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Research Trend in the Valorization of *Persea americana*: A Bibliometric Analysis of Bioactive Compounds, Extraction Technologies, and Applications (2005–2024)

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Research Trend in the Valorization of *Persea americana*: A Bibliometric Analysis of Bioactive Compounds, Extraction Technologies, and Applications (2005–2024)

Anibal Alviz-Meza[1], Segundo Rojas-Flores[2], Ángel Darío González-Delgado[1]*

[1] Nanomaterials and Computer Aided Process Engineering Research Group (NIPAC), Chemical Engineering Department, Universidad de Cartagena, Colombia

[2] Institutos y Centros de Investigación, Universidad Cesar Vallejo, Peru

***Corresponding author:** agonzalezd1@unicartagena.edu.co; aalvizm1@unicartagena.edu.co

This study, from a bibliometric perspective, analyzes, quantifies, and visualizes scientific research on bioactive compounds of *Persea americana*, extraction methods, and applications from 2005 to 2024, using Scopus data. The Biblioshiny software in RStudio was used to categorize and evaluate contributions by authors, countries, institutions, and journals. Furthermore, their collaborative networks were mapped with VOSviewer. The bibliometric analysis of 1311 articles reveals a swift expansion in research, primarily driven by regulatory pressures advocating circular-economy practices and diversification within the avocado industry. The majority of scholarly work is concentrated in Mexico, Brazil, and the United States, which together account for over 40% of research output. The focus of studies has transitioned from fundamental compositional analysis and conventional extraction methods to more sustainable extraction techniques and omics-based approaches that augment the value of each avocado component. The spectrum of technologies and applications increasingly aims at models that promote the comprehensive utilization of *Persea americana*. Emerging research domains include functional packaging, lipidomic traceability, and the development of zero-waste biorefineries. These trends offer a strategic framework for stakeholders to transition from individual product processing to integrated biorefineries, underpinned by policies that encourage waste valorization and facilitate the commercialization of sustainable avocado bioproducts.

Keywords: *Persea americana*, bioactive compounds, extraction technologies, Scopus, bibliometrix, VOSviewer.

Introduction

In the current global context, the development of cleaner generations of active compounds, energy sources, and materials across various industrial sectors is a common concern. This trend continues to drive research into the circular economy, green chemistry, and sustainability initiatives. Research on valorizing waste has gained momentum, particularly in the agricultural and industrial sectors. This is exemplified by *Persea americana*, a fruit rich in phenolic compounds, fatty acids, and other bioactive substances, and is used in pharmaceuticals, cosmetics, food, biofuels, and other related industries (Aguilar-Vasquez et al., 2024). Likewise, innovation and technological advancements in the extraction of these biocompounds are experiencing exponential growth, driven by the diverse processes involved in the sustainable use of avocado peel, seed, and pulp (Alviz-Meza and González-Delgado, 2025).

The emergence of the bioeconomy concept has also led to the proposal of multiple biorefineries to valorize agricultural and industrial waste. The case of avocado has not been immune to this trend, as the integral use of its biomass requires multi-product processes to enhance process flexibility and increase investor appeal. In this context, the pulp and seeds of the avocado contain oil-rich fatty acids that are valuable to the food and cosmetics industries (Charles et al., 2022). The peels and seeds are sources of antioxidant and anti-inflammatory compounds that support the production of nutraceutical and pharmaceutical products (Rodríguez-Martínez et al., 2021). In the energy sector, organic avocado waste is anaerobically fermented to produce biogas, while the extracted oils are converted into biodiesel via transesterification (Ginting et al., 2020). Regarding materials of biological origin, polysaccharides from waste are used to manufacture biodegradable plastics, and avocado fibers are used to develop sustainable packaging (Merino et al., 2021). Alternatively, organic waste is composted to obtain fertilizer or processed into animal feed (Nyakang'i et al., 2023). All of these refined products require specific extraction technologies that respond to the characteristics of the precursor avocado biomass. For example, avocado seeds and peels utilize microwave-assisted extraction to extract flavonoids and phenolic acids, whereas ohmic-assisted extraction is employed for avocado leaves (Páramos et al., 2020; Zbikowska et al., 2024).

On the other hand, the bibliometric perspective aims to enable the scientific community to identify new hotbeds of innovation within a defined observation window (Donthu et al., 2021). Zakaria et al. (2022) conducted one of the first analyses of *Persea americana*, revealing emerging themes related to medicinal properties, post-harvest control, and the use of agro-industrial by-products. Aguilar-Vásquez et al. (2024) employed a co-occurrence approach to demonstrate the comprehensive transformation of avocado under biorefinery schemes, highlighting bioactive compounds and their corresponding extraction methods. For their part, Alviz-Meza and González-Delgado (2025) examined the evolution of bioeconomy models and computational simulation in the avocado industry, highlighting the role of software such as Aspen Plus and ArcGIS in the design of sustainable processes. Finally, Nazir et al. (2023) focused their bibliometric analysis on the use of avocado starch for biofilm production, highlighting opportunities to enhance its functional properties. However, none of these studies have addressed, in an integrated and longitudinal manner (2005–2024), the scientific trends in the bioactive compounds of each avocado fraction, their extraction technologies, and their emerging applications from a comprehensive bibliometric perspective. This study aims to retrieve original articles indexed in Scopus and to use RStudio for bibliometric data mining. At the same time, VOSviewer is used to analyze the co-occurrence of collaborations. This article examines the annual evolution of publications, identifies the most-cited authors and articles, and determines the most productive journals. It also highlights the leading institutions and countries in the field and concludes with an analysis of thematic trends between 2005 and 2024.

This work is structured as follows: Section 2 details the design of the bibliometric study and discusses its limitations. Section 3 presents the results, including trends in annual article production, the most-cited authors and their collaborations, cited articles, journals with the highest publication counts, institutional networks, and leading countries. Section 4 explores emerging trends in *Persea americana* biocompounds, extraction methods, and applications. Finally, Section 5 summarizes the main conclusions.

Methods

Study design

This study used bibliometric analysis, a tool commonly used to map research in fuzzy scientific fields. Scientometric bibliometry uses mathematics and statistics to quantify scientific activity and its temporal evolution (Donthu et al., 2021). Typically, bibliometric analyses are multidisciplinary, providing a quantitative view of a field of study. They use metrics and knowledge graphs to map the scientific evolution in a specific field, providing objective evidence.

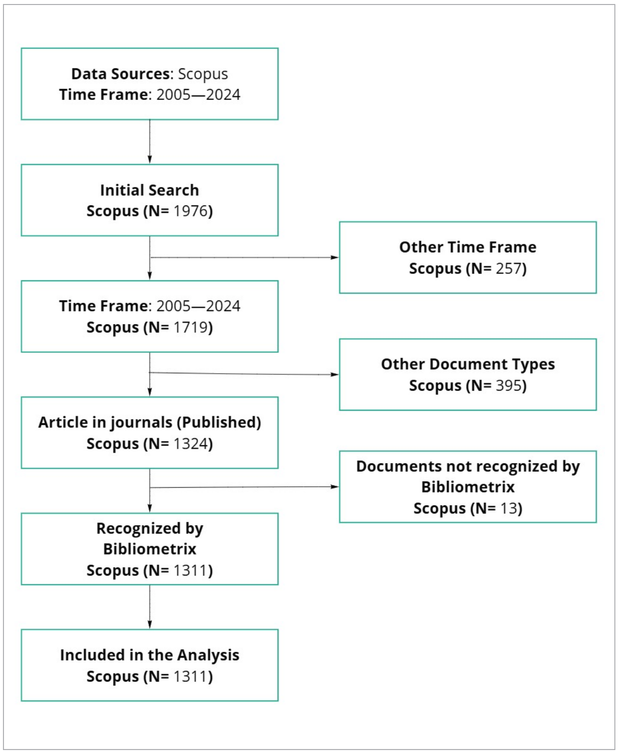
Data source

Scopus was selected for its extensive coverage of high-quality journals and research documents (Zhu and Liu, 2020). Institutional access was required to download and confirm the content of the study files.

