



Valorization of Genipap Peel and Seeds as Sources of Bioactive Compounds: a Review

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Abstract

Fruit processing generates large volumes of residues that are often underutilized, despite their functional and nutritional value being comparable to or even higher than that of fresh fruits. Genipap (*Genipa americana* L.) stands out due to its richness in bioactive compounds, including iridoids, phenolics, and flavonoids, as well as the natural blue pigment derived from the fruit. In juice production, approximately 40% of the fruit mass is discarded, representing a significant fraction of agro-industrial residues with high valorization potential. This study aimed to analyze the scientific production and technological potential of genipap residues, particularly peels and seeds, through a combined bibliographic review and scientometric analysis. Data were retrieved from the Scopus and Web of Science databases and processed using RStudio, OpenRefine, VOSviewer, and the Bibliometrix package (Biblioshiny interface). The results indicate that Brazil leads global scientific output on this topic, with a predominance of studies focused on the characterization of bioactive compounds and antioxidant activity, while overall global production remains limited. However, significant methodological heterogeneity was observed, along with a lack of studies addressing large-scale applications, including aspects related to process standardization, compound stability, and regulatory compliance. Both the fruit and its residues, especially peels and seeds, demonstrate promising potential for applications in the food, pharmaceutical, and chemical sectors, contributing to sustainability, circular economy, and value addition. These findings position genipap residues as promising resources within a circular economy framework, highlighting their potential to support sustainable valorization strategies and reduce the environmental impact associated with agro-industrial waste.

Keywords Sustainability · Bioactive compounds · Agro-industrial residues

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Introduction

Genipap (*Genipa americana* L.) presents significant economic potential for the industry, not only in the production of juice and pulps but also through the utilization of other plant parts, such as peels, seeds, and leaves. Its cultivation also represents an important opportunity for promoting family farming, particularly in tropical regions. The fruit has been widely used as a raw material in various products, including sweets, liqueurs, cakes, preserves, compotes, beverages, and spirits, contributing to the promotion of a circular economy among small-scale producers [1].

Widely recognized as a source of iron, genipap exhibits considerable ethnopharmacological relevance due to its traditional use in folk medicine [2]. Ethnobotanical records and scientific investigations indicate that the fruit and various parts of the plant are associated with a range of potential biological activities, including anti-inflammatory, analgesic, antimicrobial, antifungal, antioxidant, wound-healing, and antidiarrheal effects. In this context, the literature reports its traditional use in the management of several conditions, such as jaundice, venereal wounds, rheumatism, asthma, pharyngitis, syphilis, anemia, bronchitis, and hepatic and splenic disorders [3].

In addition, preparations derived from genipap are traditionally described as having antiseptic, antipyretic, anthelmintic, diuretic, adaptogenic, tonic, and aphrodisiac properties [4]. Ethnopharmacological and experimental studies further indicate that different parts of the plant are used for specific medicinal purposes. Among the uses reported in the literature are: fruit juice, described for the management of anemia, uterine cancer, and gastrointestinal disorders; root infusions, used for inflammation, contusions, diarrhea, and urticaria; pulp syrups, applied in respiratory conditions such as bronchitis and cough; fresh pulp, used in dental extractions, fever management, and the traditional treatment of alopecia, as well as exhibiting emetic properties; and sap, employed in cutaneous fungal infections, venereal wounds, and ocular conditions [5, 6].

Although these applications are reported in the scientific literature and supported by ethnopharmacological surveys and experimental studies, most of the available evidence is derived from preclinical models. Nevertheless, recent pharmacological investigations have provided mechanistic support for some of these bioactivities through the characterization of secondary metabolites, particularly iridoids such as genipin, which are capable of modulating pathways associated with inflammation, oxidative stress, cell survival, and energy metabolism in experimental systems [4]. Therefore, these findings should be interpreted as indicative of therapeutic potential, reinforcing the relevance of this species for the prospecting of bioactive compounds and for the development of future pharmacological and clinical studies).

Despite its high nutritional and medicinal potential [4], genipap is predominantly used for juice and pulp production, where only the pulp/mesocarp is utilized. For juice pulps in general, approximately 40% of agro-industrial residues are generated, including peels, pits, seeds, and bagasse [7]. These residues are typically discarded or used for animal feed without specific treatment or compositional knowledge. One alternative is the utilization of bioactive compounds present in these residues for incorporation into other products. Due to their high nutritional content, such applications aim to benefit consumer health while employing safe and feasible techniques [8].

