain	31	4.02%	1099	5.66%	23	2	1	0
Portugal	30	3.89%	1064	5.48%	22	2	2	0
India	26	3.37%	577	2.97%	8	9	4	2
Indonesia	26	3.37%	192	0.99%	6	4	12	2
Japan	26	3.37%	768	3.96%	12	1	5	0

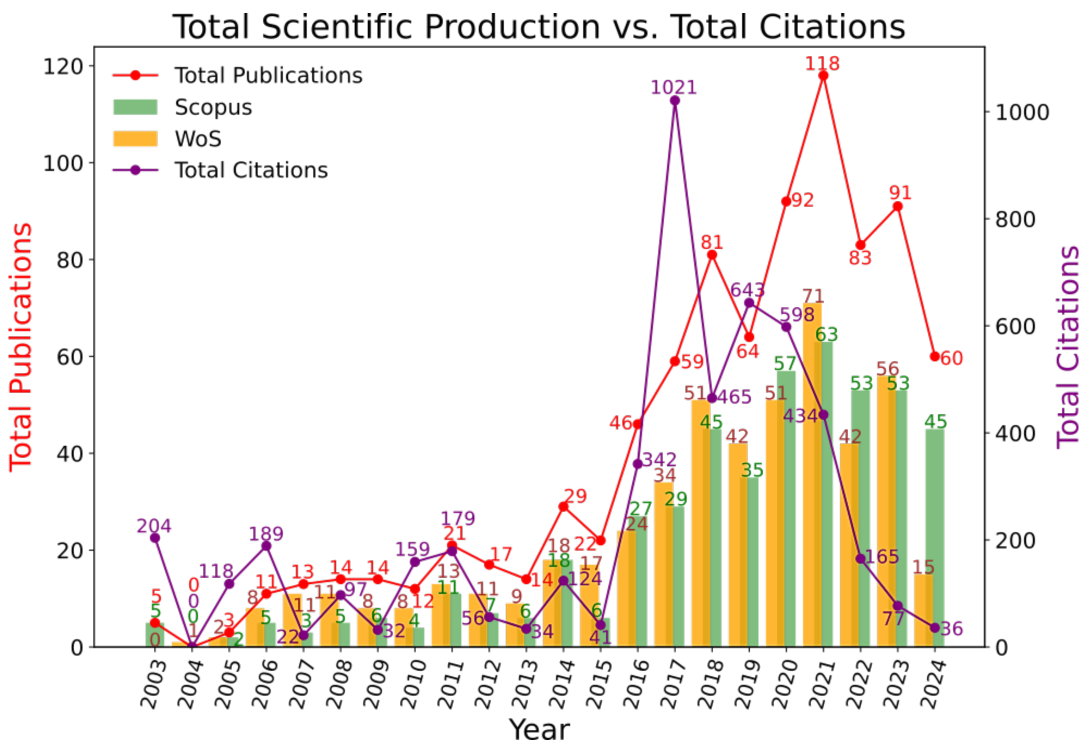

Figure 2: Correlation between total scientific production and citations in coffee bioactive compound extraction.