Search strategy

We introduced a comprehensive list of keywords covering environmental sustainability indices and bioprocesses and compiled a database of 1311 documents (*Fig. 1*). The search equation used was the following: TITLE-ABS-KEY (("avocado" OR "Persea americana") AND (("bioactive compounds" OR "phenolic compounds" OR "polyphenols" OR "antioxidants" OR "flavonoids" OR "fatty acids" OR "starch" OR "phytochemicals" OR "terpenoids" OR "nutraceuticals") OR ("extraction process" OR "green extraction" OR "supercritical fluid extraction" OR "ultrasound-assisted extraction" OR "microwave-assisted extraction" OR "solvent extraction" OR "enzymatic extraction" OR "pressurized liquid extraction" OR "valorization") OR ("functional foods" OR "cosmeceuticals" OR "bioplastics" OR "biofuels" OR "biopesticides" OR "nutraceutical applications" OR "pharmaceutical applications" OR "biorefinery" OR "waste valorization"))). These keywords were obtained through a cyclical process, beginning with the articles returned by the databases and subsequently adding terms to capture topics that were initially unforeseen. The timeframe used covered data from 2005 to 2024. The search was limited to titles and keywords to improve the equation's effectiveness in collecting papers from the target areas (Alviz-Meza et al., 2023; Camargo et al., 2022). The time window was selected based on the number of articles found using the search query, and it was determined that a 20-year time frame would be appropriate to cover the genesis of the selected topic and its evolution through 2024 (*Fig. 2*). Only original articles were considered as document types, ensuring exclusive access to the original findings and avoiding reworkings and biases that could be introduced by secondary documents such as reviews. The Scopus web page was last consulted on April 4th, 2025.

Fig. 1. *Flowchart of the used bibliometric methodology*



Bibliometric analysis

Charts and tables were created from the database data, which were downloaded in BibTeX and CSV formats. We used Biblioshiny within RStudio to obtain and organize the compiled database prior to manual manipulation. It provides data on the most productive countries, institutions, authors, research areas, journals, subject headings, h-index, impact factors, total citations, and so on (Aria and Cuccurullo, 2017). In addition, VOSviewer was used for data mining, mapping, and visualization of collaborative networks (Karahan and Gül, 2021).

Limitations

Despite Scopus's broad coverage, our analysis is constrained by the inherent limitations of bibliometric indicators, such as citation lags and coverage bias. As noted by Gaur and Kumar (2018), the transition from quantitative metrics to qualitative statements introduces subjectivity. This approach prioritizes longitudinal field evolution over in-depth content analysis, recognizing that metadata-based findings are bounded by the specific scope and indexing timelines of the selected database (Wallin, 2005).

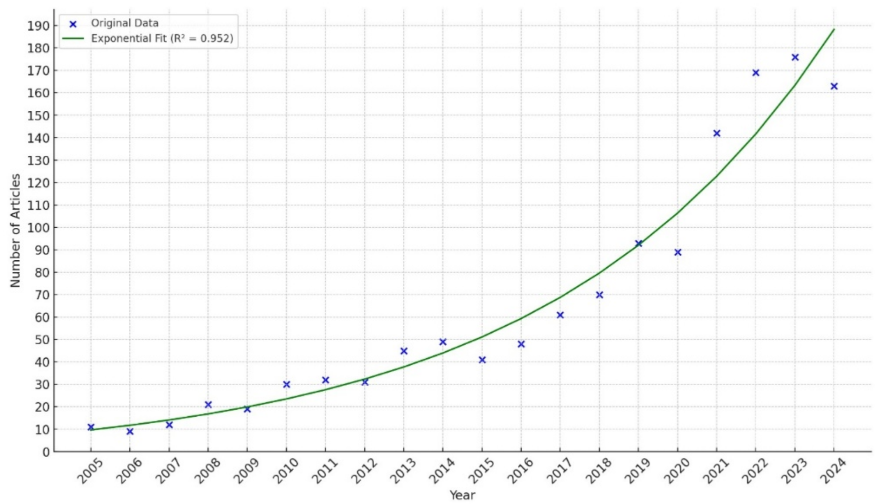
Results and Discussion

Trends in the annual production of original papers

Fig. 2 shows that interest in research on *Persea americana* active compounds, technologies, and applications has increased exponentially from 2005 to 2024, with a coefficient of determination of 0.952, peaking in 2023. Furthermore, the annual growth rate in the observed period is 15.24%. These trends are consistent with the outlook for the global avocado trade. According to the FAO, the global avocado trade accounts for more than 60% of tropical fruit sales, underscoring its importance and appeal across industries and communities (FAO, 2023). In addition, global concerns about the environmental impacts of industrial activities have encouraged the exponential growth of scientific production. The possible driving factors include increasing demand for energy efficiency, reducing polluting emissions, and minimizing waste (Basanta et al., 2007). Likewise, the evolution of international regulations, e.g., ISO 14000 standards and governmental policies, has spurred industries to adopt circular economy practices, providing a tailwind for the observed exponential growth (García-Silvera et al., 2023; Karaeva et al., 2023; Loayza and Silva, 2013). Additionally, we found that greater access to advanced analytical tools and open access to large volumes of data have facilitated scientific collaborations in this field (Monroy and Diaz, 2018).

The average total citations per year during the study period is 3.34, while the average citation per document is 24.15. A recent study found that these publications exhibit superior citation characteristics relative to other research areas (Kokorevics, 2022). This provides context for the work's average citation data, reflecting the relevance and impact of research in this sector.

Fig. 2. *Annual trend of publications from Scopus in the 2005–2024 timeframe*



Trends in the annual production of original paper

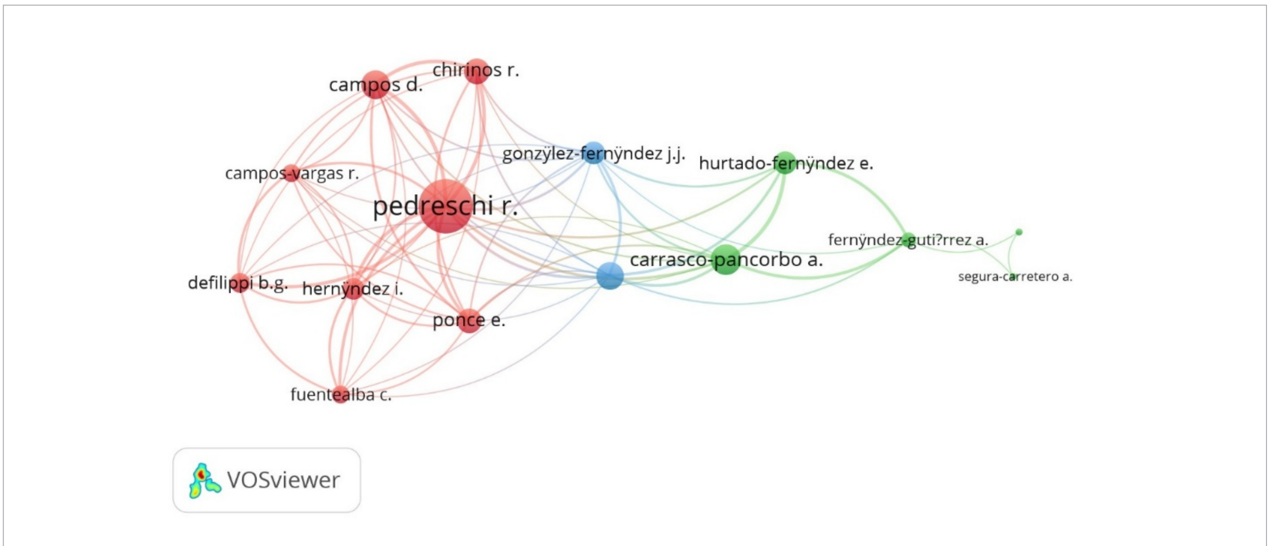
The Scopus-retrieved data highlight Pedreschi R. as the most productive researcher in the use and extraction technologies of *Persea americana* (*Table 1*). However, González-Aguilar GA has the highest total number of citations and h-index. Meanwhile, as shown in *Fig. 3*, Pedreschi R. is also the leader in the collaboration metric with a total link strength of 64, as indicated by the Size of the collaboration network (see *Table A1* from *Appendix A*). Therefore, Pedreschi R. can be considered the lead author of the present scientometric perspective on the research field of *Persea americana*. Romina

Pedreschi has advanced research on *Persea americana*, particularly by elucidating the biochemical and physiological aspects of the Hass avocado's postharvest ripening process. Her research employs targeted and untargeted metabolomics techniques applied to individual tissues via fruit biopsies to identify critical metabolites associated with variability in ripening. Additionally, she and her co-authors have analyzed how different postharvest approaches, such as temperature, ethylene treatment, and controlled-atmosphere conditions, affect the fatty acid profile, revealing that these methods do not significantly alter the fruit's lipid composition. Pedreschi and colleagues have also investigated the development of bioactive compounds, including mannoheptulose, perseitol, tocopherols, and phytosterols, from harvest through edible ripeness, emphasizing their stability and contributions to the fruit's antioxidant properties. Overall, these works integrate postharvest physiology, functional compound biochemistry, and innovative methodologies to improve avocado's quality and traceability within the agri-food sector (Campos et al., 2020; Pedreschi et al., 2016; Robledo et al., 2014).

