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COMPOSTOS BIOATIVOS E POTENCIAL BIOTECNOLÓGICO DE RESÍDUOS E PARTES SUBUTILIZADAS DE *COCOS NUCIFERA* L.: UMA REVISÃO SISTEMÁTICA COM ANÁLISE BIBLIOMÉTRICA EXPLORATÓRIA

BIOACTIVE COMPOUNDS AND BIOTECHNOLOGICAL POTENTIAL OF RESIDUES AND UNDERUTILIZED PARTS OF *COCOS NUCIFERA* L.: A SYSTEMATIC REVIEW WITH EXPLORATORY BIBLIOMETRIC ANALYSIS

COMPUESTOS BIOACTIVOS Y POTENCIAL BIOTECNOLÓGICO DE LOS RESIDUOS Y PARTES INFRAUTILIZADAS DE *COCOS NUCIFERA* L.: UNA REVISIÓN SISTEMÁTICA CON ANÁLISIS BIBLIOMÉTRICO EXPLORATORIO

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Resumo

Este estudo teve como objetivo realizar uma análise integrada (sistemática e bibliométrica exploratória) sobre os resíduos de *Cocos nucifera* L. como fonte de compostos bioativos, utilizando as bases de dados Scopus e Web of Science e os softwares VOSviewer e bibliometrix. Um total de

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27 documentos foram identificados entre 2008 e 2024, refletindo um interesse em pesquisas nesse escopo. O maior número de publicações ocorreu em 2023 (5 artigos), refletindo o fortalecimento da bioeconomia circular e da valorização de resíduos, associado ao uso de tecnologias extrativas mais sustentáveis e estratégias de otimização experimental. O termo "*Cocos nucifera*" foi central na rede, integrando estudos sobre caracterização química, bioatividades e potenciais aplicações dos resíduos da espécie. Os resultados apresentados no Diagrama de Sankey reforçam o caráter interdisciplinar do tema e indicam conexões entre autores, instituições e periódicos em diferentes frentes de aplicação. Contudo, por se tratar de um corpus reduzido, esses padrões devem ser interpretados apenas como organização interna da literatura analisada. Os resíduos evoluíram de passivo ambiental a matrizes bioativas valiosas. Partes subutilizadas de *Cocos nucifera* L., como casca, mesocarpo, testa, haustório e raízes, têm sido investigadas como fontes potenciais de compostos fenólicos, flavonoides e outros metabólitos de interesse. Os estudos analisados também indicam avanço no uso de métodos de extração mais sustentáveis, como ultrassom e CO_2 supercrítico, além de ferramentas de modelagem e otimização para melhorar a eficiência dos processos. As evidências disponíveis sugerem atividades antioxidantes, antimicrobianas, anti-inflamatórias, antidiabéticas e hepatoprotetoras, embora, em grande parte, ainda estejam associadas a ensaios *in vitro*, modelos experimentais ou aplicações laboratoriais. Nesse contexto, os extratos apresentam potencial para futuras aplicações em cosmecêuticos, alimentos funcionais, conservação pós-colheita e valorização tecnológica de biomassa vegetal, desde que sejam realizados estudos adicionais de padronização, estabilidade, segurança, escalonamento e validação em sistemas reais.

Palavras-chave: *Cocos nucifera* L.; resíduos agroindustriais; partes pouco exploradas; compostos bioativos; extração sustentável; bioeconomia circular.

Abstract

This study aimed to conduct an integrated analysis (systematic and exploratory bibliometric) of *Cocos nucifera* L. residues as a source of bioactive compounds, utilizing the Scopus and Web of Science databases alongside VOSviewer and bibliometrix software. A total of 27 documents were identified between 2008 and 2024, reflecting research interest in this scope. The highest number of publications occurred in 2023 (5 articles), reflecting the strengthening of the circular bioeconomy and waste valorization, linked to the use of more sustainable extraction technologies and experimental optimization strategies. The term "*Cocos nucifera*" was central to the network, integrating studies on chemical characterization, bioactivities, and potential applications of the species' residues. The results presented in the Sankey diagram reinforce the interdisciplinary nature of the topic and indicate connections among authors, institutions, and journals across various application fronts. However, given the limited size of the corpus, these patterns should be interpreted solely as the internal organization of the analyzed literature. The residues have evolved from environmental liabilities into valuable bioactive matrices. Underutilized parts of *Cocos nucifera* L., such as the husk, mesocarp, testa, haustorium, and roots, have been investigated as potential sources of phenolic compounds, flavonoids, and other metabolites of interest. The analyzed studies also indicate progress in the use of more sustainable extraction methods, such as ultrasound and supercritical CO_2, as well as modeling and optimization tools to enhance process efficiency. Available evidence suggests antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and hepatoprotective activities, although these findings remain largely associated with *in vitro* assays, experimental models, or laboratory-scale applications. In this context, the extracts show potential for future applications in cosmeceuticals, functional foods, post-harvest preservation, and the technological valorization of plant biomass, provided that further studies are conducted regarding standardization, stability, safety, scale-up, and validation in real-world systems.

Keywords: *Cocos nucifera* L.; agro-industrial residues; underutilized parts; bioactive compounds; sustainable extraction; circular bioeconomy.

Resumen

Este estudio tuvo como objetivo realizar un análisis integrado (bibliométrico sistemático y

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exploratorio) sobre los residuos de *Cocos nucifera* L. como fuente de compuestos bioactivos, utilizando las bases de datos Scopus y Web of Science, así como los programas VOSviewer y Bibliometrix. Se identificó un total de 27 documentos entre 2008 y 2024, lo que refleja el interés en la investigación en este ámbito. El mayor número de publicaciones se registró en 2023 (5 artículos), lo que evidencia el fortalecimiento de la bioeconomía circular y la valorización de los residuos, asociados al uso de tecnologías extractivas más sostenibles y estrategias de optimización experimental. El término "*Cocos nucifera*" fue fundamental en la red, integrando estudios sobre caracterización química, bioactividades y posibles aplicaciones de los residuos de esta especie. Los resultados presentados en el Diagrama de Sankey refuerzan la naturaleza interdisciplinaria del tema e indican conexiones entre autores, instituciones y revistas en diferentes áreas de aplicación. Sin embargo, dado que se trata de un corpus pequeño, estos patrones deben interpretarse únicamente como una organización interna de la literatura analizada. Los residuos han evolucionado de ser lastre ambiental a valiosas matrices bioactivas. Partes subutilizadas de *Cocos nucifera* L., como la cáscara, el mesocarpio, la testa, el haustorio y las raíces, se han investigado como fuentes potenciales de compuestos fenólicos, flavonoides y otros metabolitos de interés. Los estudios analizados también indican avances en el uso de métodos de extracción más sostenibles, como ultrasonidos y CO_2 supercrítico, así como herramientas de modelado y optimización para mejorar la eficiencia del proceso. La evidencia disponible sugiere actividades antioxidantes, antimicrobianas, antiinflamatorias, antidiabéticas y hepatoprotectoras, aunque gran parte de esto aún se asocia con ensayos *in vitro*, modelos experimentales o aplicaciones de laboratorio. En este contexto, los extractos muestran potencial para futuras aplicaciones en cosmecéuticos, alimentos funcionales, conservación poscosecha y valorización tecnológica de la biomasa vegetal, siempre que se realicen más estudios sobre estandarización, estabilidad, seguridad, escalado y validación en sistemas reales.

Palabras clave: *Cocos nucifera* L.; residuos agroindustriales; partes subutilizadas; compuestos bioactivos; extracción sostenible; bioeconomía circular.

1. Introduction

Growing interest in the principles of the circular bioeconomy and the valorization of agro-industrial waste has driven research aimed at the comprehensive utilization of plant biomass to produce higher-value-added products. In this context, the coconut palm (*Cocos nucifera* L.) stands out not only for its economic importance and widespread global distribution but also for the significant volume of waste generated throughout its production chain and its underutilized components. Various parts of the coconut, such as the husk, mesocarp, testa, and less-explored structures like the haustorium and roots, have attracted interest as promising sources of bioactive compounds, particularly polyphenols, flavonoids, and other secondary metabolites associated with diverse biological activities. Utilizing these under-exploited materials represents a sustainable strategy to reduce environmental impacts, add value to coconut production by-products, and expand application possibilities across sectors such as food, cosmetics, pharmaceuticals, and agriculture (Arivalagan et al., 2018;

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Narayanankutty et al., 2023; Mady et al., 2025).

Interest in these plant matrices has driven the development of various strategies for obtaining bioactive compounds. Conventional extraction methods are increasingly being replaced or complemented by technologies considered more efficient and sustainable, such as ultrasound-assisted, microwave-assisted, and supercritical fluid extraction, which are capable of increasing extraction yields, reducing solvent consumption, and minimizing processing time (Lima et al., 2015).

In parallel, optimization tools based on mathematical modeling and artificial intelligence, such as Response Surface Methodology (RSM) and Artificial Neural Networks combined with Particle Swarm Optimization (ANN-PSO), have been employed to optimize operating conditions and maximize the recovery of bioactive compounds (Yang et al., 2021; Singh et al., 2023).