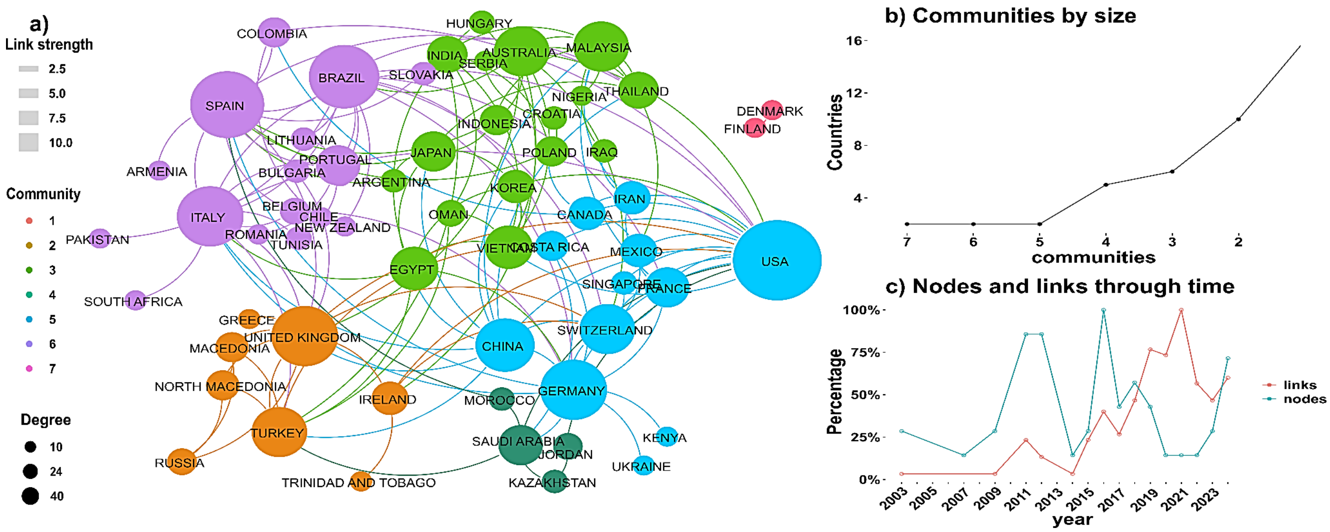

Figure 3: International research network on caffeine extraction. a) journal network, b) communities by size, and c) nodes and links through time.

extraction research had an average h-index of 32 and a median number of citations above 1,000 per author, reflecting sustained scholarly influence and high scientific productivity. For example, Professor Sauro Vittori has authored 14 publications focusing on the chemical analysis of coffee, particularly the role of organic acids and their influence on quality and sensory properties.[37,38]

Co-citation analysis revealed three main clusters dominated by authors from Spain, Brazil, and Colombia, indicating that international collaboration and thematic convergence play a central role in advancing research on bioactive compounds in coffee. Similar approaches integrating author-level indicators and co-citation mapping have recently been successfully applied.[32]

These quantitative findings confirm that author cooperation and citation connectivity are key elements driving the consolidation of this field of research.

Figure 5 represents the collaboration networks between the researchers described in Table 4, where a scientific structure composed of three main communities that share lines of research focused on the extraction of bioactive compounds from coffee is evident. Figure 5b shows the evolution over time of nodes (authors) and links (collaborations). Starting in 2020, the number of links exceeds the number of nodes, meaning there has been greater collaboration and interconnection among researchers in recent years.

The network has a modularity (Q) of 0.67, indicating a well-defined and cohesive structure among the identified communities. The average degree of connection, with a value of 4.3, reflects stable collaborative interaction within the field, while the overall clustering coefficient (0.41) shows a tendency toward collaboration among small groups of interrelated authors. In terms of degree centrality, researchers Oliveira M., Caprioli G., Vittori S., Guerrini L., and Bensassi M. stand out as key nodes, acting as connecting bridges between communities. These indicators complement the visual analysis, confirming the strong structural cohesion of the network and its role in strengthening international scientific cooperation in the extraction of bioactive compounds from coffee.

Tree of Science

Bioactive Potential and Sustainability in Coffee By-product Utilization

Coffee is one of the most studied consumer products worldwide due to its complex chemical composition and the potential for utilizing its by-products in industrial applications. Through a scientometric analysis, the scientific production surrounding coffee can be examined, encompassing key areas such as the composition of bioactive compounds, extraction methods, and sustainability in waste utilization.[39,40] The collaboration network analysis sheds light on the international partnerships and leading research institutions involved in coffee studies, particularly in Latin American coffee-producing regions. It highlights the critical role of research centers in facilitating knowledge transfer and building strategic alliances that drive advancements in understanding the bioactive compounds in coffee and improving extraction processes.