As demonstrated by [9], the use of genipap peels transformed into flour resulted in a product with good stability due to low moisture content (4,07%), which contributes to longer shelf life. Additionally, the observed ash content (7,17%) indicates potential use as a mineral-enriching agent in food or functional formulations. Beyond the food industry, these residues may also have applications in the cosmetics, chemical, and pharmaceutical sectors. As with many other fruits, genipap residues have been investigated as sources of bioactive compounds, exhibiting relevant levels of antioxidants, minerals, and dietary fiber [4]. In this context, this study aims to conduct a literature review combined with a scientometric analysis of the potential of genipap residues (peels and seeds) as sources of bioactive compounds. By integrating scientometric mapping with a critical evaluation, still limited in the literature, this work identifies research trends and scientific gaps, contributing to a better understanding of the valorization potential of these residues and supporting future studies aimed at their utilization.

Methodology

Initially, a literature review was conducted to identify studies supporting the potential use of genipap peels and seeds, residues from fruit processing, for the extraction of bioactive compounds. This survey gathered information on genipap, including its physical and chemical characteristics, as well as its bioactive compound composition. Agro-industrial residues were also analyzed regarding their production methods, raw materials, main characteristics, sources, and studies addressing their application feasibility. Additionally, works contributing to the assessment of the bioactive potential of fruits, including genipap, were highlighted.

Subsequently, a systematic review was conducted using two databases, Scopus and Web of Science, with the aim of identifying scientometric indicators related to studies on genipap. Search strings were adapted according to each database's specifics: in Scopus, the TITLE-ABS-KEY field was used, while in Web of Science, the TS (Topic Search) field was applied. The search string was: ("genipap" OR "jenipapo") OR ("genipa" AND "americana"). As illustrated in Fig. 1, filters were applied to restrict the search to scientific articles, excluding reviews and other publication types. The searches were conducted in August 2025, considering publications from January 2004 to July 2025.

This search yielded a total of 494 records. To ensure that the selected studies met the established criteria, a manual screening process was conducted. At this stage, exclusion criteria were applied, defined to restrict the analysis to studies directly related to the bioactive potential and valorization of genipap residues, excluding those of an agronomic, botanical, or plant development nature that do not directly contribute to the proposed scope. Following this step, 205 studies were considered eligible.

The eligible records were processed using OpenRefine for metadata standardization and duplicate identification. The normalization process included the harmonization of spelling and formatting in titles and author names, as well as the separation of multivalued fields using the "split multi-value cells" function. Duplicate detection was performed through clustering using key collision algorithms (fingerprint and n-gram fingerprint) and nearest neighbor methods, which are capable of grouping subtle textual variations; matches were subsequently confirmed by manual inspection.

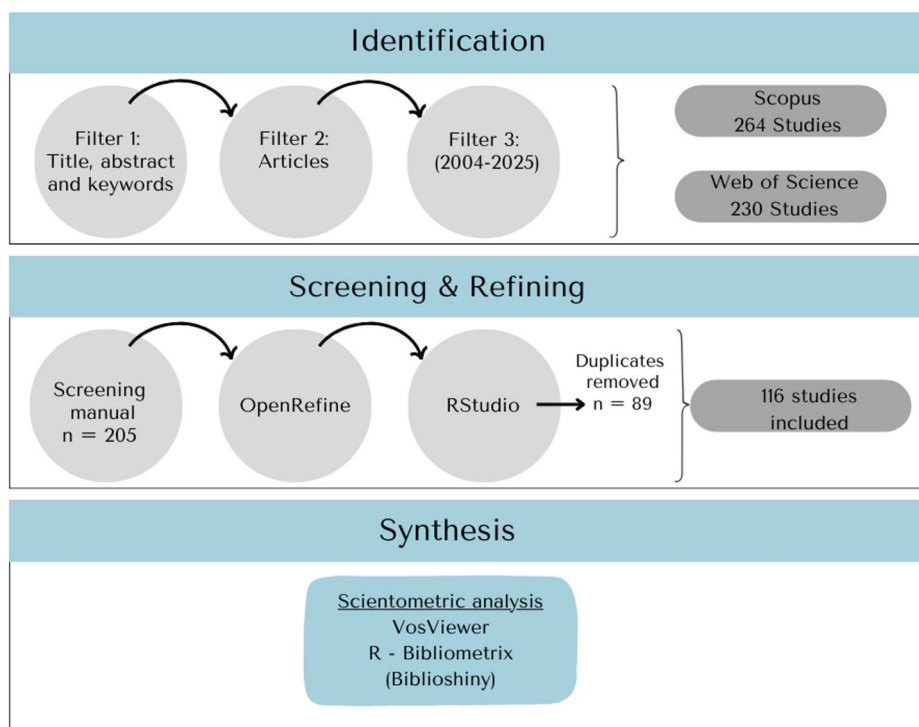


Fig. 1 Flowchart depicting the methodology and sequential steps of the scientometric analysis performed, including data collection, processing, and visualization stages

The consolidated data were then exported to RStudio, where database integration and the removal of 89 duplicate records were performed, resulting in a final dataset of 116 studies for scientometric analysis.