As a result of these advances, various studies have demonstrated that extracts obtained from residues and underutilized parts of *Cocos nucifera* L. exhibit promising biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties, indicating potential for applications in functional foods, cosmetics, biomaterials, and other products of interest. However, translating this potential into technological applications still faces significant challenges. Extraction efficiency can be influenced by the complexity of the plant matrix, the composition of the solvent system, and the enzymatic degradation of phenolic compounds during processing. Furthermore, high-efficiency technologies, such as supercritical CO_2 extraction, still present limitations related to high implementation costs and difficulties regarding industrial scale-up (Chinthra et al., 2020; Yang et al., 2021; Singh et al., 2023; Malage et al., 2024).

Despite the growing number of publications, available knowledge remains fragmented across different plant matrices, extraction methods, optimization strategies, and proposed applications. This fragmentation hinders the comparison of studies and the identification of the most promising approaches for the sustainable utilization of residues and underused parts of *Cocos nucifera* L. Furthermore, the methodological diversity found in these studies limits the consolidation of knowledge regarding extraction technologies, the bioactive

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compounds obtained, and the development stage of their applications. In this context, integrating bibliometric analysis with a systematic review offers a valuable approach to critically organize available evidence and identify research trends, knowledge gaps, and prospects for developing more efficient processes and sustainable technological applications. Therefore, this study aimed to conduct a systematic review combined with an exploratory bibliometric analysis of the literature on bioactive compounds derived from residues and underused parts of *Cocos nucifera* L., focusing on extraction methods, optimization strategies, reported biological activities, and the potential for technological application of these compounds.

2. Methodology

2.1 Study design

The study titled “Bioactive compounds and biotechnological potential of residues and underutilized parts of *Cocos nucifera* L.: a systematic review with exploratory bibliometric analysis” consists of a systematic review integrated with a bibliometric analysis, conducted in accordance with the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA, 2020) (Page et al., 2021). The systematic review was employed to identify, select, and critically synthesize available evidence regarding bioactive compounds obtained from residues and underutilized parts of *Cocos nucifera* L., while the bibliometric analysis served as an exploratory approach to characterize the evolution of scientific output, identify research trends, and visualize collaboration networks related to the topic. Integrating these approaches enabled a quantitative analysis of scientific output and a qualitative synthesis of evidence concerning the plant matrices studied, extraction methods, optimization strategies, bioactive compounds, and potential for technological application.

2.2 Search strategy

The search strategy was designed to retrieve articles investigating bioactive compounds obtained from agro-industrial residues and underutilized parts of *Cocos nucifera* L., with an emphasis on extraction methods, optimization strategies, and

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potential for technological application. Searches were conducted in March 2026 by the co-authors (RVC, GNS, WSS, and JRJC) in the Scopus (Elsevier) and Web of Science – WOS (Clarivate Analytics) databases, selected for their broad multidisciplinary coverage, indexing of high-impact peer-reviewed journals, and availability of bibliographic data suitable for bibliometric analysis (Oliveira et al., 2024; Oliveira et al., 2025). The entire search strategy was guided and reviewed by the co-author (IHSS), who has expertise in the extraction of bioactive compounds from waste and plants.

Publications ranging from January 2005 to March 10, 2026, were considered. Study eligibility was determined based on inclusion and exclusion criteria. The search strategy was adapted to the specific indexing characteristics of each database while maintaining the conceptual equivalence of the keywords used. In Scopus, the search was conducted using the title, abstract, and keyword fields (*TITLE-ABS-KEY*), whereas in WOS, the "Topic" (TS) search, which encompasses title, abstract, and keywords, was employed.

The search terms were selected based on the review's objective and preliminary exploratory searches, and were subsequently combined using Boolean operators (AND, OR, and NOT) to increase the specificity of document retrieval. The complete strategies used for each database are presented below:

Scopus

TITLE-ABS-KEY (“Cocos nucifera” OR “coconut husk” OR “green coconut shell” OR “coconut waste”) AND (polyphenols OR flavonoids OR antioxidants OR “phenolic compounds”) AND (extraction OR solvent OR method OR optimization) NOT (“coconut oil” OR “coconut water”)

Web of Science

TS (“Cocos nucifera” OR “coconut husk” OR “green coconut shell” OR “coconut waste”) AND (polyphenols OR flavonoids OR antioxidants OR “phenolic compounds”) AND (extraction OR solvent OR method OR optimization) NOT (“coconut oil” OR “coconut water”)

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Original articles published in English were included, given that this language accounts for the majority of indexed international scientific output on the topic and allows for greater standardization of the bibliometric analysis. However, this restriction may introduce language bias and should be considered a limitation of this study.

2.3 Eligibility criteria

Following the retrieval of records from the databases, pre-defined eligibility criteria were applied to select studies directly related to the objective of this review. These criteria were established to ensure the inclusion of evidence regarding the recovery of bioactive compounds from agro-industrial residues and underutilized parts of *Cocos nucifera* L., as well as extraction and optimization strategies and the potential technological applications of the extracts. The inclusion and exclusion criteria adopted are presented in Table 1.

Original articles published in English were included if they investigated agro-industrial residues and underutilized parts of *Cocos nucifera* L., such as the husk, fiber, mesocarp, endosperm, testa, haustorium, roots, and other plant by-products. Eligible studies had to address at least one of the following aspects: (i) extraction methods for bioactive compounds, with an emphasis on phenolic compounds and flavonoids; (ii) extraction optimization strategies; (iii) chemical characterization of the extracts; (iv) evaluation of biological activities, including antioxidant and/or antimicrobial activity; or (v) potential for the technological application of the obtained extracts.

Articles that focused primarily on the nutritional composition or the physical or agronomic characterization of plant matrices without investigating the extraction or application of bioactive compounds were excluded. Also excluded were studies that focused primarily on coconut oil, coconut water, or other food products that did not involve the extraction of bioactive compounds.

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Table 1. Inclusion and exclusion criteria for the manuscripts

Exclusion
- Extraction or characterization of materials not covered by the scope (lignin, dyes, proteins, RNA, enzymes)
- Studies outside the scope of the review (did not address the extraction of bioactive compounds or their technological application in residues/underutilized parts of *Cocos nucifera*)
- Studies focused on other coconut products (coconut water, coconut milk, sugar, sap, liquid smoke, ice cream, beverages)
Inclusion
Any manuscript that did not meet any of the above exclusion criteria, following an analysis of the title, abstract, and keywords.

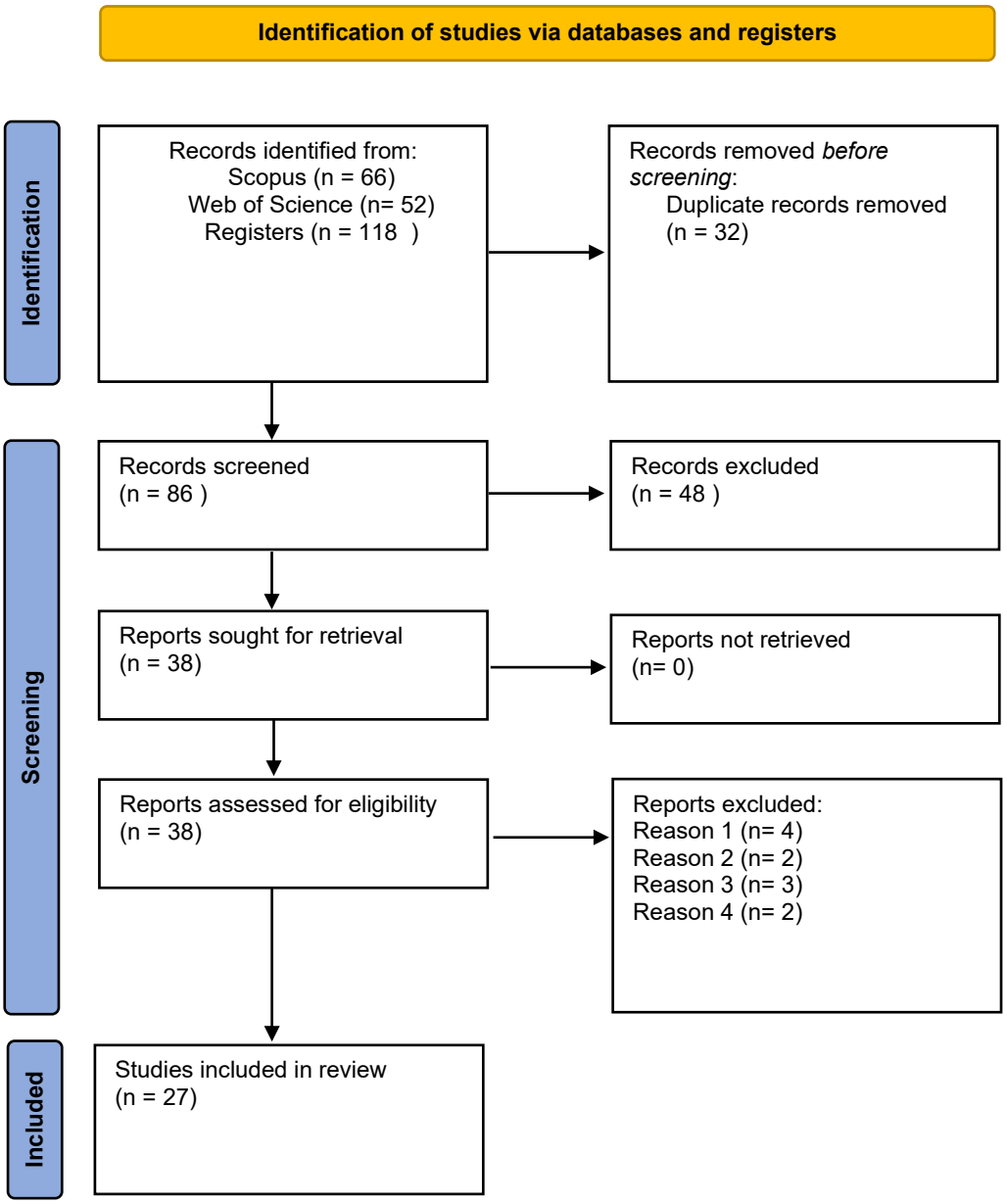
Source: Prepared by the authors (2026).