Table 1. *Top 10 most productive and cited authors*

Scopus				
Rank	Author	h-index	TC	No. of papers
1st	Pedreschi R.	38	4369	21
2nd	Hernández-Brenes C.	28	2792	14
3rd	Li Y.	5	48	13
4th	Sivakumar D.	44	6457	13
5th	Carrasco-Pancorbo A.	40	5425	11
6th	Defilippi B.G.	31	3105	11
7th	Rodríguez-Carpena J.G.	11	1012	11
8th	Yahia E.M.	48	9064	11
9th	González-Aguilar G.A.	66	13792	10
10th	Hormaza J.I.	43	6393	10

Fig. 3. *Most collaborative authors, considering a minimum of five documents in VOSviewer*



While *Table 1* ranks researchers primarily by productivity and citations, *Fig. 3* focuses on collaborative behavior and visualizes the overall strength of the co-authorship networkbond (total link strength), which depends on the minimum number of articles per author and on the choice of interconnection display. In this case, the node size is proportional to the number of links per author. The same logic applies to the following VOSviewer figures and their interpretation. On the other hand, according to Lotka's law, the Bibliometrix software indicated that four articles constitute the critical limit for published documents, beyond which the number of authors with more documents declines to below 1.1%. Lastly, the international co-authorship rate and the number of co-authors per document in the studied areas are 24.10% and 5.4, respectively.

Most cited research articles

The Analysis of the 10 most-cited articles reveals interest in the comprehensive valorization of *Persea americana*, spanning from basic characterization to high-value industrial applications (*Table 2*). Three dominant thematic axes emerge from this work. First, the main focus is on the bioactive potential of agro-industrial waste. Multiple studies confirm that avocado seeds and peels are not only waste products but also potent reservoirs of phenolic compounds, flavonoids, and proanthocyanidins, with an antioxidant capacity superior to that of the pulp (Abu Bakar et al., 2009; Wang et al., 2010; Suleria et al., 2020; Fu et al., 2011). Second, this chemical richness has driven the development of functional applications. Research has demonstrated the efficacy of these extracts in inhibiting lipid oxidation in meat systems (Rodríguez-Carpena et al., 2011) and has validated their nutritional role in cardiovascular health and dietary polyphenol intake (Dreher and Davenport, 2013; Brat et al., 2006). Finally, the third focus highlights the integration of emerging technologies to optimize these applications. This includes the use of advanced drying methods, such as Refractance Window, to preserve sensitive bioactive compounds (Nindo and Tang, 2007), the implementation of sophisticated

Table 2. *Top 10 most cited articles*

First Author, year	Document title	Journal name	TC
Fu L., 2011	Antioxidant capacities and total phenolic contents of 62 fruits	Food Chemistry	623
Dreher M.L., 2013	Hass Avocado Composition and Potential Health Effects	Critical Reviews in Food Science and Nutrition	421
Abu Bakar M.F., 2009	Phytochemicals and antioxidant activity of different parts of bambangan (*Mangifera pajang*) and tarap (*Artocarpus odoratissimus*)	Food Chemistry	395
Machado S., 2013	Green production of zero-valent iron nanoparticles using tree leaf extracts	Science of the Total Environment	292
Rodríguez-Carpena J.G., 2011	Avocado (*Persea americana Mill.*) Phenolics, In Vitro Antioxidant and Antimicrobial Activities, and Inhibition of Lipid and Protein Oxidation in Porcine Patties	Journal of Agricultural and Food Chemistry	289
Wang W., 2010	Antioxidant capacities, procyanidins, and pigments in avocados of different strains and cultivars	Food Chemistry	278
Brat P., 2006	Daily Polyphenol Intake in France from Fruit and Vegetables	Journal of Nutrition	257
Suleria H.A.R., 2020	Screening and Characterization of Phenolic Compounds and Their Antioxidant Capacity in Different Fruit Peels	Foods	244
Nindo C.I., 2007	Refractance Window Dehydration Technology: A Novel Contact Drying Method	Drying Technology	215
Gião M.S., 2007	Infusions of Portuguese medicinal plants: Dependence of final antioxidant capacity and phenol content on extraction features	Journal of the Science of Food and Agriculture	208

profiling techniques (LC-MS/MS), and the application of innovations such as the green synthesis of iron nanoparticles (Machado et al., 2013). Taken together, these studies underscore a transition toward a zero-waste biorefinery model.

Journals that host the highest number of articles

Table 3 shows that *Food Chemistry*, *Molecules*, and *Foods are* the principal journals associated with avocado industrial use cases. The cumulative proportion of research papers published in these 10 journals is approximately 13.88 %, indicating considerable diversity among journals (over 85%) that publish articles on these issues. According to Bradford's law, it is feasible to classify sources into core, related, and non-relevant areas within the field targeted by the papers published in the journals, as shown in *Equation (1)*.

$$r_0 = 2\ln(e^{\gamma}Y) \quad (1)$$

where r_0 represents the number of journals that belong to the core area, γ is Euler's constant ~0.577, and is the number of articles published in the journal with the most hosted documents (Zhu et al., 2022). For this case, $Y = 35$; $therefore\ r_0 \cong 8$. As a result, all the sources shown in *Table 3* are part of the core collection. It is also noteworthy that *Food Chemistry* is the preferred journal for publishing in these fields.

Table 3. *Top 10 journals hosting papers of the studied research field*

Scopus			
Rank	Journal name	No. of papers	Impact factor SJR (2023)
1st	Food Chemistry	35	1.745
2nd	Molecules	24	0.744
3rd	Foods	23	0.87
4th	Journal of Agricultural and Food Chemistry	17	1.114
5th	Food Research International	16	1.495
6th	International Journal of Biological Macromolecules	16	1.245
7th	Antioxidants	13	1.222
8th	International Journal of Food Science and Technology	13	0.685
9th	Postharvest Biology and Technology	13	1.3
10th	Horticulturae	12	0.552