Bibliometric analyses were conducted using VOSviewer and the Bibliometrix package (Biblioshiny interface). In VOSviewer, keyword co-occurrence analyses were performed based on data from Scopus and Web of Science. In Bibliometrix, indicators related to annual scientific production, most productive countries, journals with the highest publication frequency, most cited articles, country collaboration networks, and keyword analysis, including word clouds and thematic correlations, were generated.

The final dataset used in this study is available in an online repository, as provided in the supplementary material, ensuring the reproducibility of the analysis.

Results and Discussion

Genipap

Genipap (*Genipa americana* L.), a fruit native to the Amazon, is cultivated in regions with humid tropical and subtropical climates, predominantly across Central and South America [10, 11]. Belonging to the Rubiaceae family, it is characterized by a rounded or oval shape,

a thin, wrinkled, brownish skin when ripe, and a thin, smooth, green skin during the unripe stage. Its pulp is soft and juicy, yet exhibits a distinctive flavor and strong aroma. Each fruit may contain up to 300 seeds within the mesocarp. The seeds are also known to exhibit blue pigmentation when the fruit is still green [12].

According to [9], genipap fruits once a year, with maturation occurring from May to August. Harvesting is typically performed by collecting fruits that have fallen to the ground, although this method often results in mechanical damage, accelerating deterioration. To reduce such losses, some farmers employ long-handled tools to harvest fruits directly from the tree canopy.

Owing to the high levels of essential nutrients such as calcium and vitamins B1, B2, B5, and C, genipap has wide-ranging applications beyond medicinal use, including in the food and cosmetic industries [13]. The nutritional richness of genipap has been further confirmed by [14], who characterized its composition. In their study, the fruit contained dietary fiber at $4.64 \text{ g} \cdot 100 \text{ g}^{-1}$, calcium at $458.44 \text{ mg} \cdot 100 \text{ g}^{-1}$, iron at $15.94 \text{ mg} \cdot 100 \text{ g}^{-1}$, carotenoids ($874.49 \text{ mg} \cdot 100 \text{ g}^{-1}$) and potassium ($350.42 \text{ mg} \cdot 100 \text{ g}^{-1}$) were reported, along with evidence associating phenolic compounds with antioxidant activity and indicating the ability of the extract to delay oxidative processes, such as β -carotene degradation.

However, the carotenoid content reported by the authors ($874.49 \text{ mg} \cdot 100 \text{ g}^{-1}$) [14] should be interpreted with caution, as it substantially exceeds the ranges typically described for fruits. This discrepancy may be associated with differences in the basis of quantification, the analytical methods employed, or potential inconsistencies in the reported units. Therefore, comparison with other studies requires methodological standardization and a critical evaluation of the available data.

[15] report that the predominant bioactive compounds in genipap are iridoids, commonly found in the Rubiaceae family. Several of these iridoids are responsible for health-promoting effects. In addition, significant quantities of flavonoids, anthocyanins, and phenolic compounds have also been reported, as summarized in Table 1.

According to Table 1, variability in the quantification of bioactive compounds across studies can be observed, as evidenced by the different values reported for total phenolics [6, 16] and total polyphenols [17, 16]. These discrepancies may be associated with methodological factors, including differences in extraction protocols, solvent polarity, sample processing conditions, and analytical techniques employed.

Table 1 Bioactive compounds identified in *Genipa americana* L., including compound name, measured quantity, and the corresponding study authors

Bioactive compounds	Concentration	Author(s)
Iridoids	$0.25 \pm 0.00 \text{ mg/g}$ (ripe fruit pulp); $128.07 \pm 1.09 \text{ mg/g}$ (unripe fruit pulp)	[6]
Total phenolics	$4.17 \pm 0.07 \text{ mg/g}$ (unripe fruit pulp); 0.00 mg/g (ripe fruits pulp)	[6]
	$857.10 \text{ mg GAE/100 g}$	[16]
Total polyphenols	$61.6 \pm 3.6 \text{ mg GAE/g}$	[17]
	$176.3 \text{ mg GAE/100 g}$ (fresh fruit), $587.7 \text{ mg GAE/100 g}$ (dried fruit)	[16]
Flavonoids	728.00 mg/100 g	[16]
Anthocyanins	$4.6 \text{ mgcy-3-glu/100 g}$	[16]
Lycopene	0.63 mg/100 g	[18]
β -carotene	0.93 mg/100 g	[18]

Source: Prepared by the authors, 2025

In addition, biological factors, such as the stage of fruit ripening, also influence phytochemical composition. Studies indicate that compounds such as iridoids and phenolic acids may undergo significant reductions during ripening, due to metabolic transformations and the reduced need for defense compounds in later stages of development [6].