2.4 Selection of studies

Records retrieved from the Scopus and WOS databases were exported in BibTeX (.bib) and RIS (.ris) formats and imported into the Bibliometrix package within the R environment, where duplicate records were automatically identified and removed. The reference management software Mendeley was used throughout the screening process to select the published articles. The search strategy yielded 118 manuscripts: 66 from Scopus and 52 from Web of Science. After removing 32 duplicates, the co-authors (RVC, GNS, WSS, and JRJC) analyzed the titles and abstracts of the remaining 86 manuscripts. At this stage, 48 were excluded for failing to meet the eligibility criteria (Table 1). The 38 remaining manuscripts were evaluated in full, applying specific exclusion criteria (Table 2), resulting in a final set of 27 articles. Ultimately, 27 manuscripts met the inclusion criteria. In the event of disagreement regarding any criterion, consensus was reached through discussion. The included manuscripts were then reviewed and analyzed.

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Figure 1. Study selection flowchart according to the PRISMA 2020 protocol



Source: Prepared by the authors (2026), adapted from the PRISMA 2020 model.

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Table 2. Reasons for exclusion after full-text reading of the articles

Reason	Justification for exclusion	Registration
1	Out-of-scope materials (pigments, liquid smoke, lignin nanoparticles)	4
2	Ethnobotany and Ethnopharmacology	2
3	No information available	3
4	Other plant species or *Cocos nucifera* are merely cited	2

Source: Prepared by the authors (2026).

2.5 Data collection process

After analyzing the 27 documents and identifying their research objectives and results, it was decided that the research questions should address residues and underutilized parts of *Cocos nucifera*, extraction methods and optimization strategies, the evaluation of biological activity, and potential applications of the extracts. Some questions were answered, such as:

1 - Which residues and underutilized parts of *Cocos nucifera* L. have been investigated as sources of bioactive compounds?

2 - Which extraction methods and optimization strategies predominate in obtaining these compounds, and which technological trends can be identified?

3 - Which bioactive compounds and biological activities are most frequently reported in experimental studies?

4 - What technological applications have been proposed for the obtained extracts, and what challenges still limit their utilization at scale?

The extracted information was subsequently used to construct a general summary table of the included studies, covering the matrix evaluated, matrix classification, extraction method or approach, extraction system, type of experimental approach, technological outcome evaluated, level of experimental/technological support, and critical observations.

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2.6 Risk of bias

The researchers minimized the potential impact of information bias by ensuring that this study was an exploratory literature review. The researchers involved in this study participated in the strategy developed to minimize selection bias. The first specialist conducted the initial search using pre-defined keywords and subsequently carried out all stages of article inclusion and exclusion. The third, fourth, and fifth specialists reviewed the results obtained from the initial search and followed the same inclusion and exclusion steps. The IHSS specialist reviewed all stages.

VOSviewer software (https://www.vosviewer.com/) was used to visualize bibliometric networks, including keyword co-occurrence. Additionally, the Bibliometrix package (https://www.bibliometrix.org/) and Microsoft Excel and Word (Microsoft Office Professional Plus, 2019) were employed to assist with data analysis and representation of the number of manuscripts published by authors and the interactions among sources, authors, and institutions. Bibliometrix is open-source bibliometric software offering a variety of bibliometric methods; it is developed using the R programming language (The Comprehensive R Archive Network, https://cran.r-project.org) (Arruda et al., 2022; Souza et al., 2024). After installing the Bibliometrix package in the R environment, the Bibliometrix web interface can be accessed using the code “bibliometrix: biblioshiny ()”, allowing for the generation of graphical summaries to understand the characteristics of a group of published works. Co-occurrence analysis was based on author keywords, adopting a minimum frequency of two occurrences per term. Before network construction, a thesaurus file was applied to standardize minor variations in scientific nomenclature and terminology, thereby reducing network fragmentation without merging distinct concepts. The relationships between publication sources, authors, and institutions were evaluated using a Three-Field Plot, aiming to visualize, in an exploratory manner, how the included studies are distributed across journals, recurring authors, and institutions associated with the set of articles.

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3. Results and discussion

3.1 Bibliometric overview of scientific output

3.1.1 Temporal evolution of scientific output

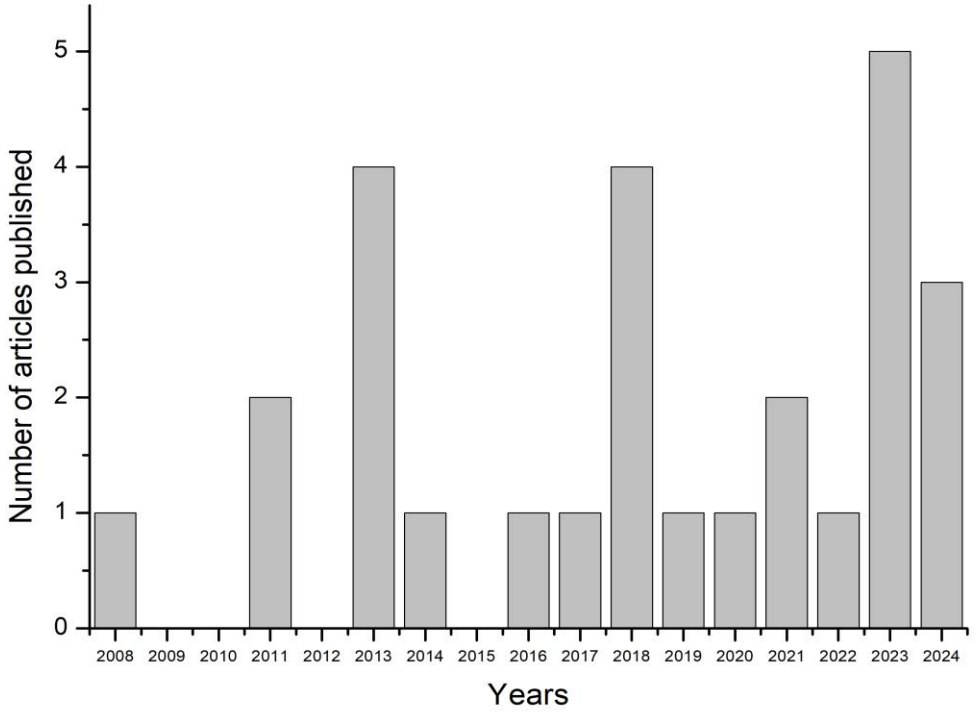
The search strategy identified 118 records in the Scopus and Web of Science databases. After applying the eligibility criteria, 27 articles were included in the review, covering publications from 2008 to 2024. Although the search strategy spanned the period from 2005 to March 2026, no eligible studies were identified for the years 2005–2007 or among publications indexed in 2025 and 2026, as the retrieved records did not meet the scope of this review, which focuses on agro-industrial residues and underutilized parts of *Cocos nucifera* L. as sources of bioactive compounds.

The temporal evolution of publications (Figure 2) reveals a general upward trend in scientific output over the analyzed period, albeit with year-to-year fluctuations. In the early years (2008–2012), the number of publications was low and sporadic, reflecting an initial phase of exploring the phytochemical potential of coconut residues and underutilized plant parts. From 2013 onwards, a more consistent increase in scientific output is observed, indicating growing interest in valorizing this biomass as a source of phenolic compounds, flavonoids, and other bioactive metabolites (Yang et al., 2021; Singh et al., 2023).

The highest number of publications was recorded in 2023, with five articles, followed by 2013 and 2018, with four publications each. This trend mirrors the advancement of research focused on the circular bioeconomy and the valorization of agro-industrial waste, driven by the adoption of more sustainable extraction technologies, such as ultrasound, microwave, and experimental optimization methodologies (Yang et al., 2021; Singh et al., 2023). Concurrently, there is a diversification of the plant matrices under investigation, including the green husk, testa, mesocarp, haustorium, and other underutilized parts of the coconut palm, as well as an expansion of the applications studied, encompassing antioxidant systems, nanotechnology, and food preservation.

