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Technology trends in extraction of bioactive compounds creole avocado and their application in lipid matrices

Tendencias tecnológicas para la extracción de compuestos bioactivos del aguacate criollo y su aplicación en matrices lipídicas

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ABSTRACT

This study aimed to identify the trends in extraction methods of bioactive compounds with antioxidant capacity from avocado co-products and their application in lipid matrices. For this purpose, the scientific production by country over the last five years was analyzed, revealing that China, India, and Spain are leading contributors to this research topic. In Colombia, studies related to avocado have primarily focused on technologies such as ultrasound and pressurized liquids with NADES solvents. Likewise, the most cited journals and areas of knowledge correspond to agricultural and biological sciences, which have made significant progress through the use of microorganisms as biological pretreatment due to their large-scale potential across different industries. Finally, the thematic map made it possible to identify that one of the most favorable alternatives to improve the yields and quality of the extractives is the combined use of assisted technologies such as electric fields, ultrasound, and enzymes enabling the improvement of oxidative stability and nutritional value of certain food matrices such as meat or bakery products through the incorporation of oleogels as fat substitutes.

Keywords:
Antioxidants
Extraction methods
Food waste
Oleogel
Persea americana
Scientific surveillance

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RESUMEN

El objetivo de este estudio fue identificar las tendencias alrededor de los métodos de extracción de compuestos bioactivos con capacidad antioxidante para el aprovechamiento de coproductos del aguacate y su aplicación en matrices lipídicas. Para ello, se hizo un análisis en los últimos cinco años de la producción científica por países, encontrando que China, India y España son líderes en estas investigaciones y que en Colombia los estudios relacionados al aguacate se han enfocado en tecnologías como ultrasonido y líquidos presurizados con solventes NADES. Asimismo, las revistas más sobresalientes y las áreas del conocimiento son las ciencias agrarias y las biológicas, que han representado un avance importante con el uso de microorganismos como pretratamiento biológico, por su potencial a gran escala en diferentes industrias. Finalmente, con el mapa temático se logró identificar que una de las alternativas más favorables para mejorar los rendimientos y la calidad de los extractivos es el uso combinado de tecnologías asistidas como campos eléctricos, ultrasonido y enzimas, brindando la capacidad de mejorar la estabilidad oxidativa y el valor nutricional de algunas matrices alimentarias como productos cárnicos o de panificación con la incorporación de oleogeles como sustitutos de grasa.

Palabras clave:
Antioxidantes
Método de extracción
Residuos alimentarios
Oleogel
Persea americana
Vigilancia científica

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Avocado (*Persea americana* Mill.) is a widely consumed fresh fruit and has a wide potential for agro-industrial applications due to its pulp and the co-products generates; for instance, peel and seed (Araújo et al. 2020; Yepes-Betancur et al. 2021). The fruit consists of an approximate proportion of 16% seed and 11% peel, which represents about 1.6 million tons of waste annually, thus causing serious ecological problems (Salazar-López et al. 2020). Likewise, studies related to oils and fats have reported that Hass avocado oil can be an alternative to olive oil due to its properties and extraction yield. In turn, some native varieties could compete with Hass avocado in terms of fat content, which ranges between 15 and 19% (Hurtado-Fernández et al. 2018; Sandoval Aldana et al. 2020). These properties have sparked interest in the industry because of their application in the development of food products through lipid matrices substitution of fats or emulsifying agents to reduce the consumption of saturated or trans fatty acids. However, the biggest challenge for the industry has been to provide or maintain textures and flavors characteristic of saturated fats (Pérez-Monterroza et al. 2014). Due to the significant growth of avocado cultivation, various process industries have shown interest in the extraction of oils and bioactive compounds with antioxidant capacity (Hurtado-Fernández et al. 2018; Salazar-López et al. 2020).

Avocado by-products are a promising source of starchy carbohydrates, lipids, proteins, fiber, minerals and bioactive compounds such as organic acids, flavonoids, benzoic acids, terpenoids, and phytosterols (Araújo et al. 2018; Barrera López and Arrubla Vélez 2017). Seed composition is characterized by a three-dimensional lignocellulosic network comprising cellulose, hemicellulose, and lignin, which can be chemically, physically or biologically degraded (Casas Godoy and Sandoval Fabián 2014; Tanpichai et al. 2022). The most commonly reported extraction method is the use of chemical solvents; however, in recent decades, alternative extraction techniques such as maceration, hot water extraction, microwave extraction, supercritical fluid extraction, ultrasound-assisted extraction, electric field-assisted extraction, and enzyme-assisted extraction have been highlighted (Gil-Martín et al. 2022; Muthusamy et al. 2021). In the food industry, catalytic processes using enzymes are widely applied, for instance, the extraction of functional compounds stands out. The most commonly used enzymes belong to the group of hydrolases, lipases, and proteases that convert large polymer chains into short chains of low molecular weight (Illanes et al. 2014).

One of the alternatives for applying avocado oil in lipid matrices are oleogels. They are viscoelastic semi-solid structures entrapping an organic liquid inside a three-dimensional network formed by self-assembly of molecules at low concentrations of structuring or gelling agents (Pérez-Monterroza et al. 2014). For its formulation, one of the most relevant aspects is the selection of the oleogelling agent that gives it the appropriate texture, which is one of the most important quality parameters in the development of agrifood products. The most studied oleogelling agents are monoglycerides, diglycerides, fatty acids, ethyl cellulose, and waxes, among others (Palla et al. 2017).

Although several studies have been carried out on this topic, limited information is available on methodology trends for using plant-based co-products and their application in avocado-based lipid matrices. Hence, industries have adopted technological tools to identify trends, methods, and projections to generate added value and respond to market demands (Acevedo-Viloria et al. 2024). One of the most widely used strategies is scientific and technological surveillance: a systematic and structured search of information that allows connecting ideas and finding opportunities for improvement to make decisions regarding specific topics at a business, technological, innovation or scientific level. Hence, this surveillance aims at identifying the advances and future research trends in extraction methods of bioactive compounds with antioxidant capacity from avocado co-products and their application in lipid matrices.

MATERIALS AND METHODS

The scientific surveillance study for information gathering followed the sequence of stages described by Andrade et al. (2017) to capture information on trends and projections in the extraction methods of functional compounds from avocado by-products and their application in lipid matrices. The stages of the monitoring are presented in Figure 1.