Most productive institutions and their collaborations

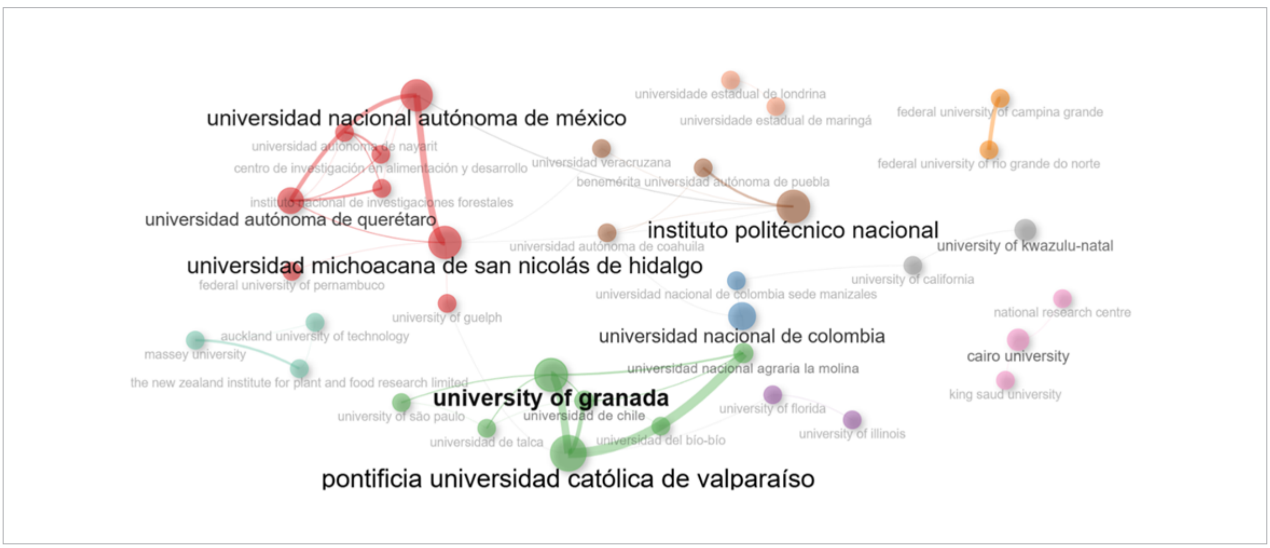
The top three universities in the field of study are the Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), the Instituto Politécnico Nacional, and the University of Granada (see *Table 4*). UMSNH has positioned itself as a key scientific hub for maximizing the value of avocados and their by-products, primarily due to its location in Michoacán, which accounts for approximately 73% of Mexico's production of *Persea americana* (Gobierno_de_México, 2023). This proximity to plantations, packing, and extraction facilities creates a "living laboratory" of year-round raw materials, facilitating research and technology transfer agreements with the National Council of Avocado Producers (CO-NAPA) and nearby processing companies. In addition, the UMSNH is home to the Institute of Agricultural and Forestry Research (IIAF), where experts in green technologies, such as supercritical fluid extraction, enzymatic hydrolysis, and microwave processing, and process simulation tools (AspenPlus, SuperProDesigner) collaborate to advance applied research. For instance, Luis Caballero-Sanchez and colleagues demonstrated the viability of a pilot-scale biorefinery using avocado seeds for bioethanol production; one tonne of dry seeds could produce approximately 178 liters of ethanol, thereby revaluing this *Persea americana* waste and validating the energy and environmental benefits of integrating this process into local biorefinery systems (Araujo et al., 2021). Additionally, in Mexico, other efforts have focused on optimizing starch extraction from seeds using microwave hydrothermal processing, achieving yields that exceeded those of traditional methods and highlighting the potential of these seeds as a film-forming agent for biopackaging (Caballero-Sanchez et al., 2023).

From a collaborative perspective, the Pontificia Universidad Católica de Valparaíso ranks first, with a betweenness centrality (number of collaborations) of 105, as shown in *Fig. 4* and *Table B1* of *Appendix B*. The Pontifical Catholic University of Valparaíso (PUCV) has be-come an important academic center for research on *Persea americana* due to three main factors: its strategic location in the Valparaíso region, a leading area for Hass avocado production in Chile; the existence of prominent teams specializing in post-harvest science and plant metabolomics, particularly within the School of Agronomy and the Ceres Regional Centre; and an institutional framework that fosters international collaborations and links with the agricultural export sector. These elements enhance its scientific output and partnerships with leading institutions, including Wageningen University & Research and the Institute of Agricultural Research (INIA). For example, in one study, Pedreschi and coworkers analyzed postharvest ripening variability in Hass avocados using metabolomic techniques, in collaboration between PUCV, INIA-La Platina, and WUR (Pedreschi et al., 2014). The same research team later assessed how commercial climate-control methods affect the fatty acid composition of avocados, showing that industrial practices do not adversely affect the fruit's lipid quality (Pedreschi et al., 2016). These significant contributions have paved the way for new research avenues in complex physiology, process modeling, and quality assurance, establishing PUCV as a regional leader in post-harvest studies.

Most productive countries and their collaborations

Recent bibliometric studies confirm that Brazil, Mexico, and the United States have the highest scientific output in biocomposite extraction technologies from avocado waste (Aguilar-Vasquez et al., 2024). This leadership position is due to a combination of factors: Mexico contributes over one-third of the world's avocado crop and is the leading exporter, creating pressure to add value to by-products and ensure safety standards are met (Fresh Plaza, 2025). Brazil has a robust public agro-industrial R&D system that invests approximately 1.1% of its GDP in research (Alvarez, 2023), thereby supporting advanced research. Strong domestic demand and funding from agencies such as the USDA-NIFA favour process engineering and industrial scaling studies in the United States (*Mederos*, 2024). According to Zakaria and colleagues,

Fig. 4. *Most collaborative institution clusters were obtained from collaboration networks in bibliometrix*



the result is a triangle of scientific output that accounts for more than 40% of the world's literature over the last decade (Zakaria et al., 2022). The co-authorship network among the three countries is equally dense: VOSviewer maps (see *Fig. 5*, *Table 5*, and *Table C1* in Appendix C) reveal interconnected clusters in which Mexican and Brazilian institutions publish in high-impact journals. This synergy aligns with the value chain logic: approximately 90% of Mexican avocado exports are destined for the North American market, necessitating joint projects on traceability, phytosanitary controls, and sustainability (Rice, 2024). Furthermore, the United States transfers know-how in green technologies that Brazilian laboratories adapt for use with tropical beans and avocado seeds. Binational initiatives, such as the blockchain system for tracking lots in Michoacán, demonstrate how the United States' regulatory pressure catalyzes joint technological collaborations (López-Pimentel et al., 2022).

Table 4. *Top 10 most productive institutions*

Scopus			
Rank	Affiliations	Country	No. of paper
1st	Universidad Michoacana de San Nicolás de Hidalgo	Mexico	51
2nd	Instituto Politécnico Nacional	Mexico	39
3rd	University of Granada	Spain	37
4th	Universidad Nacional Autónoma de México	Mexico	28
5th	Pontificia Universidad Católica de Valparaíso	Chile	26
6th	Universidad Nacional de Colombia	Colombia	25
7th	University of Kwazulu-Natal	South Africa	23
8th	Cairo University	Egypt	21
9th	Tshwane University of Technology	South Africa	19
10th	University of Chile	Chile	17

Fig. 5. *Most collaborative countries, considering a minimum of five documents in VOSviewer*

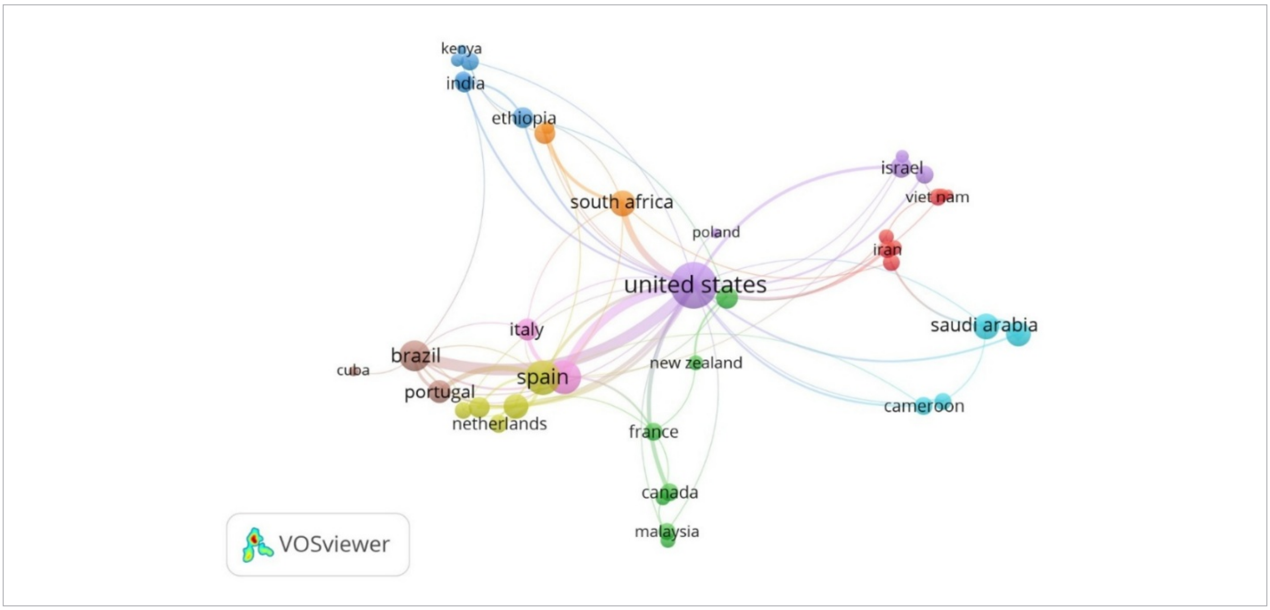


Table 5. *Top 10 countries*

Scopus			
Rank	Country	Frequency	Total Citations
1st	Mexico	595	3615
2nd	Brazil	411	2643
3rd	United States	286	3100
4th	Spain	234	3053
5th	Chile	175	1027
6th	China	142	1367
7th	Colombia	120	617
8th	Indonesia	116	230
9th	Nigeria	116	719
10th	South Africa	115	1818