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Figure 2. Temporal evolution of publications included in the systematic review (2008–2024)



Source: Prepared by the authors (2026), using Origin software.

Although 2024 yielded three publications, the studies maintain the trend observed in previous years and demonstrate continued research in the field. Conversely, records retrieved for 2025 and 2026 were excluded during the screening stage because they addressed topics outside the scope of this review, such as lignin extraction, the nutritional characterization of coconut derivatives, or studies not focused on obtaining extracts rich in bioactive compounds and their technological applications.

Overall, the temporal distribution of publications highlights the consolidation of this research field over the past two decades, with an evolution ranging from studies focused on phytochemical characterization to investigations aimed at optimizing extraction processes and developing technological applications. This

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scenario underscores the growing importance of valorizing agro-industrial residues and underutilized parts of *Cocos nucifera* L. within the context of the circular bioeconomy.

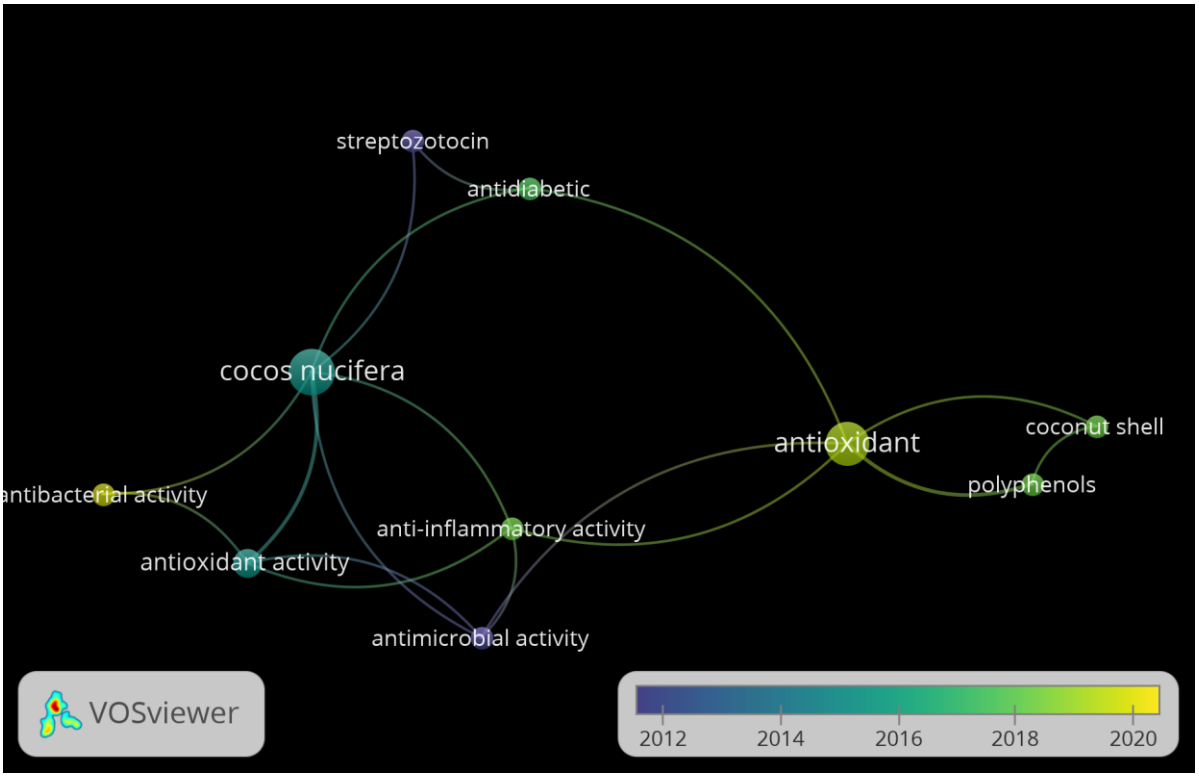
3.1.2 Keyword co-occurrence

Co-occurrence analysis identified 112 keywords across the 27 studies included in this review. A minimum threshold of two occurrences was established, along with term standardization using a thesaurus file; this was used exclusively to standardize the descriptor *Cocos nucifera* L. to *Cocos nucifera* and to unify singular/plural variations of the descriptor "antioxidant." No other term merging or semantic groupings were performed. The final network comprised 10 items organized into three clusters and connected by 17 links, with a Total Link Strength (TLS) of 19, illustrating the thematic structure of the literature regarding residues and underutilized parts of *Cocos nucifera* (Figure 3).

The term *Cocos nucifera* occupied a central position in the network, reflecting its role as an integrating element across different lines of research. Its connection to virtually all other descriptors demonstrates that research involving the species spans everything from the chemical characterization of residues to the evaluation of its biological properties and potential applications.

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Figure 3. Co-occurrence analysis of author keywords.



Source: Prepared by the authors (2026), using data from Scopus and Web of Science processed in VOSviewer software. Note: In the graphical representation, each node corresponds to a keyword, with its size proportional to the number of occurrences. Lines represent co-occurrence relationships between terms, while their thickness indicates the strength of these associations. The proximity between nodes reflects the frequency with which keywords appear together in the analyzed articles, allowing for the identification of the literature's main thematic axes. The color of each circle indicates the keyword's average year of occurrence across the publications, based on the color gradient.

The organization of the network reveals a thematic sequence in the development of the research. A primary axis links the descriptors “coconut shell”, “polyphenols” and “antioxidant” indicating that a significant portion of the literature initially focuses on the phytochemical characterization of coconut residues, particularly regarding the identification of phenolic compounds and their antioxidant capacity. This association demonstrates that the utilization of lignocellulosic residues constitutes a key strategy for obtaining bioactive compounds of biotechnological interest (Yang et al., 2021).

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Based on this chemical characterization, a second grouping is observed comprising “antioxidant activity”, “anti-inflammatory activity”, “antimicrobial activity” and “antibacterial activity”, highlighting a shift in research toward investigating the biological properties of extracts obtained from various *Cocos nucifera* plant matrices. The proximity of these descriptors indicates that such bioactivities are frequently evaluated in a complementary manner, reflecting an interest in identifying multifunctional extracts with potential applications in foods, cosmetics, and other bio-based products.

The third grouping combines the descriptors “antidiabetic” and “streptozotocin” indicating a specific line of research focused on evaluating the antidiabetic potential of bioactive compounds in experimental models (*in vitro*) related to diabetes (Naskar et al., 2011). The association between these terms demonstrates that this topic represents a consolidated strand within the set of studies analyzed.

The overlay visualization also reveals the temporal evolution of the investigated themes. Descriptors related to antioxidant activity, phenolic compounds, and coconut husk appear in colors corresponding to the most recent years of the analyzed period, suggesting growing interest in valorizing waste as a source of bioactive compounds and in developing sustainable biomass utilization strategies. In contrast, descriptors associated with experimental models of antidiabetic activity appear in colors corresponding to the early years of the time series, indicating that this line of research predated the shift toward approaches focused on phytochemical characterization and the technological utilization of waste.

Overall, the network structure demonstrates that research on the residues and underutilized parts of *Cocos nucifera* has evolved from studies focused on evaluating specific bioactivities to more integrated investigations linking phytochemical characterization, biological properties, and the sustainable valorization of biomass. However, given that the analysis was based on a set of 27 studies, the observed patterns should be interpreted as an exploratory overview of

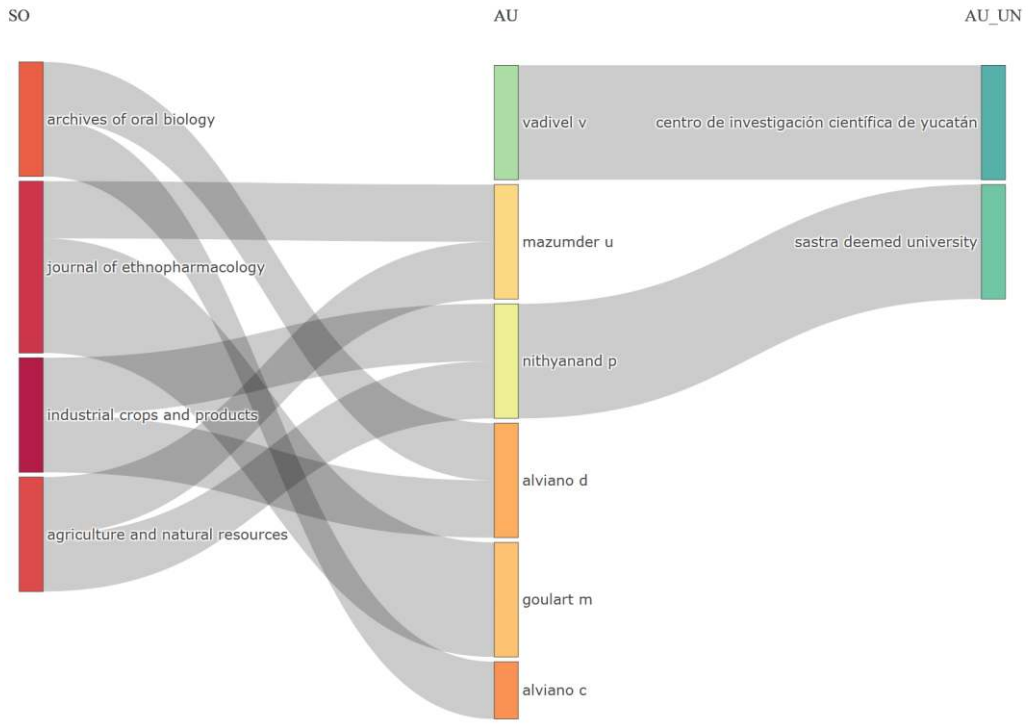
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the selected literature and do not, in isolation, represent the entire structure of international scientific output on the subject.