Citation impact analysis further identifies pivotal studies on extraction techniques, especially in the use of coffee grounds. This underscores the importance of methods like solid-liquid ultrasound-assisted extraction and liquid chromatography coupled with mass spectrometry for phytochemical characterization.[39,40] These studies reflect a trend toward the development of precise techniques that enhance the recovery of bioactive compounds without compromising their functional properties, making them valuable for nutraceutical and pharmaceutical applications. In addition to the importance of selecting the appropriate techniques to ensure the quality of the extracts, especially for high-value products.[41,42] In addition, other studies, such as that by Jung SH, have employed response surface methodologies to define optimal conditions for extracting caffeine and chlorogenic acid from coffee grounds.[43] These methodologies enable the achievement of maximum yield with minimal energy and material usage, promoting sustainable extraction.[44,45]

Figure 6 shows a bibliometric analysis of scientific publications on caffeine extraction, allowing the identification of the main trends and research areas in this field. The knowledge network displays the grouping of key concepts into clusters, reflecting the structure of current research. The largest and most densely connected nodes represent central terms such as advanced extraction techniques (ultrasound, microwaves), the bioactive properties of caffeine, and its applications in the nutraceutical and cosmetic industries. The links between nodes suggest the co-occurrence of these terms in studies, indicating the topics that are often addressed together. The clusters were grouped into three main areas: (1) food science, focusing on the optimization of extraction methods, sensory improvement of coffee, and the utilization of bioactive compounds; (2) caffeine chemistry, which studies the molecular aspects and chemical processes of extraction, and (3) bioactive applications and sustainability, exploring the use of coffee waste.

Table 3: Key publications for researchers interested in the coffee industry.

Journals	N.°	%	Country	Impact Factor	Quartile	H. index
Food Chemistry	42	0.3	Netherlands	1.745	Q1	324
Foods	36	0	Switzerland	0.87	Q1	97
Food Research International	31	0.9	Netherlands	1.495	Q1	212
Journal of Agricultural and Food Chemistry	25	0.02	United States	1.114	Q1	345
Journal of Food Engineering	18	0.26	United Kingdom	1.158	Q1	217
Journal of Supercritical Fluids	17	0.89	Netherlands	0.663	Q1	133
Molecules	16	0	Switzerland	0.744	Q1	227
European Food Research and Technology	15	1	Germany	0.674	Q1	122
Journal of Food Process Engineering	14	0.1	United Kingdom	0.588	Q2	58
Journal of the Science of Food and Agriculture	14	0.02	United Kingdom	0.746	Q1	174