Planning

The information search was carried out with the design of a search log that incorporated key words to identify the period in which the information would be sought according to trends and advances in the area. At this stage, the topic

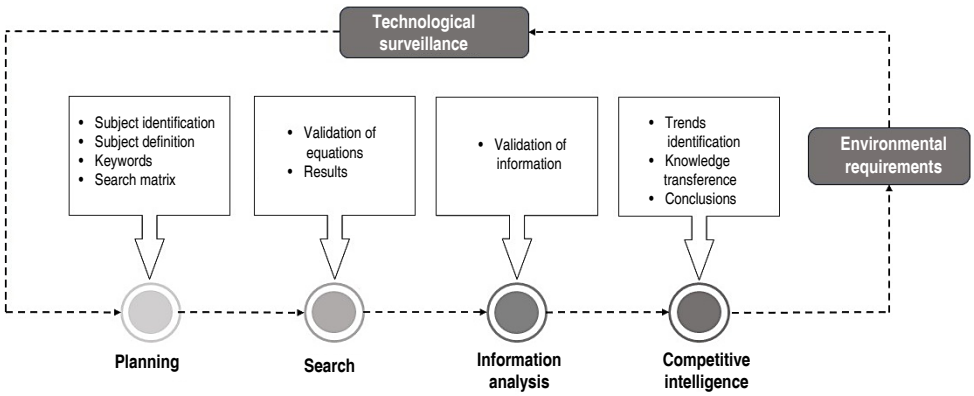


Figure 1. Technology surveillance stages.

and objectives of surveillance were identified, and the search was based on conceptual bases such as raw materials, extraction processes, properties, methods, applications, and functionality. To this end, tools that gather thesauri globally, such as AGROVOC Multilingual Thesaurus and Cambridge Thesaurus were used. 26 keywords were obtained and validated considering temporal aspects, document type, and thematic relevance. With this information, 17 search equations consisting of logical expressions combined with Boolean operators were structured (Table 1).

Table 1. Search matrix.

Search matrix	Results
(TITLE-ABS-KEY (avocado AND ultrasound AND antioxidants OR "bioactive compounds" OR oil) AND PUBYEAR > 1993) OR (TITLE-ABS-KEY (avocado AND microwave AND "bioactive compounds" OR antioxidants OR oil) AND PUBYEAR > 1993) OR (TITLE-ABS-KEY (avocado AND "Supercritical Fluid Extraction" AND polyphenols OR antioxidants OR oil) AND PUBYEAR > 1993) OR (TITLE-ABS-KEY (avocado AND mechanical AND polyphenols OR antioxidants OR oil) AND PUBYEAR > 1993) OR (TITLE-ABS-KEY (avocado AND solvents AND "bioactive compounds" OR antioxidants OR oil) AND PUBYEAR > 1993)	819

Search

Once the search matrix was defined, a search was conducted on the Scopus platform, validating all the information found about worldwide advances in different areas of science and technology fields. This database included publications between 2019 to 2024. A single database was used to avoid duplicate records and inconsistencies in metadata, improving the reproducibility of the bibliometric analysis.

Data analysis

VOSviewer was used to identify trends. This software allows the visualization of bibliometric data from maps based on network data (Acevedo-Viloria et al. 2024). With the help of this tool, the information obtained from the Scopus search was filtered and, with the advice of an expert researcher in biotechnology, the most appropriate keywords relevant to the research objective were selected. Similarly, repeated terms were eliminated, and finally, four clusters related to the extraction methods from avocado and its application in lipid matrices were identified. In addition, the analysis identified the most active journals, contributing countries, representative authors, and related research areas.

Competitive intelligence

Trends and emerging research areas were identified, and related areas of research were projected. The information was related to the different extraction methods that could be implemented to obtain bioactive compounds from avocado and their applications in the development of lipid matrices.

RESULTS AND DISCUSSION

The search comprising the period 2019-2024 yielded 819 publications related to conventional and emerging extraction methods of functional compounds from avocado and other plant residues, especially seeds and peels, and their application in food matrices.

Figure 2A shows exponential growth in the publication of articles associated with this topic; with a peak in the year 2024, with more than 200 articles. For the period 2019-2020, about 150 articles on the use of emerging methods for the extraction of bioactive compounds from plant residues such as potato peel or avocado seed were published. Methods such as ultrasound, microwaves, supercritical fluids and the use of enzymes are some of the most relevant to enhance both extraction yields and analyte´s quality (Ibarra-Buenavista et al. 2020; Wang et al. 2020). Meanwhile, there is extensive research on the incorporation of bioactive compounds into food matrices such as beverages, bakery, and meat products (Feichtinger and Scholten 2020). Likewise, in the following years, documents that report the use of combined methods for the extraction of analytes from plant material were found. Bioactive compounds are not only used as antioxidants, but their antifungal and anti-inflammatory properties, are also highlighted.

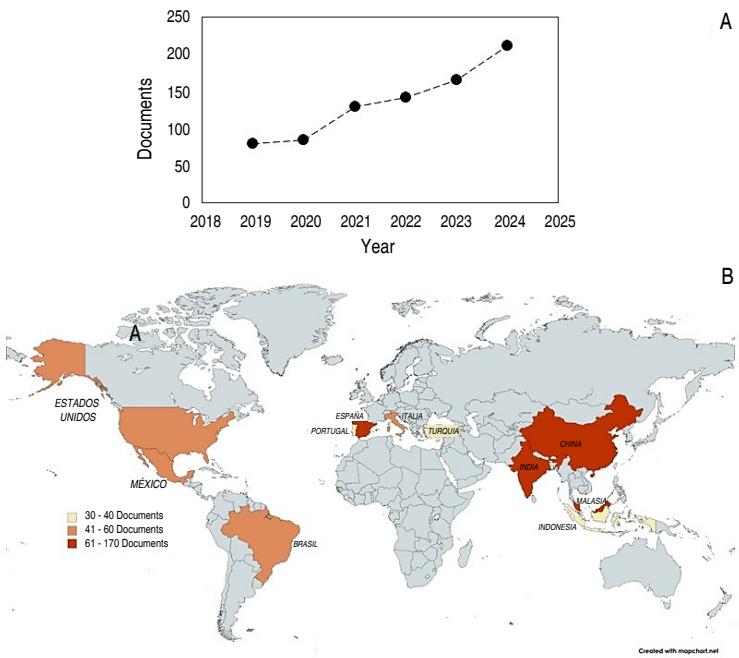


Figure 2. A. Publications by year, and **B.** Publication participation by country.