3.1.3 Relationship between sources, authors, and institutions

A Sankey diagram was used to visualize, in an exploratory manner, the connections among publication sources, authors, and affiliated institutions within the analyzed corpus. Figure 4 links the fields SO (sources or journals), AU (authors), and AU_UN (authors' affiliated institutions). The gray bands indicate the connections between the fields, while their thickness represents the frequency of these relationships within the set of included studies.

Figure 4. Three-field plot relating publication sources (SO), authors (AU), and authors' affiliated institutions (AU_UN) from the studies included in the review



Source: Prepared by the authors (2026) based on data collected from the Scopus and Web of Science databases, using Bibliometrix/Biblioshiny. Note: The thickness of the connections indicates the frequency of relationships between the fields within

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the analyzed corpus. The visualization displays the most connected items within the configured limit for each field.

Overall, the figure shows that studies on residues and underutilized parts of *Cocos nucifera* L. are distributed across journals in various fields, such as natural products, ethnopharmacology, agriculture, biotechnology, and experimental health sciences. Notable sources include *Archives of Oral Biology*, *Journal of Ethnopharmacology*, *Industrial Crops and Products*, and *Agriculture and Natural Resources*. This distribution underscores the interdisciplinary nature of the subject, as the valorization of *Cocos nucifera* L. materials encompasses diverse areas, including phytochemical characterization, antioxidant and antimicrobial activity, functional applications, nanotechnology, post-harvest preservation, and the technological utilization of plant biomass.

Regarding the authors, connections emerge involving Mazumder U., Alviano D., Goulart M., Vadivel V., Nithyanand P., and Alviano C., highlighting recurring authors within the analyzed dataset. These authors are linked to various sources and institutions, such as SASTRA Deemed University and the Centro de Investigación Científica de Yucatán, suggesting the existence of specific clusters within the set. For instance, connections linked to SASTRA Deemed University point to studies on biotechnological applications, antimicrobial activity, and the utilization of plant extracts, whereas connections to the Centro de Investigación Científica de Yucatán suggest a focus on agricultural and post-harvest applications.

However, these results should be interpreted with caution. The presence of specific authors, journals, or institutions in the figure reflects the frequency and internal connections within the analyzed set, rather than necessarily indicating greater scientific impact, institutional leadership, or editorial dominance in the field. This caution is particularly important given that the review included a limited number of articles. Thus, the primary value of the three-field plot lies in highlighting the internal organization of the selected studies and reinforcing the multidisciplinary nature of the literature regarding residues and underutilized parts of *Cocos nucifera* L.

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3.2 Overview of experimental studies on residues and underutilized parts of *Cocos nucifera* L.

The qualitative synthesis of the included studies revealed a heterogeneous set of investigations focused on the valorization of various *Cocos nucifera* L. matrices, encompassing both direct agro-industrial residues and underutilized botanical parts or fractions of the plant. Notable among the evaluated matrices were the green husk, husk fiber, mesocarp, endocarp, testa, haustorium, inflorescence, spadix, roots, and solid endosperm. This diversity underscores the need to define the scope of the present review as focusing on "residues and underutilized parts of *Cocos nucifera* L", given that not all matrices investigated in the literature strictly correspond to agro-industrial residues generated during conventional coconut processing (Alviano et al., 2008; Naskar et al., 2011; Silva et al., 2013; Arivalagan et al., 2018; Kim et al., 2023; Narayanankutty et al., 2023; Haque et al., 2024).

Overall, the studies analyzed present diverse objectives, including the extraction and quantification of phenolic compounds and flavonoids, the assessment of antioxidant and antimicrobial activities, the phytochemical characterization of specific fractions, the optimization of extraction processes, and the investigation of potential technological applications in food, cosmetics, nanotechnology, and agriculture. This thematic breadth demonstrates the biotechnological potential of the matrices evaluated but also highlights significant limitations regarding direct comparisons between studies, particularly due to differences in the plant part used, extraction method, solvent system, operating conditions, and the outcomes evaluated (Arivalagan et al., 2018; Oliveira et al., 2021; Yang et al., 2021; Singh et al., 2023; Rizwana et al., 2023; Hernández-Flores et al., 2023; Shen et al., 2024).

To organize this body of evidence, Table 3 presents a general characterization of the 27 studies included in the qualitative synthesis. The table goes beyond merely describing the studies; it seeks to classify them based on matrix type, experimental approach, extraction system, primary technological outcome evaluated, and the level of experimental or technological support. This

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classification was adopted because the aim of this review is not to establish a hierarchy of clinical evidence, but rather to assess the methodological consistency and experimental maturity of studies focused on obtaining and applying bioactive extracts from *Cocos nucifera* L.

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Table 3. General characterization of the studies included in the qualitative synthesis on residues and underutilized parts of *Cocos nucifera* L.

Author/year	Evaluated matrix	Matrix rank	Extraction method/approach	Solvent/Extraction system	Type of experimental approach	Technological outcome evaluated	Level of experimental/ technological support	Critical observation/Caution
Singh et al., 2023	Green husk	Direct agro-industrial residue	UAE and MAE	Methanol	Optimization by ANN-PSO	Extraction yield, antioxidant, and antimicrobial activity	Optimized and validated extraction	AI-optimized model (ANN-PSO), but without discussion of industrial scalability or economic analysis
Oliveira et al., 2013	Bark fiber	Direct agro-industrial residue	Percolation	Ethanol	Phytochemical characterization	Total phenolic content and antioxidant activity	Comparative extraction	It compares varieties, but biological activity was evaluated only *in vitro* and requires process optimization.
Arivalagan et al., 2018	Forehead	Underutilized by-product	Agitation + UAE	Acidified 80% acetone (0,3 M HCL) – best condition	Comparison of solvents	Total phenolic and flavonoid content	Comparative extraction	It compares various solvent systems but uses organic solvents with lower compatibility for direct food application
Naskar et al., 2013	Spadix	Underutilized botanical part	Cold maceration	Methanol 20%	Complementary biological assay	Antioxidant activity associated with functional potential	Descriptive extraction	Focus on robust *in vivo* assays, but without extraction optimization or in-depth analytical validation of the

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								compounds.
Silva et al., 2013	Bark fiber	Direct agro-industrial residue	Infusion	Water	Complementary biological assay	Antioxidant and antimicrobial activity	Descriptive extraction	Biological activity is evaluated *in vivo*, but the technological application is restricted to traditional use (infusion)
Yang et al., 2021	Mesocarp	Direct agro-industrial residue	UHAE (hybridized)	Acetone 60% - best condition	Optimization by RSM	Total phenolic and flavonoid content	Optimized and validated extraction	Hybridized optimization (UHAE) is confirmed, but without economic analysis or industrial scalability assessment.
Naskar et al., 2011	Spadix	Underutilized botanical part	Cold maceration	Methanol 80%	Complementary biological assay	Antihyperglycemic activity	Descriptive extraction	Robust *in vivo* preclinical study for diabetes, but relying on basic extraction technology (maceration)
Bankar et al.,2011	Endocarp	Direct agro-industrial residue	Soxhlet	Ethanol 95%	Phytochemical characterization	Total phenolic and flavonoid content	Initial characterization	Identification of phenols by HPLC, but the study is restricted to a single matrix (endocarp)
Renjith, Chikku, and Rajamohan	Inflorescence	Underutilized botanical part	Immersion	Methanol 80% and Ethanol 95% (tested	Complementary biological assay	Antioxidant activity associated with functional potential	Descriptive extraction	Biological results were evaluated *in vivo*, but analytical