Bioactive Compounds, Extraction Technologies, and *Persea americana* Applications and Trends

Classification based on the avocado source

Below are the results of the extraction techniques examined in this study based on the source of avocado biocompounds for various industrial applications of *Persea americana* (see *Table 6*).

Seed

The avocado seed exemplifies key research in polyphenolic biorefinery. The basic hydroalcoholic maceration and Soxhlet methods are widely used for yield and kinetic estimation, although their environmental and energy balances are unfavorable (De et al., 2025). Advanced techniques such as microwave-assisted extraction (MAE) deliver volumetric dielectric heating, rapidly releasing flavan-3-ols and increasing total phenol content (TPC) by up to 8-fold with minimal degradation, provided that power and ethanol-water ratios are carefully controlled (Weremfo et al., 2020). Ultrasound-assisted extraction (UAE) enhances catechin diffusion by 30–40% through cavitation and micro-jetting compared to traditional methods (Razola-Díaz et al., 2023). To extract less-polar compounds, supercritical CO_2 extraction (SFE) with ethanol as a cosolvent isolates oils and soluble procyanidins, yielding residue-free, phytosterol-rich extracts (Restrepo-Serna et al., 2022). Natural eutectic solvents (DES), such as choline chloride or glycerol, offer ethanol-like efficiency without toxicity or flammability, making them suitable for food applications and clean-label formulations (Rodríguez-Martínez et al., 2022). Electrical pulses, pulsed electric field (PEF), or Controlled Instantaneous Decompression (CID) induce electroporation, rapidly tripling antioxidant levels and reducing processing times (De et al., 2025).

For broad-spectrum food or nutraceuticals, ultrasound extraction offers optimal performance and cost efficiency, particularly when combined with PEF/DIC pretreatment, provided the equipment is available. DES is preferred for high-purity cosmetic or pharmaceutical ingredients due to its lower capital costs and moderate operating temperatures. At the same time, SFE is ideal when pressurized infrastructure is available and solvent-free extracts are required. In bio-refinery operations focused on seed production, PEF, DES, and enzymatic hydrolysis collectively facilitate the production of polyphenols, fermentable sugars, and energy from a single waste stream, thereby promoting circular economy principles.

Leaves

The leaf contains the most diverse phenolic chemotype of the tree, but the extraction technique affects the final product. Hydrodistillation yields an essential oil rich in estragole (78.12 %), α-cubebene, methyl eugenol, and β-caryophyllene, which can serve as repellents and traditional aromatic agents (Nasri et al., 2022; Sagrero-Nieves and Bartley, 1995). In contrast, polyphenols such as quercetin-rutinoside and chlorogenic acid are most effectively extracted using ohmic heating (1 V/cm, 80°C for four minutes) (Gumustepe et al., 2023). This process doubles the TPC compared to standard MAE methods while preserving antioxidant activity. Maceration and UAE are used as initial steps for medicinal infusions, achieving an antioxidant IC_{50} of approximately 45 ppm (Yamassaki et al., 2017).

Peel

Hydroalcoholic maceration involves using 40% v/v ethanol at a temperature of 25–40°C for 60–120 minutes. This method requires minimal equipment and extracts approximately 158 ± 26 mg of (gallic acid equivalents) GAE per gram of polyphenols (García-Ramón et al., 2023). This method is slow and solvent-intensive, and is therefore mainly suitable for laboratory or research standardisation.

Table 6. *Persea americana extraction methods by compounds, sources, and applications*

Avocado source	Extraction method	Compounds	Applications/Observations	References
Seed	Maceration	Polyphenols (flavan-3-ols such as catechin, epicatechin, and procyanidins; phenolic acids such as chlorogenic acid, p-coumaric acid, and 4-hydroxybenzoic acid) have strong antioxidant activity.	For use as natural food preservatives, nutraceuticals, cosmetics, and pharmaceuticals.	(Munthe et al., 2023)
	Soxhlet	Similar polyphenols to those obtained from maceration (up to ~189 mg GAE/g) are extracted more quickly.	Antioxidant and antimicrobial extracts.	(Hue et al., 2021)
	MAE	Approximately 8 times increase in total phenolic content compared to maceration; maintains the integrity of flavan-3-ols.	Accelerating production of antioxidant extracts for functional beverages and capsules.	(Weremfo et al., 2020)
	UAE	Polyphenols and tannins are obtained in higher yields than with static methods. Cavitation enhances the release of phenolic compounds, such as flavanols, from the matrix, resulting in a 31–41% increase in phenolic content compared to traditional extraction methods.	Antioxidant extracts for food fortification and preservatives — they delay lipid oxidation.	(Husen et al., 2014)
	Supercritical CO_2 extraction (SFE) (250–400 bar, 40–80°C; optional polar co-solvent)	(+)-catechin, (–)-epicatechin, and oligomeric procyanidins.	Antioxidant, anti-inflammatory, lipid-lowering, anti-obesity; pharmaceutical and cosmetic potential.	(Restrepo-Serna et al., 2022)
	Ionic solvents / DES	Antioxidant phenolics are effectively extracted using a 1:1 mixture of choline chloride and glycerol with 30% water, which yields higher total polyphenol and flavonoid levels than 50–80% ethanol. Optimizing temperature and time yielded approximately 19.7 mg EAG per gram and a high antioxidant capacity.	Phenolic extracts that are free of toxic organic solvents are suitable for use in functional foods and eco-friendly cosmetics. The delipidated solid residue remaining after DES treatment is more prone to hydrolysis, which can produce bioethanol or other bioproducts, supporting integrated seed utilization.	(Del-Castillo--Llamosas et al., 2023b)
	Electrical pulses as pretreatments.	Enhanced cellular permeabilization promotes the release of compounds during subsequent extractions. In avocado seeds, a CID treatment increased the antioxidant capacity of the methanolic extract by 3-fold compared to untreated samples.	Methanolic extracts.	(Ibarra-Buenavista et al., 2020)
Leaves	Maceration	Alta concentración de polifenoles totales (Hass: ~300 mg EAG/100 g extracto).	Traditionally used in medicinal infusions for their antidiabetic, diuretic, and digestive properties, ethanolic leaf extracts also show antioxidant and antimicrobial activity, making them a potential natural pharmaceutical ingredient.	(Velderrain-Rodríguez et al., 2021)
	Hydrodestilation	In Mexican varieties, methyl chavicol is the main component, constituting 50–78%, along with methyl eugenol, α-cubebene, β-caryophyllene, α-pinene, d-limonene, and others. The yield is moderate, around 0.1–0.3% w/w based on dry leaves.	Traditional seasoning, bug repellent, and post-harvest antifungal.	(Nasri et al., 2022)
	MAE	23.3 mg EAG 100 g^{-1}; quercetin-3-rutinoside predominant.	Anti-AGE extracts for infusions and dermocosmetics.	(Gumustepe et al., 2023)
	UAE	Flavonoids and phenolic acids	Antioxidants.	(De Montijo-Prieto et al., 2023)
	Ohmic heating-assisted extraction	The ohmic system, compared to conventional control, leads to higher extraction yield of phenolic compounds and antioxidant potency.	Antioxidant extracts suitable for the food and cosmetics industries.	(Markhali et al., 2022)