For the years 2023-2024, numerous studies investigated the effect of natural deep eutectic solvents (NADES) and electric pulse fields on the recovery of bioactive compounds from different agricultural wastes such as avocado, hemp, water hyssop, and grape pomace (Faizah et al. 2024; Grisales-Mejía et al. 2024b; Pojić et al. 2024; Vo et al. 2024; Zhang et al. 2024a). Increasing attention is being repaid to these compounds' bioaccessibility and bioavailability in the human body upon consumption (Sánchez-Quezada et al. 2024; Sharma et al. 2024). Thus, there is scientific evidence of the incorporation of secondary analytes in foods, edible coatings, and in intermediate food matrices such as oleogels for the development of processed foods with health properties (Acquavia et al. 2023; Chen et al. 2023; Rahayu et al. 2023; Sharma et al. 2024).

With respect to territorial participation on a global scale, China's contribution stands out, accounting for 20% of the publications reported in the search period, followed by India, Spain, Brazil, and Mexico with 10, 8, 7 and 5%, respectively. Most of these studies show the effect of extraction methods, applied either individually

or combined, on the physicochemical, biological, and structural properties of target analyses such as tannins, flavonoids, polysaccharides, proteins, fatty acids, among other (Figure 2B). It should also be noted that China is the country with the most publications related to the study of oleogelsas lipid matrices with high tendency to oxidative deterioration (Chen et al. 2024; Jiang et al. 2023; Yang et al. 2024). In the case of Colombia, in 2019, studies involving avocado residues for the extraction of bioactive compounds using conventional technologies such as solvent extraction, with applications in the pharmaceutical industry were reported. In addition, enzymes were used to extract flavonoids from corn leaves (Hennessey-Ramos et al. 2019; Zuorro et al. 2019). For the years 2020-2021, Colombian research began to evaluate other methods of extraction of phenolic compounds like ultrasound and microwave-assisted extraction from different agro-industrial waste, including avocado leaf (Che-Galicia et al. 2020; Montes et al. 2020).

Subsequent studies demonstrated progress in the use of emerging technologies assisted by solvents such as ethanol, pressurized liquids, and supercritical fluid extraction, applied to avocado residues to evaluate their antioxidant and antimicrobial properties. In the same context, simulation software were incorporated to validate the feasibility of using creole avocado for oil production; more specifically, it is necessary to validate the bioaccesibility and bioavailability of bioactive compounds to demonstrate their functional nature (David et al. 2022; Grisales-Mejía et al. 2022; Herrera-Rodríguez et al. 2022; Herrera-Rodríguez and González-Delgado 2024; Otero-Guzman and Andrade-Pizarro 2025).

Recently, scientific research in Colombia in avocado (Hass) residues has focused on comparing different emerging extraction methods, such as ultrasound and pressurized liquids, particularly using NADES solvents. This approach aims to reducing environmental impact and demonstrate reduced extract toxicity for food applications, as well as to validate their potential neuroprotective function (Grisales-Mejía et al. 2024a; Grisales-Mejía et al. 2024b; Restrepo-Serna and Cardona-Alzate 2024). Specifically, the creole avocado has been the subject of limited research. Recent publications have reported, through simulation studies, the viability of using the creole-Antillean avocado in the production of chlorophyll, bio-oil, and biopesticides in a biorefinery framework (García-Maza et al. 2024). However, a gap in the potential of native avocado and in the complementarity of extraction methods is identified, highlighting the need for adopting technologies that enhance both the yield and quality of the extracts.

Agricultural and biological sciences were the thematic areas of greatest interest in the search period, representing 23.1% of the reported publications (Figure 3A). The application of microorganisms and enzymes as biological pretreatment has gained relevance, not only due to their biological benefits but also because of their potential for large-scale use in the food, pharmaceutical, and chemical industries. Likewise, the biological properties of some bioactive compounds extracted from plant material are highlighted in these investigations, emphasizing antioxidant, anti-inflammatory, and antifungal properties. In some instances, these properties are considered not only from a food science perspective but also from a medical standpoint (Lacerda et al. 2024; Phongthai and Rawdkuen 2020; Zhang et al. 2024b).

The chemical area accounted for 12.5% of the publications, highlighting the importance of bioactive compounds such as antioxidants and their potential effect on food matrices. For example, in this area, significant attention has been given to research focused on oleogels, particularly regarding the plant-based origin of the oil, different types of oleogelators, and their application according to their thermodynamic, structural, viscoelastic, and physical properties (Zulfiqar et al. 2024).

In the area of genetic biochemistry and molecular biology, the evaluation of different extraction methods of phenolic compounds from tubers and cereals has been relevant. These methods include enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction. The studies highlight the disadvantages of solvent-based methods, particularly due to their high cost and extended processing times (Gupta et al. 2024; Li et al. 2024). Meanwhile, Li et al. (2021) suggested different techniques for the extraction of polysaccharides, using physical pretreatments such as particle size reduction and evaluating the structural, rheological, and antioxidant properties of the white, brown fruit (*Morus alba*). Regarding the application of oils extracted

from vegetable sources, the development of oleogels from natural waxes and their incorporation in food preparations such as rice cooking have been reported (Xu et al. 2024).

Figure 3B shows the relevance of the journals publishing studies on this topic. It is evident that the journals Food Chemistry, International Journal of Biological Macromolecules, Molecules, Antioxidants and Foods account for the highest number of publications during the search period. These high-impact journals show that extracts from plant materials with antioxidant capacity and their application in different food matrices has been a trending topic. Likewise, it is reported that more than 75% of the related scientific dissemination corresponds to research articles, followed by review papers with 17.5% and book chapters with 4.4%. This provides greater strength to the research foundation supported by this format.

The leading authors in the field of bioactive compounds and their antioxidant capacity, as well as their application in food matrices, are reported in Table 2.