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(2013)				hydroalcoholic systems)				validation of individual compounds in the extract is lacking.
Kim et al., 2023	Haustorium	Underutilized botanical part	Reflux	Methanol 70%	Phytochemical characterization	Profile of phenolic acids, flavonoids, and terpenoids	Initial characterization	Detailed molecular profiling study, but without tested technological application or yield optimization
Narayanankutty et al., 2023	Haustorium	Underutilized botanical part	Soxhlet	Methanol	Phytochemical characterization	Antioxidant activity and enzyme inhibition	Initial characterization	Initial phytochemical evaluation with only *in vitro* biological results, limiting functional translation
Jose et al., 2018	Solid endosperm	Direct agro-industrial residue	Soxhlet	Ethanol	Phytochemical characterization	Antioxidant activity and free radical scavenging	Descriptive extraction	Preliminary *in vitro* antioxidant screening and lack of comparison between different extraction methods
Rizwana et al., 2023	Solid endosperm	Cosmetible fraction/food by-product	Heated extraction	Water	Synthesis of nanoparticles	Synthesis of AgNPs and antimicrobial activity	Preliminary technological application	Promising *in vitro* green synthesis of AgNPs, but lacking discussion of regulatory barriers or toxicological safety
Balogun et al.,2014	Bark fiber	Direct agro-industrial	Sequential solvent extraction	Hexane – ethyl acetate – Methanol	Complementary biological assay	Phytochemistry and reduction of	Descriptive extraction	The only solid *in vivo* evidence for malaria,

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		residue				parasitemia (functional potential)		albeit without advanced extraction technology support
Shen et al., 2024	Mesocarp	Direct agro-industrial residue	SE and alkaline extraction	Water (SE) and NaOH 4M – optimized conditions	Process optimization	Recovery of phenolic compounds via resin purification	Optimized extraction	Efficient recovery using resins, but limited to the laboratory scale, without discussion of process stability.
Hernandez-Flores et al., 2023	Mesocarp	Direct agro-industrial residue	Agitation	Distilled water	Post-harvest application	Postharvest antifungal activity against blue mold	Preliminary technological application	Promising post-harvest application, yet restricted to a controlled laboratory environment and a single fungal matrix
Malage et al., 2024	Shredded coconut	Cosmetible fraction/food by-product	$scCO_2$ supercritical	$scCO_2$ + ethanol 30% - optimized condition	Food application	Stability of “bigels” and enzymatic activity associated with functional potential	Preliminary technological application	Stability in “bigels” was evaluated over 16 days, but an industrial cost-benefit analysis is lacking.
Alviano et al., 2008	Bark fiber	Direct agro-industrial residue	Infusion	water	Complementary biological assay	Antibacterial activity against biofilms and antioxidant potential	Descriptive extraction	Efficacy against biofilms *in vitro*; lack of validation in oral clinical models or formulation stability
Kalina e Navaratne (2019)	Mesocarp	Direct agro-industrial residue	Soxhlet	Ethanol 95%	Food application	Food stability/preservation (texture and antioxidant)	Preliminary technological application	The study focused on texture and antioxidant retention, but the results were

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								expressed in units that limit direct comparison.
Sinsinwar et al., 2018	Endocarp	Direct agro-industrial residue	Sequential solvent extraction	Hexane – chloroform – ethyl acetate - methanol	Synthesis of nanoparticles	Synthesis of AgNPs and antimicrobial activity	Preliminary technological application	Well-characterized nanoparticle synthesis, but biological activity evaluated only against pathogens *in vitro*
Dzib-Guerra et al., 2016	Inflorescence	Underutilized botanical part	Maceration and infusion	Methanol – best condition	Complementary biological assay	Anti-glycation activity and antioxidant activity	Descriptive extraction	Initial phytochemical screening for antiglycation activity without optimization of yield or solvent system
Siramon and Wongsheree, 2022	Peel powder	Underutilized by-product	UAE	Ethanol 50%	Cosmetic application	Tyrosinase inhibition and antimicrobial activity	Preliminary technological application	Tyrosinase inhibition was identified, but application in actual cosmetic formulations remains merely prospective.
Prakash et al., 2018	Endocarp	Direct agro-industrial residue	MAE	Methanol – best condition	Comparison of extraction methods	Recovery of phenolic compounds and antimicrobial activity	Comparative extraction	Detailed comparison of methods, but without discussion regarding the toxicity of organic solvents to the final product
Oliveira et al.,	Bark fiber	Direct agro-	Percolation	Ethanol	Cosmetic	Photoprotective	Preliminary	It evaluated safety in

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2021		industrial residue			application	potential and antiglycation activity	technological application	macrophages and efficacy (SPF), but lacks long-term stability analysis.
Chithra et al., 2020	Inflorescence	Underutilized botanical part	Maceration	Acetone	Complementary biological assay	Enzymatic activity associated with functional potential	Descriptive extraction	Solid evidence of hepatoprotective effects in animals, but lacking technological optimization to maximize the yield of bioactive compounds
Shen et al., 2017	Floral axis	Underutilized botanical part	Hydrodistillation	Water	Phytochemical characterization	Antimicrobial activity and antioxidant potential	Initial characterization	Comprehensive phytochemical characterization of hydrolats, but without chemical stability testing during storage
Haque et al., 2024	Roots	Underutilized botanical part	UAE	Methanol – best result	Complementary biological assay	Antioxidant activity associated with functional antitumor potential	Initial characterization	Promising computational (in silico) model, but biological antitumor evidence is limited to the laboratory level.

Source: Prepared by the authors (2026) based on the studies inclued in the systematic review. Note: UAE = ultrasound-assisted extraction;
MAE = microwave-assisted extraction; UHAE = ultrasound-assisted extraction/homogenization;
$scCO_2$ = supercritical carbon dioxide extraction; ANN-PSO = particle swarm-neural network optimization;
RSM = response surface methodology; SE = steam explosion; AgNPs = synthesis of silver nanoparticles.
The level of experimental/technological support was defined based on the predominant methodological approach of each study.
“Initial characterization” refers to studies focused primarily on phytochemical screening, the overall quantification of bioactive compounds, or a preliminary assessment

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of activity. “Descriptive extraction” corresponds to studies that employed an extraction method without a systematic comparison of conditions “Comparative extraction” refers to studies that compare solvents, methods, or operating parameters. “Optimized extraction” refers to studies that employed experimental design, statistical modeling, or computational tools to determine optimal conditions. “Optimized and validated extraction” refers to studies that, in addition to optimization, experimentally confirmed the predicted conditions. “Preliminary technological application” corresponds to studies that evaluated the use of extracts or fractions in applied systems, such as food, cosmetics, nanotechnology, or post-harvest applications, while still at the laboratory or experimental scale.

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3.3 Extraction methods applied in the studies

The recovery of bioactive compounds from *Cocos nucifera* L. waste has been carried out using a wide variety of approaches, which can be divided into conventional methods and intensified or "green" technologies. Among the conventional methods, maceration and percolation stand out, frequently applied to obtain crude extracts of fibers and husks; the Soxhlet method for exhaustive extractions of endocarp and mesocarp; and infusion, which replicates traditional use. In parallel, there is a rise in assisted methods aimed at greater efficiency and sustainability, such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), the use of supercritical CO_2 ($scCO_2$), and steam explosion (SE), methods discussed by Singh et al., (2023); Malage et al., (2024) e Shen et al., (2024). Additionally, specialized approaches are emerging, such as the green synthesis of silver nanoparticles (AgNPs), which utilize aqueous extracts as reducing and stabilizing agents to produce materials with high functional potential (Sinsinwar et al., 2018; Rizwana et al., 2023).

Analysis of these methods reveals that conventional techniques, while useful for initial phytochemical screenings, present severe operational limitations, such as the requirement for long exposure times (reaching up to 72 hours in percolation) and the consumption of large volumes of solvents (Oliveira et al., 2021). In contrast, assisted methods drastically reduce processing time; ultrasonic optimization, for example, has shown that just 15 to 30 minutes can be sufficient to maximize yield. However, methodological caution is required: the efficiency of these technologies depends critically on power, temperature, and the plant matrix. Excessive mechanical force or heat can be detrimental, generating reactive oxygen species (ROS) via cavitation or promoting the release of the enzyme polyphenol oxidase (PPO), which drives the oxidative degradation of polyphenols and the browning of the extract (Yang et al., 2021).

The role of the solvent is another determining factor, since the recovery of metabolites such as phenolic acids and flavonoids is strictly dependent on the

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polarity of the extractor system. A clear tendency towards the superiority of binary systems (hydroalcoholic or hydroacetonic) over pure solvents is observed; in the study of Yang et al., (2021), using the mesocarp, for example, 60% acetone was shown to recover 551,99 mg of rutin g^{-1} and 289,48 mg GAE g^{-1} of total phenolics, values higher than those obtained with anhydrous acetone. Although methanol and acetone appear to be effective solvents in the laboratory, it is notable that few studies systematically evaluate the interaction between different solvents using mixture designs; this presents an opportunity for research aimed at balancing polarity with the recovery of phenolics and flavonoids.

The heterogeneity of extraction methods, solvent systems, and result-reporting units limits the identification of a single superior technique for all *Cocos nucifera* L. matrices. Although methods such as supercritical CO_2, ultrasound, and microwave-assisted extraction offer advantages regarding selectivity, extraction time, and the preservation of sensitive compounds, their efficiency depends on the matrix, solvent, and operating conditions. In this context, a major gap in the literature is the scarcity of controlled comparisons between extraction methods and systems using a standardized analytical protocol. Strategies based on mixture design can help evaluate the individual and combined effects of solvents, enabling the selection of systems that are both efficient and suitable for food applications. Beyond extraction, the practical viability of these extracts depends on strategies that enhance their stability and acceptability. Encapsulation emerges as a promising alternative in this regard, protecting bioactive compounds from degradation, mitigating potential sensory issues, and enabling direct consumption of the extract in forms such as powders, capsules, sachets, or functional ingredients. This approach can expand the potential use of extracts derived from coconut residues and underutilized parts in food systems and products aimed at technological valorization and the circular economy.