Avocado source	Extraction method	Compounds	Applications/Observations	References
Peel	Maceration	High levels of total polyphenols (Hass: approximately 300 mg EAG per 100 g), mainly phenolic acids and flavonoids, are present. The adherent mesocarp also contains xanthophyll carotenoids and triterpenes.	Extracts with antioxidant and antimicrobial properties are suitable for use as natural food preservatives, nutraceuticals, cosmetics, and pharmaceuticals.	(Velderrain-Rodríguez et al., 2021)
	Soxhlet	Similar to maceration, typical yields are below 30%. Hot extraction can also remove additional apolar compounds from the peel, such as resins, cuticular waxes containing alkanes, and phytosterols.	Crude antioxidant utilized in active biofilm research and edible coatings. Its resinous component can serve as an additive in fuels or natural waxes.	(Zbikowska et al., 2024)
	UAE	Polyphenols and flavonoids are extracted more effectively than with traditional techniques. The key compounds identified in UAE peel extracts include benzoic acid, vanillic acid, resveratrol, and syringic acid. Sonication shortens the extraction process and improves solvent-solid diffusion while preserving the antioxidants.	Extract with high antioxidant activity and low cytotoxicity. Suitable for human consumption.	(Hefzalrahman et al., 2022)
	MAE	Temperature, duration, ethanol concentration, and solvent–sample ratio significantly influenced extractable phenol yield. Optimal MAE conditions were 130 C for 39 min, 36% ethanol, and a 44 mL/g solvent–sample ratio.	The extract contains 53 usable polar compounds.	(Figueroa et al., 2021)
	SFE	The shell's lipophilic fraction includes waxes, fats, and pigments. Using SFE at 80°C and 250 bar with ethanol as a co-solvent yields lower yields than seed or pulp, but the extract is solvent-free.	Oils with triglycerides, waxes, and some bioactives like tocotrienols, squalene, and phytosterols are extracted from the cuticle.	(Restrepo-Serna et al., 2022)
	PLE	Some authors have reported that the most effective extraction conditions are 200°C with a 1:1 v/v ethanol:water solvent.	PLE is regarded as a more environmentally friendly alternative to Soxhlet extraction.	(Figueroa et al., 2018)
	NaDES	The best extraction results were obtained with choline chloride in combination with acetic acid and lactic acid, which showed higher extraction efficiency than ethanol.	It offers high antioxidant and antimicrobial activity, especially against *Staphylococcus aureus, Streptococcus dysgalactiae, Escherichia coli*, and *Pseudomonas putida.*	(Rodríguez--Martínez et al., 2022)
Pulp	Mechanical	The maximum recovery, approximately 80%, was obtained using a water-to-avocado ratio of 5:1, a pH of 5.5, a centrifugal force of 12,300×g, and 5% $CaCO_3$ or $CaSO_4$.	Gourmet edible oil with oxidative stability and a healthy profile. In cosmetics, it's used as a moisturizing base oil and as a vehicle for active ingredients. Its use in cardioprotective nutraceuticals is being investigated.	(Qin and Zhong, 2016)
	Solvent extraction	Crude oil extracted from pulp yields more than pressing methods, with over 95% of the oil content obtainable. Using moderate heat in Soxhlet or percolation extraction speeds up oil release from the matrix. However, the oil might have higher pigment levels and will need refining.	Using solvents involves desolventization steps and may decrease minor compounds, but it is still the most cost-effective method for large-scale oil extraction from pulp.	(Costagli and Betti, 2015)
	SFE	High-quality pulp oil comparable to pressed virgin oil, free from solvents, with maximum retention of minor compounds such as tocopherols, phytosterols, and carotenoids, due to the absence of oxygen and low processing conditions temperatures.	Extra virgin oil.	(Pinheiro Pantoja et al., 2024)
	Ultrasound, electrical Pulses	Auxiliary technologies, such as sonication of the pulp either before pressing or in a solvent disrupt cells and increase oil and bioactive compound release by approximately 5–15%. Likewise, pulsed electric fields applied to avocado paste induce electroporation, aiding in the release of oil and enzymes. Pilot studies have reported increases of around 10% in pressed oil yield.	PEF, in particular, is being industrially assessed to improve energy efficiency and yield in avocado oil production plants, ensuring that their nutritional qualities are maintained.	(Baylis et al., n.d.)

In contrast, Soxhlet extraction with hexane targets lipids, yielding approximately 30% w/w of a dark oil rich in chlorophyll and containing 70% oleic acid at 60–70°C over 4 hours (Diriba Muleta et al., 2022). This process produces feedstock for biodiesel, waxes, or cosmetics, but desolventising and decolourising are required. Prolonged heating can degrade polyphenols, thereby reducing the efficiency of Soxhlet extraction of antioxidants. Among all residues, the epicarp contains the highest phenolic content. UAE, combined with Natural deep eutectic solvents (NaDES), produces 92 mg of GAE per gram and 186 mg of RE per gram, demonstrating antibacterial activity (Della Posta et al., 2023). PLE with a water/ethanol mix at 200°C and 10–15 MPa can extract up to 47 compounds, mainly hydroxycinnamic acids, in under 30 minutes (Figueroa et al., 2018). MAE at 130°C for 40 minutes yields a similar array of compounds but consumes less energy and targets B-type procyanidins (Figueroa et al., 2021). Lipids are extracted using supercritical CO_2 at 80°C and 250 bar, making this method suitable for natural cosmetic products (Restrepo-Serna et al., 2022).

Pulp

The main goal is oil extraction. The Soxhlet/hexane technique can extract up to 95% of the available oil because the solvent thoroughly penetrates cells, extracting triglycerides, squalene, and chlorophyll (Costagli and Betti, 2015). This method is popular in industries that prioritize volume, such as biodiesel and cosmetics. However, exposure to high temperatures and prolonged contact can reduce α-tocopherol and carotenoid levels, resulting in dark-green oils that require refining (Flores et al., 2019). Cold mechanical pressing at temperatures below 45°C preserves a monounsaturated oil profile of 70–80% and produces 70–190 mg/kg of α-tocopherol, meeting the standards for extra virgin oil (Wong et al., 2024). SFE with CO_2 (300–350 bar, 35–45°C, 10% ethanol) yields approximately 60% of the dry weight while retaining 20% more carotenoids and sterols (Corzzini et al., 2017). This eliminates the need for refining. Physically assisted techniques complement each other: pre-pressing with aqueous sonication increases oil recovery by 10–15% (Tamborrino et al., 2021), whereas applying PEF to the pulp increases yield by 5–6% without affecting quality parameters (Yang et al., 2024).

Other, less familiar, yet promising extraction techniques complement the primary methods. For instance, subcritical water extraction (SWE) can isolate vasoprotective catechins from seeds without solvent use (Ong et al., 2022), whereas pressurized PLE can yield results comparable to UAE in less than 30 minutes (Grisales-Mejía et al., 2022). Microwave-assisted autohydrolysis (MAAH) releases sugars and polyphenols for biorefinery use (Del-Castillo-Llamosas et al., 2023a). Aqueous enzymatic extraction (AEE) simultaneously retrieves oils and phenolic compounds, reducing free fatty acids and peroxides (De et al., 2025). Solventless microwave distillation (SFME) concentrates estragole-rich oils in under 15 minutes with less energy consumption (Huang et al., 2024). For the peel, the combination of AEE and UAE increases phenol levels by 28% (Hefzalrahman et al., 2022). In pulp, combining AEE with Ultrasonic Aqueous Assisted Extraction (UAAE) can recover up to 74% of oil with low free fatty acid and peroxide index values, making it suitable for high-quality oil production (Flores et al., 2019). CO_2-expanded ethanol (CXE) yields a recovery comparable to that of hexane while preserving carotenoids (Corzzini et al., 2017). These less common methods expand the range of options and offer benefits such as solvent removal and hydrolysis, making them ideal for high-purity or circular-economy applications.