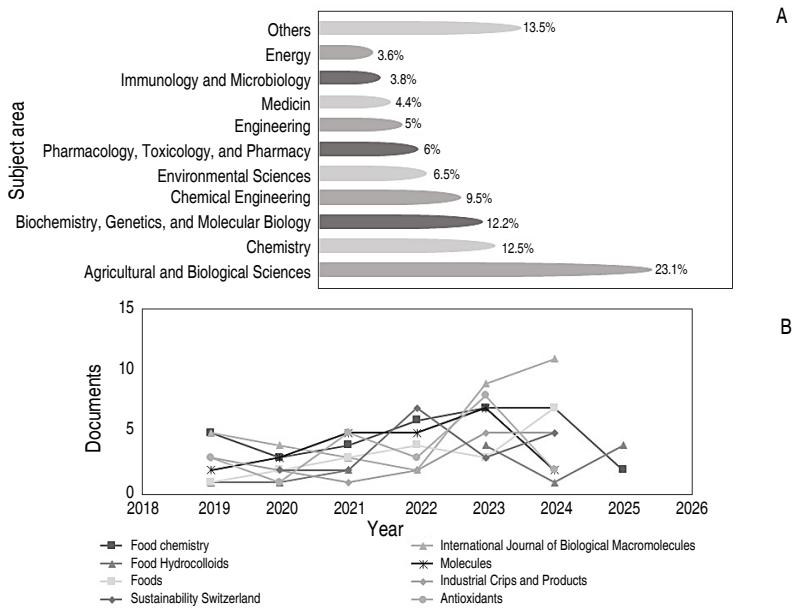


Figure 3. A. Participation by areas, and **B**. Publications by journals.

Table 2. Leading authors and associated institutions.

Author	Nº of publications	Affiliated institution
Beatriz Gullón	7	University of Vigo
José Manuel Lorenzo	6	Meat Technology Center Foundation
Vassilis Athanasiadis	5	University of Thessaly
Eleni Bozinou	5	
Margarita María Andrade-Mahecha	5	Universidad Nacional de Colombia – Palmira Headquarters
Hugo Alexander Martínez Correa	5	
Gabriela Alves Macedo	5	State University of Campinas
Lilian Barros	4	Polytechnic Institute of Bragança
Gangliang Huang	4	Chongqing Normal University
Manoj M. Kumar	4	ICAR - Central Research Institute of Cotton Technology, Mumbai

Research carried out at the University of Vigo has addressed the extraction of bioactive compounds from avocado seeds and peels, with particular emphasis on the use of deep eutectic solvents and microwave- or ultrasound-assisted extraction techniques (Del-Castillo-Llamosas et al. 2023; Gullón et al. 2021). José Manuel Lorenzo, from the Meat Technology Center Foundation, has co-authored review papers and book chapters in collaboration with Gullón, as well as research articles on berry extracts as natural antioxidants in meat products and the effect of fat substitution by oleogels on the technological, sensory, oxidative and nutritional properties of Bolognese-type sauce (da Silva et al. 2019; Lorenzo et al. 2018). More recently, Lorenzo contributed to scientific knowledge with the publication of articles evaluating the oxidative stability of foods with polyphenols derived from apple by-products, as well as different extraction methods for cottonseed oil, its characterization and its industrial application (Kumar et al. 2023; López-Fernández et al. 2022).

At the University of Thessaly, authors Vassilis Athanasiadis and Eleni Bozinou have recently contributed to science with publications related to the use of different emerging extraction methods of bioactive compounds with antioxidant capacity from different agro-industiral wastes (Athanasiadis et al. 2022; Chatzimitakos et al. 2023). Margarita Andrade and Hugo Martínez Correa from the Universidad Nacional de Colombia (Palmira Headquarters), have identified the biological properties of some agro-industrial wastes, including avocado, by exploring different green extraction technologies (Grisales-Mejía et al. 2024a). In Latin America, the work of researcher Gabriela Macedo, from the State University of Campinas, Brazil, also stands out for her research on the enzymatic extraction of analytes from agro-industrial waste co-products (Barbosa et al. 2021).

The surveillance carried out through the Scopus and the VOSviewer tool generated the thematic map shown in Figure 4 with reference to the extraction methods of bioactive compounds from avocado and their applications in food matrices. Three clusters were precisely identified that explain the studies carried out in relation to the search topic, the significant advances and the projection trends.

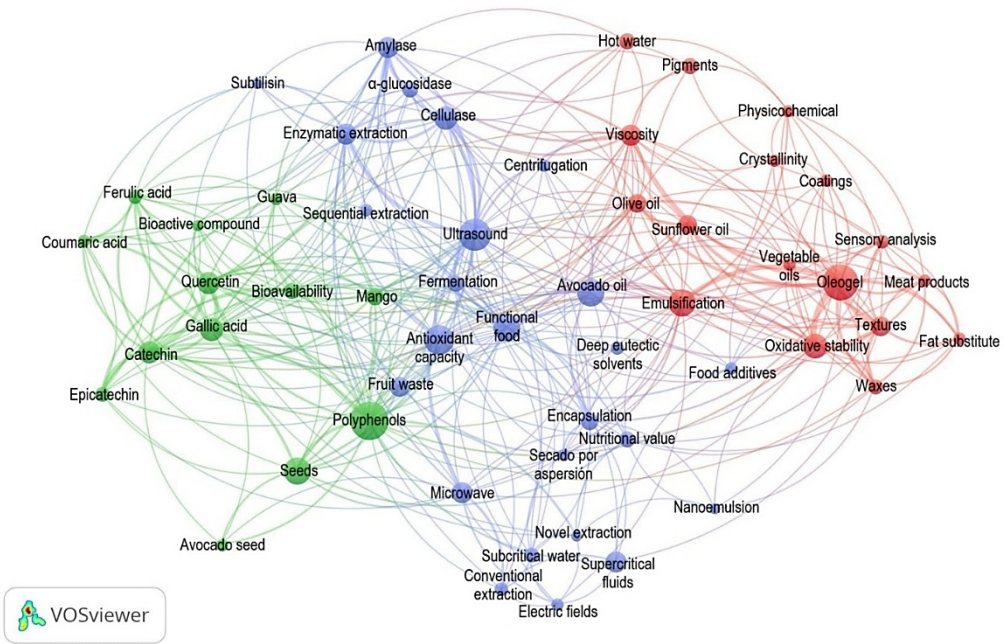


Figure 4. Thematic map of extraction methods for avocado bioactive compounds and their application in lipid matrices.