Therefore, although the variability observed across studies should be interpreted in light of methodological and biological factors, the available data indicate that genipap contains relevant concentrations of bioactive compounds. These findings reinforce its potential as a source of metabolites of biotechnological and functional interest.

Scientometric Data

Among the 116 studies that met the inclusion criteria, Table 2 was constructed to present the ten most relevant articles on genipap. These studies were initially ranked based on the total number of accumulated citations. However, it can be observed that citations per year and normalized citations do not always correspond to the overall ranking position, as exemplified by the seventh most cited article, which presents the third highest number of annual citations.

Normalized metrics adjust citation counts according to the publication's exposure time and the average impact within the field, allowing for a more balanced comparison between older and more recent studies. Therefore, these metrics were used as complementary criteria, alongside thematic relevance and methodological consistency, to ensure a more comprehensive and balanced assessment of the scientific impact of the analyzed studies.

Additionally, there is a clear predominance of Brazilian authors: among the ten most cited studies, eight are of national origin, highlighting the prominence of Brazilian scientific output on this topic.

According to [19], the most cited article involving genipap examined this fruit, along with twelve other plants from the Brazilian Cerrado, regarding the potential of their extracts to inhibit tyrosinase. Genipap extract was obtained from leaves, bark, and the whole fruit using solvents such as ethanol and hexane, followed by an aqueous extraction by infusion. As the sole representative of the Rubiaceae family in this study, genipap extract exhibited low tyrosinase inhibitory activity, proving less effective compared to kojic acid and the extracts of *Pouteria torta* and *Eugenia dysenterica*.

The study by [22] provided the chromatographic profile of phytosterols present in the pulp and seeds of genipap. The total phytosterol content in the pulp was 216 mg/100 g, while the seeds contained a considerably higher concentration of 233 mg/100 g. The compounds identified included campesterol, stigmasterol, β -sitosterol + sitostanol, Δ^5 -avenasterol + Δ^7 -stigmasterol, and Δ^7 -avenasterol. The predominant compound in both the pulp and seeds was β -sitosterol + sitostanol, quantified at 150 mg/100 g in the pulp and 123 mg/100 g in the seeds. This study confirms the potential of the fruit and its seeds, which are typically discarded. Its phytosterol composition suggests applications in food and pharmaceutical products due to antioxidant activity and cholesterol-lowering properties.

[20] reported that when genipap extract was used in the synthesis of gold nanoparticles [GNPs], the bioactive compounds in the fruit acted as reducing and stabilizing agents. Key bioactive compounds involved in this process included genipin, genipaol, geniposide, and ranolazine, all abundantly present in the fruit. This study demonstrated the feasibility of genipap extract as a promising platform in nanoscience, particularly for the formulation of nano-structured systems for controlled drug release.

Table 2 Most cited studies on *Genipa americana* L., showing authors, first author's affiliation, total citations, and average citations per year

Paper	1st author's affiliation	Total citations	Citations per year	Normalized citations
[19]	Department of Food Science, Federal University of Lavras, Lavras, MG, Brazil	169	12.07	2.711
[20]	Center for Nanoscience and Nanotechnology, Universidad de las Fuerzas Armadas ESPE, Ecuador	101	10.10	2.104
[21]	Federal University of Ceará, Department of Chemical Engineering, Pici Campus, Fortaleza CE, Brazil	97	5.39	2.575
[22]	Department of Food Science, Faculty of Food Engineering, University of Campinas, Campinas, SP, Brazil	93	5.81	2.583
[23]	Department of Pharmaceutical Sciences, School of Health Sciences, Campus Darcy Ribeiro, University of Brasília, Brasília, Brazil	84	6.00	1.348
[17]	Federal University of Alagoas (UFAL), Institute of Chemistry and Biotechnology, Tabuleiro do Martins, Maceió, AL, Brazil	81	5.79	1.299
[24]	Department of Biosciences, Federal University of São Paulo (UNIFESP), Santos, São Paulo, Brazil	65	9.29	2.671
[25]	Enzymology Laboratory, Food Science and Technology Institute, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil	54	6.75	2.628
[26]	LASEFI - Department of Food Engineering, School of Food Engineering, University of Campinas (UNICAMP), Campinas, SP, Brazil	49	5.44	3.206
[27]	School of Agriculture, Kyushu Tokai University, Kumamoto, Japan	49	2.33	1.633