3.4 Strategy for optimizing extraction processes

An analysis of the scientific landscape regarding *Cocos nucifera* L. residues reveals that most studies are still based on descriptive extractions or simple

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comparisons of operating conditions. Classic works focused on biological assays use conventional extraction protocols without any optimization design, such as cold maceration, percolation for long periods, or simple infusions that reproduce traditional use, as demonstrated in the studies of Naskar et al., (2011); Naskar et al., (2013); Oliveira et al., (2013) e Oliveira et al., (2021). Other studies focus on comparative extraction, systematically evaluating the performance of different solvents (pure vs. hydroalcoholic mixtures) or distinct methods (UAE vs. MAE vs. Soxhlet), but without mathematically seeking an optimal yield point (Arivalagan et al., 2018).

The transition toward optimized extraction is observed in a select group of studies employing advanced modeling tools. Response Surface Methodology (RSM) was applied to maximize the total flavonoid content (TFC) and total phenolic content (TPC) of the mesocarp, evaluating variables such as ultrasonic power (180-360 W), temperature (20-80 °C), and extraction time (20-100 min) (Yang et al., 2021). In a more advanced technological approach, the integration of Artificial Neural Networks and Particle Swarm Optimization (ANN-PSO) was used to standardize green husk extraction, optimizing sonication time (10-30 min), temperature (30-40 °C), and the solid-to-solvent ratio (1:10-1:30 g mL^{-1}) (Singh et al., 2023). Other modeling strategies include the use of the severity factor ($logR_0$) to optimize steam explosion processes and the application of adsorption and desorption models (Langmuir and Freundlich) for the selective purification of phenols using macroporous resins (Shen et al., 2024). In supercritical CO_2 ($scCO_2$) extraction, optimization focused on the co-solvent concentration (30% ethanol) and the raw material mixture ratio to enhance the solubility of bioactives (Malage et al., 2024).

It is crucial to distinguish between theoretical modeling and experimental validation. Tools such as ANN-PSO and RSM can predict mathematical peaks that do not always translate into practical feasibility. Studies such as those of Singh et al. (2023) and Yang et al. (2021) are examples of optimized and validated extraction, as they not only generated predictive models but also experimentally confirmed the optimal conditions, showing low margins of error (less than 2,35%) between

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predicted and actual values. Although modeling and optimization strategies help define more efficient extraction conditions at the bench scale, the literature still presents gaps regarding controlled comparisons of solvent systems, extraction methods, and the stability of the resulting extracts. In this context, studies based on mixture design and experimental validation represent a crucial intermediate step between laboratory screening and future scale-up evaluations, as they enable the selection of solvent combinations that are suitable, reproducible, and compatible with food applications. Thus, before scaling up to industrial processes, it is necessary to establish robust extraction protocols, validate the optimized conditions, and assess the stability and functionality of the extracts in applied technological systems.

3.5 Phytochemical profile of the extracts

The phytochemical profile of *Cocos nucifera* L. extracts is characterized by a wide diversity of secondary metabolites, with phenolic compounds and flavonoids being the most recurrent classes in all analyzed sources. Among the main groups, condensed tannins (procyanidins) stand out, especially in the husk fiber, and a wide range of phenolic acids, such as protocatechuic, p-coumaric, ferulic, gallic, vanillic, and chlorogenic acids, as reported in studies of Oliveira et al., (2013) e Silva et al., (2013). Within the flavonoid group, the presence of catechin, epicatechin, and quercetin is consistently cited as a biomarker of antioxidant and photoprotective potential (Arivalagan et al., 2018). Additionally, less explored classes found in unconventional locations, such as terpenoids and steroidal derivatives, emerge as key components in specific matrices, such as the haustorium (Kim et al., 2023).

The distribution of these compounds varies across matrices, reflecting the biological role of each tissue; Peel, Fiber, and Mesocarp: concentrate the highest amounts of total phenolics and tannins, acting as defensive barriers; Testa (brown skin): serves as a reservoir of highly bioavailable phenolic acids and flavonoids, notably protocatechuic acid and catechin; Haustorium (embryo): presents a unique profile combining phenolics with high levels of triterpenoids and saponins, surpassing the other fruit parts in chemical diversity; Inflorescence and Roots:

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exhibit profiles associated with specific bioactivities (antidiabetic and antitumor), containing flavonoids, lignans, and alkaloids (Arivalagan et al., 2018; Kim et al., 2023).

Analysis of the chemical profile reveals that the solvent and extraction method directly influence the final composition. Solvent polarity is observed to determine selectivity: binary systems (such as 60% acetone or 80% methanol) are significantly more effective than pure solvents for recovering flavonoids. Although solvent acidification drastically increases total phenolic content by releasing cell-wall-bound compounds, it can be detrimental due to flavonoid degradation. Furthermore, intensified methods such as steam explosion (SE) and ultrasound-assisted extraction (UAE) are capable of disrupting complex lignocellulosic structures, recovering molecules, such as bound insoluble phenolics, that conventional maceration fails to extract (Arivalagan et al., 2018; Yang et al., 2021).

However, the interpretation of phytochemical profiles must take into account the scope and limitations of the methods employed. Many studies rely exclusively on global methods, such as TPC (Folin-Ciocalteu) and TFC (AlCl3), which are useful for estimating total phenolic and flavonoid concentrations, comparing extraction conditions, and guiding optimization and technological application steps. Yet, since these methods do not identify individual molecules, they must be complemented by techniques such as HPLC, LC-MS, or UHPLC-MS/MS when the goal is to identify specific chemical compounds. Furthermore, the use of different units of measurement (mg GAE g^{-1}, mg QE g^{-1}, mg TAE g^{-1}) hinders direct comparisons of efficiency across studies. Finally, the literature indicates that a higher TPC value does not guarantee superior technological application; in the mesocarp, for instance, prolonged extraction times that increase TPC also activate the enzyme polyphenol oxidase (PPO), resulting in the degradation of the extract's chemical and functional integrity (Yang et al., 2021; Singh et al., 2023).

3.6 Bioactivities associated with technological potential

The bioactivities identified in the residues and underutilized parts of *Cocos nucifera* L. constitute a key basis for their biotechnological valorization, as they demonstrate that these matrices need not be treated merely as agro-industrial

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waste but can instead be viewed as potential sources of compounds valuable for various technological applications. Among the reported activities, antioxidant capacity is the most frequently observed in the analyzed studies, primarily linked to the presence of phenolic compounds, flavonoids, and tannins. This property supports potential applications in food and cosmetic systems, particularly due to the extracts' contribution to oxidative stability, lipid protection, and the preservation of formulations against free-radical-induced degradation. Assays such as DPPH, ABTS, and FRAP indicate that certain fractions derived from husk fiber, the testa, and the mesocarp show promise as sources of natural antioxidants, suggesting potential for the partial replacement of synthetic additives and for the development of functional ingredients or protective agents in formulations (Alviano et al., 2008; Oliveira et al., 2013).

In addition to antioxidant activity, studies also demonstrate antimicrobial and antifungal properties, which heighten technological interest in these extracts. Aqueous extracts from the mesocarp, for instance, have been experimentally evaluated for controlling fungi associated with post-harvest spoilage, indicating potential for application in preservation systems for fruits and agricultural products. Similarly, extracts from various parts of the coconut have been used in the green synthesis of silver nanoparticles exhibiting antimicrobial activity against relevant pathogens, including resistant strains. While these results are promising, their application requires caution, as it still depends on greater control over stability, dosage, toxicity, reproducibility, and environmental safety. In another area of application, *in vitro* studies using husk extracts indicated the inhibition of bacterial biofilms associated with oral health, suggesting the possibility of future incorporation into products such as mouthwashes, gels, or oral hygiene formulations, provided this is accompanied by further assessments of safety and technological efficacy (Alviano et al., 2008; Hernandez-Flores et al., 2013; Rizwana et al., 2023).

Enzymatic and functional activities also contribute to expanding the scope of application for *Cocos nucifera* L. extracts. The tyrosinase inhibition observed in husk powder extracts, for example, supports interest in cosmetic applications aimed at evening out skin tone and developing natural depigmenting agents. The *in vitro*

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inhibition of enzymes such as α-amylase and α-glucosidase, observed in haustorium extracts and other fractions, indicates functional potential associated with the modulation of carbohydrate digestion; however, these findings should be interpreted as preliminary experimental evidence rather than proof of a physiological effect in humans. The antiglycation activity reported for bark fiber extracts further reinforces the potential of these matrices in cosmetic and functional food products, particularly in strategies aimed at protecting protein structures and preventing oxidative and glycative processes in biological or technological systems (Oliveira et al., 2021; Siramon e Wongsheree, 2022; Narayanankutty et al., 2023).