The blue cluster (I) focused on the **extraction technologies for plant-derived functional compounds with antioxidant capacity**. Numerous authors have reported research focused on the extraction of functional compounds from various plant sources, including avocado. The most studied methods are the conventional ones, specifically, solvents.

In fact, recent research often uses these methods as a reference to report advances in their findings. Likewise, there is interest in studies on subcritical water extraction, supercritical fluids, microwave-assisted extraction, electric field-assisted extraction, ultrasound and enzymatic extraction. Among the enzymes studied, cellulases, amylases, and proteases are the most frequently reported. The use of deep eutectic solvents has also been evaluated as a more environmentally friendly alternative compared to conventional solvents (Grisales-Mejía et al. 2024b; Vo et al. 2024; Zhang et al. 2024a). The combination of extraction processes has become a trend, particularly highlighting the use of electric field-assisted and enzyme-assisted techniques, either in mixtures, simultaneously or sequentially (Chen et al. 2024; Wen et al. 2018; Zuorro et al. 2019).

Thus, the extracted compounds have been scaled up for application either freely or through encapsulation as food additives in the formulation of functional foods with antioxidant capacity and high nutritional value (Kitrytė et al. 2020; Plazzotta et al. 2019). In this way, studies have shown that the combination of emerging methods contributes to the use of green technologies and improves both extraction yields and the quality of extractives (Wang et al. 2019; Xu et al. 2024; Yang et al. 2024). Macedo et al. (2021) evaluated the simultaneous use of enzymes and microwaves in relation to the extraction and composition of phenolic compounds from olive pomace, finding that enzyme-assisted microwave extraction processes improved total polyphenol content yields by approximately 113%.

The green cluster (II) focused on **raw materials for the extraction of bioactive compounds from agro-industrial wastes and their main components**. The study of the biological potential of plant residues has been the subject of research due to their medicinal, pharmaceutical, and antioxidant properties. Furthermore, the contribution to any matrix in which they are incorporated is of great interest, particularly considering their bioavailability (David et al. 2022; Sharma et al. 2024). It is important to highlight that these compounds are found primarily in the cell wall of plants, trapped within lignocellulosic material and, in some cases, form a highly complex matrix with starch, as in the case of avocado seed. The most studied compounds include flavonoids (catechins, epicatechins, p-coumaric acid, quercetin), carotenoids, certain polysaccharides such as starch and fatty acids, with antioxidant capacity (Ibarra-Buenavista et al. 2020; David et al. 2022; Grisales-Mejía et al. 2022).

Most studies related to extraction methods have focused on by-products from the agricultural food industry. The main justification lies in the valorization of waste to mitigate environmental pollution and promote a circular economy approach. In this sense, some of the most interesting wastes include fruit and vegetable seeds and peels. Several studies have reported methods for using grape and olive seeds, due to the large scale of their industries and the disposal of waste generated during the wine and olive oil production. (Jia et al. 2021; Macedo et al. 2021). However, studies have described the potential of other raw materials such as avocado, on which some research has been reported, especially for the Hass variety, describing methods for the extraction of oil from the pulp and seed, as well as the use of the seed and peel for the recovery of bioactive compounds (David et al. 2022; Grisales-Mejía et al. 2022). Although recent studies have explored the biorefinery potential of creole avocado, the available information—particularly regarding the seed—remains limited (García-Maza et al. 2024).

The red cluster (III) referred to the **agro-industrial application of vegetable oils in lipid matrices**. The industry's main interest in avocados has been the extraction of oil from the pulp (Yepes-Betancur et al. 2017). Therefore, many studies have tried to report its nutritional properties according to different extraction methods, so that it can compete on a nutritional level with oils such as extra virgin olive oil (Tang et al. 2024). The main quality parameters for these oils are related to textural, chemical, physicochemical and structural properties. In this context, studies have been reported in recent decades on the substitution of fats in food products by oleogels, which provide a greater nutritional contribution while preserving their properties. da Silva et al. (2019), have reported the development of meat products with fat substitution by sunflower oil oleogels and their effect on technological, sensory, and oxidative properties. Several studies have been reported on the formulation of oleogels from different

vegetable oils such as soybean, sunflower or canola, among others (Thakur et al. 2022; Yang et al. 2020). Studies of oleogels with Hass avocado oil have been reported; however, scientific production on the subject remains limited, especially in Colombia, where there are still technological gaps regarding the development of food products with oleogels as fat substitutes, made with the incorporation of natural antioxidants that allow preserving products quality (Pérez-Monterroza et al. 2014; Pérez-Monterroza et al. 2016).

CONCLUSION

Analyses conducted in this study show that one of the most relevant alternatives to improve extraction yields and the quality of extracted compounds from avocado is the combination of technologies assisted especially by electric fields, ultrasound, and enzymes. The main trends in this research area include the application of NADES in assisted green technologies, which have proven to enhance the quality of the bioactive compounds and yield extraction rate. These methodologies represent a considerable advance in the study of extraction methods for bioactive compounds and could contribute significantly to improving the quality of the food matrices in which they are incorporated. Therefore, the use of creole avocado is a highly promising alternative for the development of products with high nutritional and functional value, such as oleogels. Their application is projected not only to the food industry, but also to the pharmaceutical industry; thus, it is proposed to deepen the study of processes such as the encapsulation of extracts to ensure bioavailability and bioaccessibility in consumer health. These processes must be explored further considering the potential of incorporating antioxidant compounds into such matrices, the challenges that the food industry currently faces, and consumer requirements for healthy eating habits and lifestyle. This leads to the viability of approaching biorefinery as a line of research for avocado.

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CONFLICT OF INTERESTS

The authors declare no conflicts of interest.