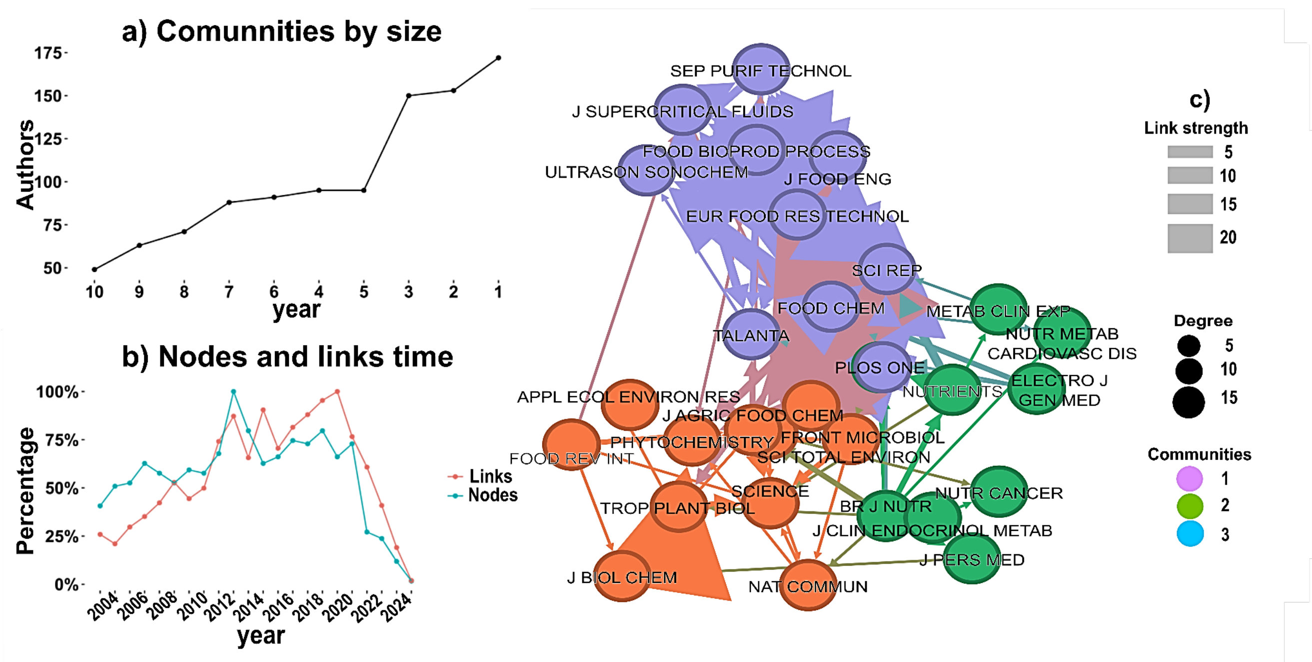

Figure 4: Evolution of the thematic network in studies on caffeine extraction. a) communities by size, b) nodes and links through time and c) journal network.

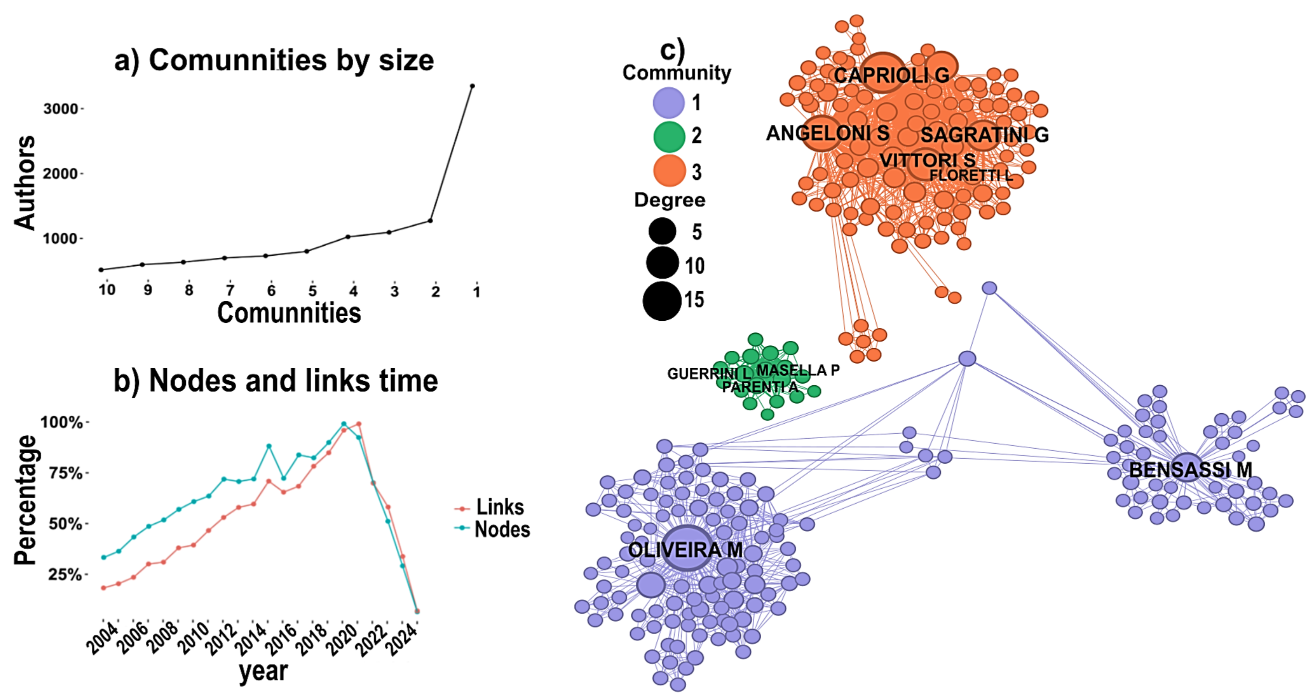

Figure 5: Scientific collaboration network: a) communities grouped by size, b) evolution of nodes and links over time, and c) representation of the authors' network.