Trendings

Keywords accurately represent scientific articles and often highlight key trends in a field study. The visualization of the Scopus keyword clusters and trend topics (*Figs. 6 and 7*) highlights the most significant research areas related to the use of *Persea americana*. We highlight the keywords avocado oil, antioxidants, biorefinery, fatty acids, chitosan, phenolic compounds, oxidative stress, phytochemicals, lipomics, and food packaging and preservation (see also *Table D1* in Appendix D).

According to the thematic map in *Fig. 6*, covering 2008–2014, research on *Persea americana* focused primarily on analyzing its oil's chemical composition. Studies by Berasategi and coworkers showed the oil contains a significant amount of monounsaturated fats and measurable levels of α-tocopherol and pigments (Berasategi et al., 2012). Its thermal stability in olive oil was also carefully assessed, thereby laying the groundwork for its classification as extra-virgin oil. After 2014, efforts shifted toward developing methods to improve polyphenol extraction. Using MAE techniques on seeds and peel increased total phenolic content by up to eight times, with antiradical IC50 values below 25 µg/ml (Weremfo et al., 2020). This supports the idea that these extracts have strong nutraceutical and antidiabetic benefits. During this period, reports highlighted the functional and commercial value of virgin avocado oil, prompting the food industry to move beyond fundamental fat analysis (Tan, 2019). By 2019, research using technological and omics approaches had shown that sustainable antioxidant extraction with UAE and NaDES outperformed traditional hydroalcoholic methods, producing extracts suitable for clean-label

Fig. 6. *Trend topics obtained through the software bibliometrix*

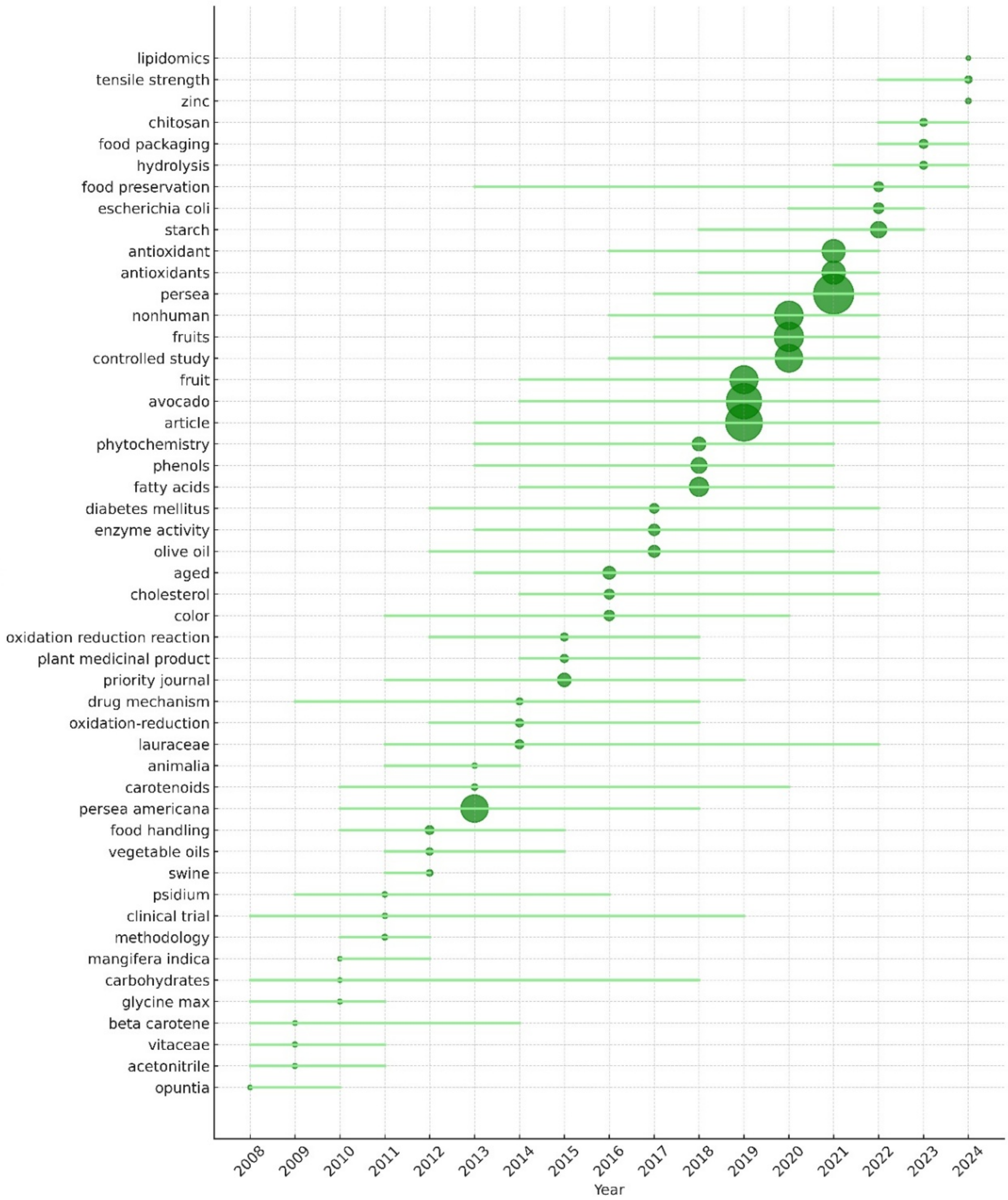
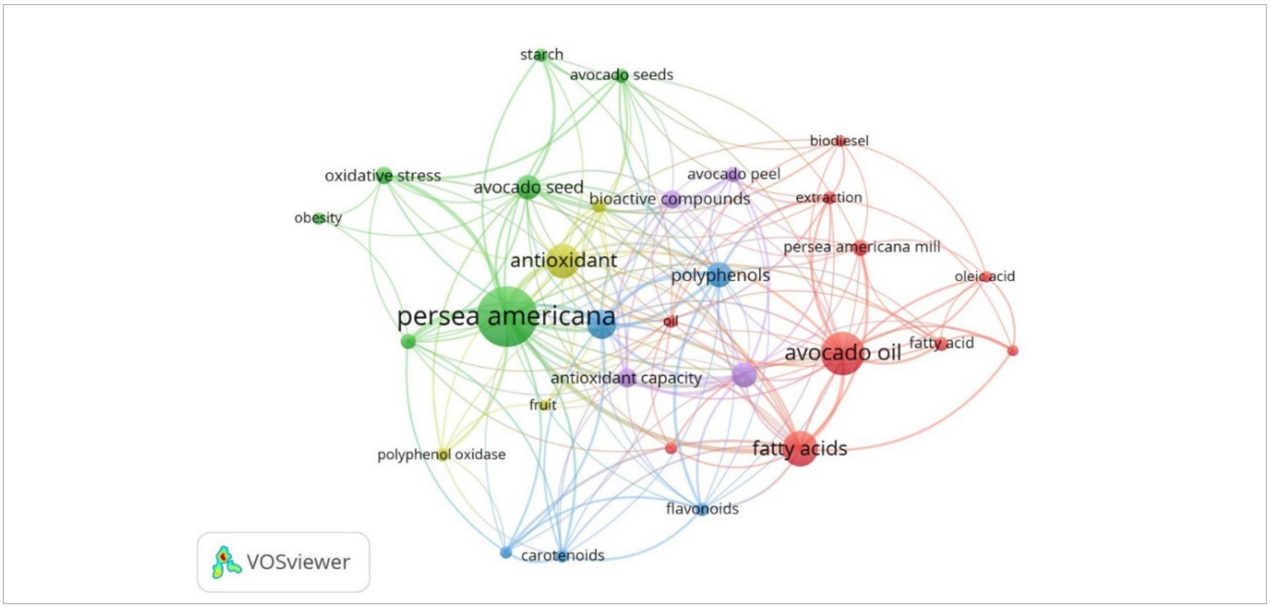


Fig. 7. *Trend topics obtained through the software Bibliometrix*



products (Della Posta et al., 2023). Lipidomics has become crucial for identifying over 240 lipid species in peel and seed, aiding traceability and authenticity, and expanding its use in active packaging and biofilms (Neves et al., 2024). For example, peel fibers or phenolic extracts can be integrated into chitosan matrices to create films with improved mechanical strength and antimicrobial activity against E. coli and S. aureus (Ahmed and Janaswamy, 2023). The research focus has evolved from simply identifying avocado components to converting each fraction into functional ingredients or advanced materials, opening new opportunities in innovative packaging, omics-based authenticity testing, and solvent-free extraction methods.