REFERENCES

Acevedo-Viloria N, Cervera-Ricardo M, Figueroa-Flórez J et al (2024) Vigilancia científica y tecnológica en procesos de modificación físico-enzimática en gránulos de almidón. Revista UDCA Actualidad & Divulgación Científica 27. https://doi.org/10.31910/RUDCA.V27.N1.2024.2416

Acquavia MA, Benítez JJ, Bianco G et al (2023) Incorporation of bioactive compounds from avocado by-products to ethyl cellulose-reinforced paper for food packaging applications. Food Chem 429:136906. https://doi.org/10.1016/J.FOODCHEM.2023.136906

Andrade JM, Ramírez Plazas E and Quintero A (2017) Vigilancia tecnológica del sector agroindustrial. Entornos 30:23–35. https://doi.org/10.25054/01247905.1404

Araújo RG, Rodriguez-Jasso RM, Ruiz HA et al (2020) Process optimization of microwave-assisted extraction of bioactive molecules from avocado seeds. Ind Crops Prod 154:112623. https://doi.org/10.1016/j.indcrop.2020.112623

Araújo RG, Rodriguez-Jasso RM, Ruiza HA et al (2018) Avocado by-products: Nutritional and functional properties. Trends Food Science & Technology 80:51–60. https://doi.org/10.1016/j.tifs.2018.07.027

Athanasiadis V, Chatzimitakos T, Kotsou K et al (2022) Optimization of the extraction parameters for the isolation of bioactive compounds from orange peel waste. Sustainability 14:13926. https://doi.org/10.3390/su142113926

Barbosa P de PM, Ruviaro AR and Macedo GA (2021) Conditions of enzyme-assisted extraction to increase the recovery of flavanone aglycones from pectin waste. Journal of Food Science and Technology 58:4303–4312. https://doi.org/10.1007/s13197-020-04906-4

Barrera López RS and Arrubla Vélez JP (2017) Análisis de fitoesteroles en la semilla de *Persea americana* Miller (var. Lorena) por cromatografía de gases y cromatografía líquida de alta eficiencia. Revista Facultad de Ciencias Básicas 13:35–41. https://doi.org/10.18359/rfcb.2013

Casas Godoy L and Sandoval Fabián GC (2014) Enzimas en la valorización de residuos agroindustriales. Revista Digital Universitaria 15.

Chatzimitakos T, Athanasiadis V, Kalompatsios D et al (2023) Sustainable valorization of sour cherry (*Prunus cerasus*) by-products: Extraction of antioxidant compounds. Sustainability 16:32. https://doi.org/10.3390/su16010032

Che-Galicia G, Váquiro-Herrera HA, Sampieri Á and Corona-Jiménez E (2020) Ultrasound-assisted extraction of phenolic compounds from avocado leaves (*Persea americana* Mill. var. Drymifolia): Optimization and modeling. International Journal of Chemical Reactor Engineering 18. https://doi.org/10.1515/IJCRE-2020-0023

Chen BJ, Liu Y, Yang K et al (2023) Amylase-assisted extraction alters nutritional and physicochemical properties of polysaccharides and saponins isolated from *Ganoderma* spp. Food Chem X 20:100913. https://doi.org/10.1016/J.FOCHX.2023.100913

Chen H, Bai Z, Tao S et al (2024) Optimization of enzyme-assisted microwave extraction, structural characterization, antioxidant activity

and *in vitro* protective effect against H2O2-induced damage in HepG2 cells of polysaccharides from roots of *Rubus crataegifolius* Bunge. International Journal Biological Macromolecules 276:133969. https://doi.org/10.1016/J.IJBIOMAC.2024.133969

da Silva SL, Amaral JT, Ribeiro M et al (2019) Fat replacement by oleogel rich in oleic acid and its impact on the technological, nutritional, oxidative, and sensory properties of Bologna-type sausages. Meat Science 149:141–148. https://doi.org/10.1016/J.MEATSCI.2018.11.020

David D, Alzate AF, Rojano B et al (2022) Extraction and characterization of phenolic compounds with antioxidant and antimicrobial activity from avocado seed (*Persea americana* Mill). Bionatura 7. https://api.semanticscholar.org/CorpusID:254725390

Del-Castillo-Llamosas A, Eibes G, Ferreira-Santos P et al (2023) Microwave-assisted autohydrolysis of avocado seed for the recovery of antioxidant phenolics and glucose. Bioresource Technology 385:129432. https://doi.org/10.1016/j.biortech.2023.129432

Faizah N, Widiyastuti W, Setyawan H and Nurtono T (2024) Extraction of antioxidant and antibacterial agents from avocado (*Persea americana*) seed using Pulsed Electric Field method. Industrial Crops and Products 222:119803. https://doi.org/10.1016/j.indcrop.2024.119803

Feichtinger A and Scholten E (2020) Preparation of protein oleogels: Effect on structure and functionality. Foods 9. https://doi.org/10.3390/FOODS9121745

García-Maza S, Herrera-Rodríguez TC and González-Delgado ÁD (2024) Process simulation and technical evaluation using Water-Energy-Product (WEP) analysis of an extractive-based biorefinery of creole-antillean avocado produced in the Montes de María. Sustainability 16:9575. https://doi.org/10.3390/su16219575

Gil-Martín E, Forbes-Hernández T, Romero A et al (2022) Influence of the extraction method on the recovery of bioactive phenolic compounds from food industry by-products. Food Chemistry 378:13198. https://doi.org/10.1016/j.foodchem.2021.131918

Grisales-Mejía JF, Álvarez-Rivera G, Torres-Castañeda HG et al (2024a) Hass Avocado (*Persea americana* Mill.) residues as a new potential source of neuroprotective compounds using pressurized liquid extraction. The Journal of Supercritical Fluids 204:106117. https://doi.org/10.1016/j.supflu.2023.106117

Grisales-Mejía JF, Cedeño-Fierro V, Ortega JP et al (2024b) Advanced NADES-based extraction processes for the recovery of phenolic compounds from Hass avocado residues: A sustainable valorization strategy. Separation and Purification Technology 351:128104. https://doi.org/10.1016/J.SEPPUR.2024.128104

Grisales-Mejía JF, Torres-Castañeda H, Andrade-Mahecha MM and Martínez-Correa HA (2022) Green extraction methods for recovery of antioxidant compounds from Epicarp, seed, and seed tegument of avocado var. Hass (*Persea americana* Mill.). International Journal of Food Science 2022. https://doi.org/10.1155/2022/1965757

Gullón P, del Río PG, Gullón B et al (2021) Pectooligosaccharides as emerging functional ingredients: Sources, extraction technologies, and biological activities. In: Sustainable Production Technology in Food. Elsevier, pp 71–92.