The analysis reveals the need for future research to deepen the integration of sustainable technologies, improve the economic viability for coffee producers, and explore new applications for coffee by-products in other sectors. Specifically, the biorefinery concept has not been integrated into the coffee industry, so there is still no comprehensive utilization of coffee biomass through connected processes. This concept aims to offer unprocessed primary products (coffee beans, mucilage, husks, grounds) and value-added products (food for humans and animals, biofuels, chemicals, among others). The biorefinery approach has been demonstrated at laboratory scale by Cenicafé, Colombia, which, through 85 years of research, has developed a model for applying the circular bioeconomy to the waste-free coffee processing process.[1] Aristizábal-Marulanda[46] studied two biorefinery systems using cut coffee stems, within the context of a supply chain that considers the availability of raw materials and the demand for the main products (bioethanol, biomass for electricity). The results show that plants to produce bioethanol could supply up to

40% of the demand for this product in several states of Colombia. Recently, Pérez-Merchán,[47] reported a biorefinery system for which he obtained hemicellulosic liquors rich in monosaccharides (22 ± 1 g/100 g), which, through catalytic processes, generated furfural (50%) and 5-hydroxymethylfurfural (90%), platform chemicals for various environmentally friendly industries.

This biorefinery approach does not consider the amount of residual coffee biomass as an operational problem but rather transforms it into an opportunity for the productive and economic sectors of coffee-producing and trading countries. The generation of new value-added products (with bioactive compounds) could have a positive and differentiating impact, both due to their biological properties and their contribution to sustainability and increased permanent employment opportunities in the field, and not just during the coffee harvest seasons.

Sustainable extraction and innovation in the coffee industry: Advancing circular economy and bioactive compound recovery

The coffee industry seeks to reduce pollution generated during coffee processing through mitigation strategies.[48] In this context, recent research has focused on identifying active compounds present in harvest residues, such as coffee husks, as these are among the most abundant waste products generated and one of the most significant sources of environmental pollution.[49-52] These advancements have led the coffee sector to reevaluate the processing of its byproducts, analyzing aspects ranging from grain fermentation to variations in aroma depending on the coffee variety, with a focus on eco-friendly processes.

Efforts have been made to design equipment that can recover coffee harvest residues. However, there are still two barriers: technological, related to the short-term reduction in moisture content, and operational, because coffee harvesting requires a large amount of labor in a very short period, precluding the treatment of residues such as husks and mucilage, which decompose rapidly. There are some successful cases of integrated use, in which composting systems, bioreactors for energy production, briquette manufacturing, or the use of specialized machinery to minimize water consumption have been implemented. Since research on the scalability of these processes is scarce, technical and economic studies based on biorefinery analyses, using primary technical information and life cycle assessments, have been reported.

Aristizábal-Marulanda[46] studied two biorefineries to produce ethanol and biomass for electricity from coffee stems, through a model that considered the availability of raw materials, product demand, and socioeconomic and geographical conditions in 32 Colombian states. The results show that ethanol biorefineries have a positive impact compared to bio-based power plants. Bioethanol plants could supply up to 40% of the demand for this product in several Colombian states and are limited by their geographical location. Atabani AE[53] presents a quantitative

Table 4: Authorial collaboration patterns in coffee bioactive compound studies.

Authors	Total Publications	Affiliation
Vittori S	14	Università degli Studi di Camerino
Caprioli G	13	Università degli Studi di Camerino: Camerino, Marche, IT
Angeloni S	11	University of Camerino: Camerino, Macerata, IT
Sagratini G	10	University of Camerino
Oliveira M	9	Universidade do Porto Faculdade de Farmácia: Porto, Porto, PT
Angeloni G	8	Università degli Studi di Firenze
Benassi M	8	Universidade Estadual de Londrina: Londrina, PR, BR
Fioretti L	8	Research and Innovation Coffee Hub, Via Emilio Betti 1, 62020 Belforte del Chienti, Italy
Guerrini L	8	Università di Padova
Masella P	8	DAGRI Dipartimento di Scienze e Tecnologie Agrarie, Alimentari Ambientali e Forestali
Parenti A	8	Università di Firenze
Bellumori M	7	University of Florence
Innocenti M	7	Department of Neurofarba, Division of Pharmaceutical and Nutraceutical Sciences, University of Florence, via Ugo Schiff, 6, 50137 Sesto Fiorentino, Italy
Lim L	7	Ontario Veterinary College
Mazzafera P	7	Universidade Estadual de Campinas
Muthiah C	7	Department of Petroleum Technology, Aditya University
Rostagno M	7	Universidade Estadual de Campinas (UNICAMP)
Scarminio I	7	Universidade Estadual de Londrina
Wang X	7	Department of Food Science, University of Guelph

analysis and discussion of the research carried out over the last 20 years on Spent Coffee Grounds (SCG) as a feedstock in circular bioeconomy systems. The literature links SCG with renewable energy, biofuels, and bio-oil, with pyrolysis as a potential valorization approach from a biorefinery.