Some studies extend to more complex biological models, including experimental evaluations of anti-inflammatory, analgesic, hepatoprotective, vasorelaxant, antitumor, and antimalarial activities. These results provide complementary evidence regarding the behavior of the extracts in cellular, enzymatic, or animal systems, but they should not be interpreted as proof of therapeutic efficacy. Preclinical models, such as paw edema, the formalin test, paracetamol-induced liver injury, isolated aortic rings, tumor cell lines, and experimental *Plasmodium berghei* infection, serve as proofs of concept for future investigations into bioactive compounds and potential functional applications. However, translating these findings into products for human use or therapeutic recommendations requires further studies on toxicity, bioavailability, stability, safety, and efficacy (Bankar et al., 2011; Silva et al., 2013; Balogun et al.,2014; Rizwana et al., 2023).

Thus, the bioactivities reported in the literature reinforce the potential of *Cocos nucifera* L. residues and underutilized parts as sources of bioactive compounds for applications in food, cosmetics, nanotechnology, agriculture, and functional systems. However, most of the evidence still focuses on laboratory assays, experimental models, or preliminary applications. Consequently, establishing these extracts as technological ingredients depends on the standardization of extraction processes, the identification of marker compounds, the assessment of extract stability, and the validation of their functionality in real-world

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application systems, including food matrices, cosmetic formulations, and preservation systems.

3.7 Potential technological applications

The potential technological applications of *Cocos nucifera* L. extracts span various industrial sectors, driven by the transformation of these residues from an environmental liability into a high-value-added biotechnological asset. Although phytochemical characterization and *in vitro* and *in vivo* bioactivities are well documented, the maturity level of these applications ranges from laboratory proof-of-concept to the development of functional prototypes, depending on the sector in question. The applications are detailed below by sector:

3.7.1 Food

This sector demonstrates an advanced level of maturity regarding prototype formulation and the replacement of synthetic additives. Extracts, particularly those derived from husk fiber and the testa, show promise as natural antioxidants for extending product shelf life, offering an alternative to BHT (butylated hydroxytoluene) and BHA (butylated hydroxyanisole). Incorporating residues into functional confections (such as small spheres) and using co-extracts in "bigels" (hybrid systems) aim to create foods with antidiabetic properties and facilitate the replacement of saturated fats. Furthermore, the inhibition of α-amylase and α-glucosidase enzymes by haustorium extracts suggests potential for glycemic control through the food matrix. Industrial applications face flavor-related challenges, as residue concentrations exceeding 30% can impart bitterness to the product. Color is another concern due to the action of polyphenol oxidase (PPO), which causes enzymatic browning. Additionally, the residual toxicity of solvents such as methanol or acetone necessitates a definitive shift toward extraction systems using ethanol or supercritical CO_2 to ensure compliance with food regulations (Jose et al., 2018; Narayanankutty et al., 2023; Malage et al., 2024).

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3.7.2 Cosmetics

Its cosmetic application demonstrates technological promise, particularly in the development of sunscreens and anti-aging agents. Ethanolic bark extracts incorporated into creams exhibited photoprotective potential, with an SPF reaching 15,94, comparable to commercial chemical filters. Anti-glycation activity (inhibition of AGEs) in collagen models surpassed that of the standard control, aminoguanidine, indicating efficacy for anti-aging products. Additionally, extracts from the powdered bark inhibit tyrosinase, supporting their use as skin-lightening agents. Although in vitro dermal safety studies show no cytotoxicity in macrophages, standardizing the extract across different cultivars is crucial to ensure SPF reproducibility. The presence of fatty acids in hydrolats may cause skin irritation, necessitating more rigorous dermatological testing (Oliveira et al., 2021; Siramon e Wongsheree, 2022).

3.7.3 Nanotechnology

The nanotechnology sector is rapidly expanding, utilizing extracts as tools for green chemistry. The use of aqueous extracts (from kernels, peels, or inflorescences) as natural reducing and stabilizing agents for the green synthesis of AgNPs is a growing trend. These nanoparticles exhibit potent antimicrobial activity against multidrug-resistant pathogens, such as MRSA (methicillin-resistant *Staphylococcus aureus*) and *Candida* species, by disrupting bacterial cell wall integrity. Key challenges include the need to assess the *in vivo* toxicity of these particles and their environmental fate following disposal. Regulatory safety regarding the use of nanomaterials in direct human contact and the reproducibility of synthesis (strict control of size and shape) remain areas requiring further attention (Sinsinwar et al., 2018; Rizwana et al., 2023).

3.7.4 Agriculture and post-harvest

This sector offers promising practical applications as an alternative to conventional pesticides. Aqueous extracts from the mesocarp act as natural antifungal agents and biopesticides, proving effective in controlling blue mold (*Penicillium italicum*) on Persian limes and combating *Rhizopus stolonifer* on soursops. The extract functions

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as a protective barrier, reducing disease incidence and severity during storage. The efficacy of these treatments depends heavily on stability at various storage temperatures; for instance, protection was effective at 15°C but diminished at 25°C. Large-scale field trials are required to determine the optimal dosage and ensure the absence of phytotoxicity in the treated crops (Hernandez-Flores et al., 2023).

3.8 Study limitations and future perspectives

A consolidated analysis of the 27 sources reveals that although the valorization of *Cocos nucifera* L. has advanced significantly, the field faces challenges that hinder the translation of laboratory findings into industrial applications.

The primary barrier identified is the heterogeneity of the matrices and varieties studied, as their phytochemical profiles vary according to the stage of maturity and the botanical part used (haustorium, husk, testa, or inflorescence). Compounding this is the lack of standardization in extraction methods, involving widely varying solvents and proportions (methanol, acetone, ethanol, and water at concentrations ranging from 50% to 100%), which prevents direct comparison of yields across different geographic regions. It is evident that most research still lacks a robust experimental design; few studies compare distinct methods under identical controlled conditions, hindering the consolidation of a standardized technology. From an analytical perspective, many studies rely predominantly on aggregate assays, such as total phenolics (TPC) and total flavonoids (TFC), to estimate the bioactive composition of the extracts. While these assays are useful for screening, comparing extraction conditions, and making preliminary selections of solvent systems, they do not allow for the individual identification of the compounds responsible for the observed activities. Consequently, the absence of complementary techniques, such as HPLC, LC-MS/MS, or UHPLC-MS/MS, limits the definition of specific chemical markers and impedes the establishment of a direct correlation between phytochemical composition and the functional performance of the extracts.

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Future research should prioritize experimental approaches that allow for a controlled comparison of the effects of solvent systems and extraction methods on the recovery of bioactive compounds from *Cocos nucifera* L. In this regard, mixture design represents a relevant strategy, as it enables the evaluation of the individual and combined effects of solvents, the identification of polarity interactions, and the selection of more efficient extraction systems. When combined with a comparison between conventional and assisted methods, this type of experimental design can contribute to establishing protocols that are both reproducible and technically justified. Beyond optimization, the experimental validation of predicted conditions must be considered an essential step, as it confirms the model's adequacy and enhances the reliability of the extraction process. However, selecting an optimal extraction condition is not sufficient to guarantee the technological application of the extracts; further progress is also required regarding stability assessment, the protection of bioactive compounds, and their incorporation into actual application systems.

In this context, microencapsulation strategies emerge as promising alternatives to enhance extract stability and mitigate sensory limitations. Incorporating these extracts into food coatings or active systems represents a significant step toward evaluating their performance in curbing oxidative and microbiological processes, thereby extending shelf life. Thus, integrating mixture design, method validation, extract stability, microencapsulation, and application in food matrices can bolster the technological valorization of coconut residues and underutilized parts within a circular economy framework.

4. Conclusion

This review highlights that agro-industrial residues and underutilized parts of *Cocos nucifera* L. constitute promising sources of bioactive compounds, particularly phenolics and flavonoids, with potential for applications in green chemistry, the circular bioeconomy, and technological development. Bibliometric analysis, interpreted through an exploratory lens, revealed a recent rise in scientific interest, the interdisciplinary nature of the subject, and connections among authors, journals,

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and institutions across diverse fields, such as natural products, ethnopharmacology, biotechnology, agriculture, and experimental health sciences.

The studies analyzed also indicate advances in phytochemical characterization, bioactivity assessment, and the use of both conventional and assisted extraction methods. However, the heterogeneity of matrices, varieties, maturation stages, and extraction systems limits comparisons between studies and hinders the standardization of protocols. Furthermore, global assays, such as TPC and TFC, have proven useful for guiding the selection and optimization of extraction conditions, as well as for supporting subsequent stages of validation, encapsulation, and the application of extracts in active systems. Nevertheless, future studies employing complementary analytical techniques could deepen the identification of specific chemical markers and broaden the understanding of the relationship between composition, stability, and functional performance.

Thus, future research should prioritize more robust experimental designs, validation of optimized conditions, the use of advanced analytical techniques, and the assessment of the stability and applicability of the extracts in real-world systems. Consequently, the valorization of residues and underutilized parts of *Cocos nucifera* L. offers significant prospects but still requires further standardization, validation, and scale-up for effective technological application.

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