Gupta A, Bobade H, Sharma R and Sharma S (2024) Technological and analytical aspects of bioactive compounds and nutraceuticals from roots and tubers sources. Bioactive Compounds and Nutraceuticals from Plant Sources 121–155. https://doi.org/10.1201/9781003455172-5

Hennessey-Ramos L, Murillo-Arango W and Guayabo GT (2019) Evaluation of a colorant and oil extracted from avocado waste as functional components of a liquid soap formulation. Revista Facultad Nacional de Agronomía Medellin 72:8855–8862. https://doi.org/10.15446/RFNAM.V72N2.74573

Herrera-Rodríguez T, Parejo-Palacio V and González-Delgado Á (2022) Computer-Aided simulation of avocado oil production in North Colombia. Chemical Engineering Transactions 92:415–420. https://doi.org/10.3303/CET2292070

Herrera-Rodríguez TC and González-Delgado ÁD (2024) Inherent safety index evaluation of an extractive-based creole-antillean avocado biorefinery in Montes de María, Colombia. Sustainability 17:168. https://doi.org/10.3390/su17010168

Hurtado-Fernández E, Fernández-Gutiérrez A and Carrasco-Pancorbo A (2018) Avocado fruit—*Persea americana*. In: Exotic Fruits, Academic P. pp 37–48

Ibarra-Buenavista AE, Vázquez-Celestino D, Vázquez-Barrios ME et al (2020) The use of instant controlled pressure drop (DIC) method improves the extraction of bioactive compounds from 'Hass' avocado seed. Acta Horticulturae 1299:377–382. https://doi.org/10.17660/ACTAHORTIC.2020.1299.56

Illanes A, Wilson L and Vera C (2014) Problem solving in enzyme biocatalysis. J. Wiley & Sons, Ltd. 344p.

Jia M-Z, Fu X-Q, Deng L et al (2021) Phenolic extraction from grape (*Vitis vinifera*) seed via enzyme and microwave co-assisted salting-out extraction. Food Biosci 40:100919.

Jiang F, Chen R, Tang C et al (2023) Polysaccharide extracted from cultivated Sanghuangporous vaninii spores using three-phase partitioning with enzyme/ultrasound pretreatment: Physicochemical characteristics and its biological activity *in vitro*. International Journal of Biological Macromolecules 253:126622. https://doi.org/10.1016/J.IJBIOMAC.2023.126622

Kitrytė V, Narkevičiūtė A, Tamkutė L et al (2020) Consecutive high-pressure and enzyme assisted fractionation of blackberry (*Rubus fruticosus* L.) pomace into functional ingredients: Process optimization and product characterization. Food Chem 312:126072.

Kumar M, Zhang B, Potkule J et al (2023) Cottonseed oil: Extraction, characterization, health benefits, safety profile, and application. Food Anal Methods 16:266–280. https://doi.org/10.1007/s12161-022-02410-3

Lacerda VR, Bastante CC, Machado ND et al (2024) Supercritical extraction of betalains from the peel of different pitaya species. Journal of the Science of Food and Agriculture 104:5513–5521. https://doi.org/10.1002/JSFA.13383

Li D, Chen M, Meng X et al (2024) Extraction, purification, structural characteristics, bioactivity and potential applications of polysaccharides from *Avena sativa* L.: A review. International Journal of Biological Macromolecules 265:130891. https://doi.org/10.1016/J.IJBIOMAC.2024.130891

Li M, Li T, Hu X et al (2021) Structural, rheological properties and antioxidant activities of polysaccharides from mulberry fruits (*Murus alba* L.) based on different extraction techniques with superfine grinding pretreatment. International Journal of Biological Macromolecules 183:1774–1783. https://doi.org/10.1016/j.ijbiomac.2021.05.108

López-Fernández O, Bohrer BM, Munekata PES et al (2022) Improving oxidative stability of foods with apple-derived polyphenols.

Comprehensive Reviews in Food Science and Food Safety 21:296–320. https://doi.org/10.1111/1541-4337.12869

Lorenzo JM, Pateiro M, Domínguez R et al (2018) Berries extracts as natural antioxidants in meat products: A review. Food Research International 106:1095–1104. https://doi.org/10.1016/J.FOODRES.2017.12.005

Macedo GA, Santana AL, Crawford LM et al (2021) Integrated microwave- and enzyme-assisted extraction of phenolic compounds from olive pomace. LWT - Food Science and Technology 138:110621.

Montes CF, Rojas-González AF and Rodríguez-Barona S (2020) Evaluation of extracts obtained from fruitwastes using different methods. Ingeniería 26:77–92. https://doi.org/10.14483/23448393.16525

Muthusamy S, Udayakumar GP and Narala VR (2021) Recent advances in the extraction and characterization of seed polysaccharides, and their bioactivities: A review. Bioactive Carbohydrates and Dietary Fibre 26:100276.

Otero-Guzman N and Andrade-Pizarro R (2025) Bioactive compounds from tropical fruit by-products: Extraction, characterization and therapeutic potential. Journal of Agriculture and Food Research 21:101983. https://doi.org/10.1016/j.jafr.2025.101983

Palla C, Giacomozzi A, Genovese DB and Carrín ME (2017) Multi–objective optimization of high oleic sunflower oil and monoglycerides oleogels: Searching for rheological and textural properties similar to margarine. Food Structure 12:1–14. https://doi.org/10.1016/j.foostr.2017.02.005

Pérez-Monterroza EJ, Ciro-Velásquez HJ and Arango Tobón JC (2016) Study of the crystallization and polymorphic structures formed in oleogels from avocado oil. Revista Facultad Nacional de Agronomía Medellin 69:7945–7954. https://doi.org/10.15446/rfna.v69n2.59139

Pérez-Monterroza EJ, Marquez-Cardozo CJ and Ciro-Velasquez HJ (2014) Rheological behavior of avocado (*Persea americana* Mill, cv. Hass) oleogels considering the combined effect of structuring agents. LWT - Food Science and Technology 59:673–679. https://doi.org/10.1016/j.lwt.2014.07.020

Phongthai S and Rawdkuen S (2020) Fractionation and characterization of antioxidant peptides from rice bran protein hydrolysates stimulated by in vitro gastrointestinal digestion. Cereal Chem 97:316–325. https://doi.org/10.1002/CCHE.10247

Plazzotta S, Calligaris S and Manzocco L (2019) Structure of oleogels from κ-carrageenan templates as affected by supercritical-CO2- drying, freeze-drying and lettuce-filler addition. Food Hydrocolloids 96:1–10. https://doi.org/10.1016/j.foodhyd.2019.05.008