Banu JR[54] performed the primary techno-economic assessment and life cycle analysis of the SCG biorefinery, comparing it with a single-phase biorefinery under operating conditions for small-scale SCG collection. The authors explain different process routes, effective bioconversion, and recovery of different value-added products, which allowed for a viable economic balance. Likewise, the concept of circular economy promotes the management and valorization of SCG, reducing greenhouse gas emissions through a low-carbon economy, addressing some global environmental problems. SCG biorefineries present successful results on a small scale; however, the viability of industrial-scale production, where an integral environmental and techno-economic analysis is addressed, is lacking.

In Brazil, Ribeiro TC[55] studied the valorization of coffee husks to produce carbon nanofibers through fungal bioprocesses. This study offers a promising avenue for the development of a cost-effective and sustainable energy storage solution, presenting cleaner and more environmentally friendly energy technology. Lourenço VA[56] used waste generated in coffee farms together with pig waste for hydrogen production. Pig waste positively influenced the process stability due to its buffering capacity derived from the high ammonium (NH_4) content, generating scenarios for hydrogen production on coffee and pig farms, through co-digestion.

Hu S presents a comprehensive review of the effect of extraction methods (conventional and alternative) on the recovery of bioactive compounds from coffee pulp (caffeine, polyphenols) to identify the most appropriate techniques for the valorization of coffee pulp as a functional ingredient, with a focus on technology transfer and economic and environmental sustainability. The bioactive compounds obtained from Coffee Pulp (CP) have demonstrated antioxidant, anti-inflammatory, anti-aging, antimicrobial, and hepatoprotective activities, among others. Techniques such as Deep Eutectic Solvent (DES) extraction, supramolecular solvent (SUPRAS) extraction, and supercritical fluid extraction (SFE) are projected as candidates to overcome the disadvantages of conventional solvent extraction methods.[57]

Other extraction techniques, such as Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), or Pressurized Fluid Extraction (PEF), are alternatives to conventional methods due to their high sustainability, efficiency, safety, and reproducibility, for application in the food industry. Finally, the challenges for scaling these technologies to the