Below, we provide a more detailed discussion of the growing contributions and trends in avocado uses and extraction technologies, organized by the five clusters presented in *Fig. 7*.

Lipid applications of *Persea americana*

This cluster focuses on assessing the functional quality of oil and verifying its origin. Supercritical CO_2 extraction has been shown to yield oils with 10%–15% higher levels of carotenoids and phytosterols than cold-press methods, making it particularly suitable for nutraceutical and cosmetic applications (Pinheiro Pantoja et al., 2024). High-resolution lipidomics has been recognized as a reliable method for assessing the authenticity and extraction conditions of fatty acid esters and alcohols, enabling rapid detection of adulteration in commercial blends (Marín-Obispo et al., 2025). Furthermore, the potential of new kinetic models to describe the transesterification of hexane-extracted oil into biodiesel is particularly promising. These models have achieved yields exceeding 98% and properties that meet ASTM standards, depending on the optimized temperature and methanol-to-oil ratio (Alale et al., 2025).

Phytochemicals and metabolic health

Recent in vivo studies indicate that seed powder or extract can lower weight gain and enhance insulin sensitivity in mice fed a high-calorie diet (Velázquez-González et al., 2023). These effects are linked to increased thermogenesis and occur without liver or kidney toxicity. Pressurized hydrothermal extraction released catechins that mitigate oxidative stress and influence endothelial metabolites in cell models hinting at vasoprotective benefits (Ong et al., 2022). Moreover, biosynthesized silver nanoparticles derived from seed extract improve blood glucose regulation in diabetic mice, suggesting a new delivery method for seed-based antidiabetic phytochemicals (Al-Hammood et al., 2024).

Polyphenols, flavonoids, and carotenoids

In this context, the trend is shifting toward highly efficient, environmentally friendly processes. Using natural eutectic cartridges (choline-Cl:glycerol) with ultrasound yielded a total phenolic extract from shell and seed, which is 60% greater than that obtained by hydroalcoholic methods (Grisales-Mejía et al., 2022). For waste pulp matrices, microwave-assisted autohydrolysis at 180°C for 10 minutes simultaneously extracted carotenoids and fermentable sugars, supporting integrated biorefinery applications (Del-Castillo-Llamosas et al., 2023a). At pilot scale, response surface analysis optimized MAE conditions (130°C for 40 minutes with 36% ethanol), increasing the TPC in defatted pulp to 72 mg GAE/g, with particular emphasis on B-type procyanidins (Araújo et al., 2020).

Antioxidant activity

Methodological advances aim to connect chemical assay outcomes with biological effectiveness. Optimizing flavan-3-ol extraction from seeds using UAE lowered the DPPH (2,2-diphenyl-1-picrylhydrazyl) IC50 to 17 μg/mL and safeguarded plasmid DNA against peroxyl radicals (Razola-Díaz et al., 2023). The application of DES revealed that ABTS (2,2'-azino-bis(3-ethylbenzotiazoline-6-sulfonico)) and FRAP (Ferric Reducing Antioxidant Power) capacities are significantly affected by the solvent's water content (Del-Castillo-Llamosas et al., 2023b). Additionally, fractions rich in chlorogenic acid showed notable synergy between DPPH/ABTS results and lipid peroxidation inhibition in liver microsomes, strengthening the link between in vitro tests and biological models (Izu et al., 2024).

Bioactive compounds and active packaging

Integrating shell or seed extracts into polymer matrices is advancing the development of new packaging materials. Biodegradable shell fiber films, created via acid-alkaline hydrolysis, achieved viable tensile strength and cut water vapor permeability, making them viable substitutes for petrochemical-based films (Ahmed and Janaswamy, 2023). Adding an antioxidant seed extract to seed flour films doubled DPPH radical inhibition and increased the shelf life of sunflower oil by 30% during accelerated storage (Grisales-Mejía et al., 2024). Finally, Shell extract-loaded chitosan nanoparticles demonstrated bactericidal activity against E. coli and S. aureus and enhanced tumor inhibition, underscoring their potential as active packaging and controlled-release systems (Donoso et al., 2024).

Finally, the thematic map shown in *Fig. E1* of the appendix indicates that the conceptual framework centers on key terms, including avocado oil, phenolic compounds, and antioxidants. Major themes include antioxidant activity, oxidative stress, avocado seeds, and monostearate fatty acids, which shape the scientific focus on validating cardiometabolic benefits and reevaluating byproducts. Niche themes such as adulteration, bioplastics, chitosan, mechanical properties, and avocado starch reflect specialized research areas, such as biodegradable packaging or quality control, which could gain prominence if integrated into larger value chains. Additionally, emerging or declining themes, such as functional foods and biorefineries, highlight potential research avenues for integrated utilization models that have yet to achieve widespread adoption.

Conclusions

This bibliometric review examines the growing interest among institutions, journals, researchers, countries, and funding agencies in avocado extraction technologies, biocompounds, and applications. The key conclusions for each research question are summarized below. The number of original papers published on this topic is growing exponentially. In terms of scientific productivity and impact, the analysis indicates that becoming a leading author typically requires 10 publications, with research primarily focused on optimizing antioxidant activity and phenolic content for food and health applications. These studies are predominantly published in high-impact journals such as *Food Chemistry*, which has an SJR exceeding 0.552. Furthermore, the institutional landscape is led by organizations that have produced at least 17 documents, with global research output geographically concentrated in Mexico, Brazil, and the United States. In addition, research trends and thematic evolution reveal a shift from traditional extraction methods, such as hydroalcoholic maceration and Soxhlet, which are suitable for initial characterization but tend to be inefficient and environmentally harmful, to more sustainable techniques such as UAE, MAE, PEF + DES, and SFE. These greener methods improve the extraction of phenols, carotenoids, and lipids from various plant parts, including seeds, peels, pulp, and leaves, while also reducing processing time and reducing organic waste. This shift is driven by the rising demand for nutraceutical and clean-label products, enabling targeted valorization: seeds for antidiabetic polyphenols; peels for antioxidants used in active packaging; leaves for essential oils with repellent properties; and pulp for extra-virgin oils or biodiesel. An emerging trend is to integrate these processes into circular biorefinery systems that combine electrical or enzymatic pretreatments with selective extraction and omics analyses to enhance traceability, authenticity, and sustainability in industry.

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Appendix A

Table A1. *Top 5 collaborative authors*

Scopus			
Rank	Author	No. of paper	T. link strength
1st	Pedreschi R.	21	64
2nd	Carrasco-Pancorbo A.	11	35
3rd	Campos D.	9	33
4th	Hormaza J. I.	10	32
5th	Chirinos R.	8	29

Appendix B

Table B1. *Top 5 collaborative institutions according to bibliometrix*

Scopus			
Rank	Institution	Betweenness	PageRank
1st	Pontificia Universidad Católica de Valparaíso	105	0.076
2nd	Universidad Michoacana de San Nicolas de Hidalgo	99	0.050
3rd	Universidad Nacional de Colombia	83	0.023
4th	University of Guelph	79	0.013
5th	Universidad Nacional Agraria La Molina	53	0.050

Appendix C

Table C1. *Top 5 countries*

Scopus		
Rank	Country	Total link strength
1st	United States	74
2nd	Mexico	39
3rd	Spain	39
4th	Brazil	29
5th	Chile	15

Appendix D

Table D1. *Top 10 most used author keywords according to Bibliometrix*

Scopus		
Rank	Terms	Frequency
1st	Avocado	205
2nd	Persea americana	150
3rd	Avocado Oil	92
4th	Antioxidant	69
5th	Fatty Acids	69
6th	Phenolic Compounds	45
7th	Avocado Seed	43
8th	Bioactive Compounds	29
9th	Oxidative Stress	27
10th	Phytochemicals	23

Appendix E

Fig. E1. *Thematic map according to bibliometrix*