Pojić M, Teslić N, Banjac V et al (2024) Natural deep eutectic solvents for efficient recovery of bioactive compounds from by-product of industrial hemp processing: Pretreatment, modeling and optimization. Industrial Crops and Products 222:119617. https://doi.org/10.1016/j.indcrop.2024.119617

Rahayu N, Gunawan S and Aparamarta HW (2023) Extraction of bioactive compound from mangosteen peel (*Garcinia mangostana* L.) using ternary system solvent. AIP Conference Proceedings 2828. https://doi.org/10.1063/5.0164608

Restrepo-Serna DL and Cardona-Alzate CA (2024) The avocado peel as a source of catechins: A comparison between extraction technologies and the influence of fruit variety. Sustainable Chemistry and Pharmacy 39:101556. https://doi.org/10.1016/j.scp.2024.101556

Salazar-López NJ, Domínguez-Avila JA, Yahia EM et al (2020) Avocado fruit and by-products as potential sources of bioactive compounds. Food Research International 138 Part A:1–57. https://doi.org/10.1016/j.foodres.2020.109774

Sánchez-Quezada V, Velázquez-Guadarrama N, Mendoza-Elizalde S et al (2024) Bioaccessibility of bioactive compounds present in *Persea americana* Mill. seed ingredient during oral-gastric digestion with antibacterial capacity against *Helicobacter pylori*. Journal of Ethnopharmacology 331:118259. https://doi.org/10.1016/j.jep.2024.118259

Sandoval Aldana A, Forero Longas F, García Lozano J and Londoño Bonilla M (2020) Cosecha, manejo de poscosecha y agroindustria. In: Actualización tecnológica y buenas prácticas agrícolas (BPA) en el cultivo de aguacate. pp 651–714.

Sharma P, Nickerson MT and Korber DR (2024) Valorization of berry pomace for extraction of polyphenol compounds and its co-encapsulation with probiotic bacteria. Food Bioscience 62:105124. https://doi.org/10.1016/j.fbio.2024.105124

Tang F, Banker T, Green HS et al (2024) Analysis and authentication of avocado oil by low-field benchtop NMR spectroscopy and chemometrics. Journal of Food Science 89:4276–4285. https://doi.org/10.1111/1750-3841.17142

Tanpichai S, Boonmahitthisud A, Soykeabkaew N and Ongthip L (2022) Review of the recent developments in all-cellulose nanocomposites: Properties and applications. Carbohydrate Polymers 286:119192. https://doi.org/10.1016/j.carbpol.2022.119192

Thakur D, Singh A, Prabhakar PK et al (2022) Optimization and characterization of soybean oil-carnauba wax oleogel. LWT - Food Science and Technology 157:113108. https://doi.org/10.1016/j.lwt.2022.113108

Vo TP, Nguyen THP, Nguyen VK et al (2024) Extracting bioactive compounds and proteins from *Bacopa monnieri* using natural deep eutectic solvents. PLoS One 19:e0300969. https://doi.org/10.1371/journal.pone.0300969

Wang J, Wang J, Ye J et al (2019) Influence of high-intensity ultrasound on bioactive compounds of strawberry juice: Profiles of ascorbic acid, phenolics, antioxidant activity and microstructure. Food Control 96:128–136. https://doi.org/10.1016/J.FOODCONT.2018.09.007

Wang S, Lin AHM, Han Q and Xu Q (2020) Evaluation of direct ultrasound-assisted extraction of phenolic compounds from potato peels. Processes 2020, Vol 8, Page 1665 8:1665. https://doi.org/10.3390/PR8121665

Wen C, Zhang J, Zhang H et al (2018) Advances in ultrasound assisted extraction of bioactive compounds from cash crops – A review. Ultrasonics Sonochemistry 48:538–549. https://doi.org/10.1016/J.ULTSONCH.2018.07.018

Xu L, Liu L, Wang Y et al (2024) Oleogel for improving the texture and flavor in rice cooking: Preparation from natural wax and rice bran oil and characterization. Journal of Cereal Science 118:103955. https://doi.org/10.1016/J.JCS.2024.103955

Yang M, Gong H, Jiang C gong et al (2024) Effects of different extraction methods on the structure and function of blackberry seed polysaccharides. International Journal of Food Science Technology 59:4866–4879. https://doi.org/10.1111/IJFS.17215

Yang S, Yang G, Chen X et al (2020) Interaction of monopalmitate

and carnauba wax on the properties and crystallization behavior of soybean oleogel. Grain & Oil Science and Technology 3:49–56. https://doi.org/10.1016/j.gaost.2020.05.001

Yepes-Betancur DP, Sánchez Giraldo L and Márquez Cardozo CJ (2017) Extracción termomecánica y caracterización fisicoquímica del aceite de aguacate (*Persea americana* Mill. cv. Hass). Informador Técnico 81:75–85. https://doi.org/10.23850/22565035.728

Yepes-Betancur DP, Márquez-Cardozo CJ, Cadena-Chamorro EM et al (2021) Solid-state fermentation – assisted extraction of bioactive compounds from Hass avocado seeds. Food and Bioproducts Processing 126:155–163. https://doi.org/10.1016/j.fbp.2020.10.012

Zhang S, Lin S, Zhang J and Liu W (2024a) Ultrasound-assisted natural deep eutectic solvent extraction of anthocyanin from *Vitis davidii* Foex. pomace: Optimization, identification, antioxidant activity and stability. Heliyon 10:e33066. https://doi.org/10.1016/j.heliyon.2024.e33066

Zhang Z-fa, Lv G-ying, Song T-ting et al (2024b) Effects of different extraction methods on the structural and biological properties of *Hericium coralloides* polysaccharides. Food Chemistry 445:138752. https://doi.org/10.1016/J.FOODCHEM.2024.138752

Zulfiqar A, Shabbir MA, Tahir F et al (2024) Development of oleogel by structuring the blend of corn oil and sunflower oil with beeswax to replace margarine in cookies. Food Chem X 23. https://doi.org/10.1016/j.fochx.2024.101676

Zuorro A, Lavecchia R, González-Delgado AD et al (2019) Optimization of enzyme-assisted extraction of flavonoids from corn husks. Processes 7:804. https://doi.org/10.3390/PR7110804