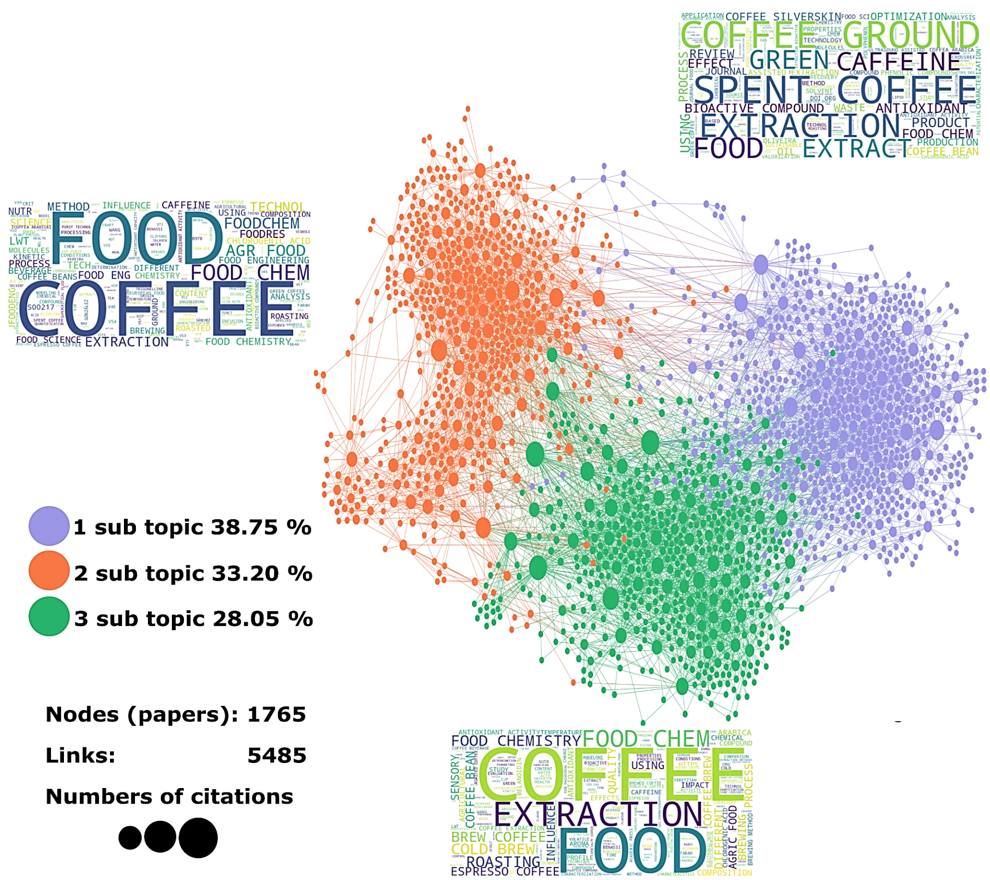

Figure 6: Visualization of information related to caffeine extraction, highlighting the networks and nodes that represent the main research topics in this field.

industrial sector include energy consumption, the transfer of scientific knowledge, costs associated with equipment and high-pressure handling, and the training of operating staff.

The integration of digital technologies and artificial intelligence tools also represents a promising avenue for optimizing extraction parameters and predicting the yield of bioactive compounds from coffee byproducts. Recent applications of machine learning in precision agriculture and plant monitoring have demonstrated their potential to improve process automation and sustainability.[58-60] Incorporating these computational approaches could strengthen decision-making and scalability within biorefinery systems, contributing to the coffee industry's circular economy model.

CONCLUSION

The research focused on the extraction of bioactive compounds (antioxidants and caffeine) from coffee byproducts. Advances in extraction processes have contributed to a circular economy model, with an emphasis on the reuse of coffee waste for the generation of both new products (added value) and energy.

Advances in caffeine recovery have led to more efficient and environmentally friendly methods, such as ultrasound-assisted extraction, microwave extraction, and cold extraction technologies, which help reduce energy consumption while preserving bioactive compounds. Despite these advances, there are still areas that require improvement, particularly to achieve sustainable and efficient caffeine extraction.

Scientometric analysis shows that little progress has been made in the simultaneous or sequential combination of various extraction techniques. Further exploration of these combinations will address challenges related to scaling these technologies to the industrial sector, including energy consumption, waste stabilization, scientific knowledge transfer, operating costs, and other issues.

The scientometric review addressed the importance of integrating the biorefinery concept into the coffee industry at a pilot or industrial scale. This biorefinery approach provides a prospective vision for future work, including scalability and technology transfer components to the industrial sector, which would open new markets for coffee processing byproducts.

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ABBREVIATIONS

CP: Coffee Pulp; **CSV:** file format used for data export from Scopus; **DES:** Deep Eutectic Solvent; **DOI:** Digital Object Identifier; **EG:** Ethylene Glycol; **FNC:** Federación Nacional de Cafeteros de Colombia; **FWCI:** Field-Weighted Citation Impact; **H-index:** Quantitative bibliometric indicator; **MAE:** Microwave-Assisted Extraction; **PEF:** Pressurized Fluid Extraction; **Q:** Modularity; Q1, Q2, Q3, **Q4:** quartile ranking of journals; **RH:** Running Head/Title; **RIS:** file format used for data export; **SCG:** Spent Coffee Grounds; **SPA:** Scientific Production Adjustment; **SUPRAS:** Supramolecular solvent extraction; **ToS:** Tree of Science; **UAE:** Ultrasound-Assisted Extraction; SFE: supercritical fluid extraction; WOS / **WoS:** Web of Science; **$ZnCl_2$:** Magnesium chloride used in the synthesis of a DES.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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