Source: Prepared by the authors based on data retrieved from the Web of Science and Scopus databases, 2025

In the study by [26] on the extraction of bioactive compounds from genipap, the authors reported that the primary source of these compounds, especially iridoids, is the green fruit. However, analysis of individual fruit parts revealed distinct characteristics, such as higher antioxidant activity in the mesocarp and endocarp, higher genipin content in the endocarp, and higher geniposide content in the mesocarp. These findings provide useful guidance for selecting specific fruit parts when extracting targeted compounds.

In addition to the extensively studied bioactive compounds, the blue pigment obtained from green-stage genipap fruit also demonstrates significant scientific potential [28]. reported the feasibility of using green technologies to extract genipap dye, yielding promising results and economic viability for its application, promoting a product with high impact in the natural dye sector [29]. demonstrated that genipap dye produced a coloration similar to the commercially available synthetic dye n° 2, showing excellent stability and potential for application in foods.

The relationship between countries, authors, and keywords in genipap studies, illustrated in Fig. 2, highlights the predominance of Brazilian researchers, who contribute the majority of scientific output on this topic. Among the keywords associated with the authors, besides the botanical designation of the species, terms related to bioactive compounds and antioxidant activity are prominent. This recurrence underscores the nutritional potential of the fruit. Over the past two decades, the literature has emphasized its composition and potential applications, including methods for the full utilization of the fruit.

Among the authors with the highest scientific output, the first listed in Fig. 2, Ramos de la Peña, has coauthored publications with Mexico, France, the United States, and Belgium, being responsible for the output originating from Mexico. Additionally, this author maintains the highest number of connections with different countries. Following him, Dickson L. occupies the second position; besides contributing to Brazilian research, he is responsible for a substantial portion of genipap-related scientific production in France. Although other countries show lower percentages of authors and contributions compared to Brazil, significant international collaborations are evident. Countries such as France, Mexico, the United States, Spain, and Portugal maintain links with several authors primarily affiliated with Brazilian institutions. This scientific exchange facilitates the dissemination of knowledge regarding genipap attributes and contributes to the development of more robust and highly relevant research.

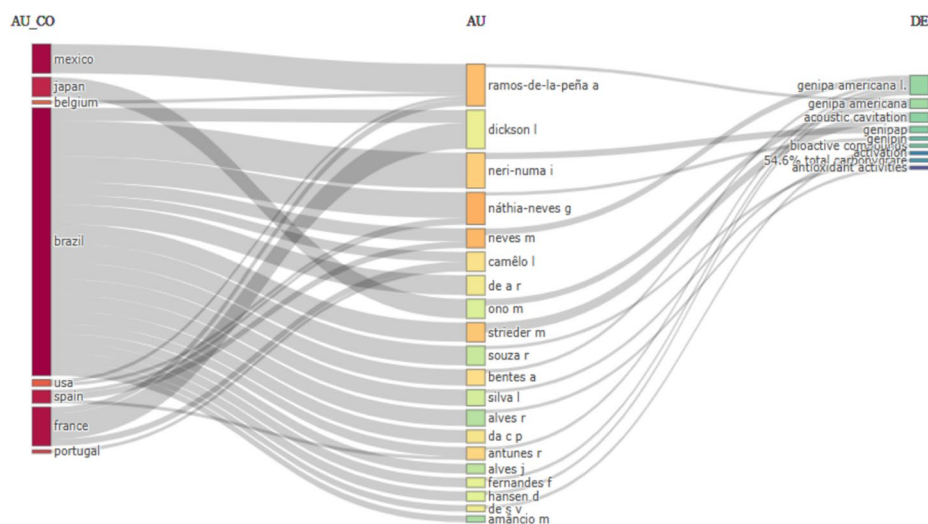


Fig. 2 Network map illustrating correlations between countries, authors, and keywords, highlighting collaborative relationships and research clusters in the field. Source: Prepared by the authors with R and biblioshiny, 2025

In Fig. 3b, representing the co-occurrence of keywords extracted from Scopus, a higher incidence of terms is observed compared to Fig. 3a, along with the presence of an additional cluster. This increase in the number of terms may be due to the larger volume of articles indexed in Scopus, suggesting that it is a more comprehensive database. The analysis resulted in four clusters. The two largest clusters show groupings similar to those identified in the WoS database. The green cluster is associated with the Rubiaceae family and plant extracts,

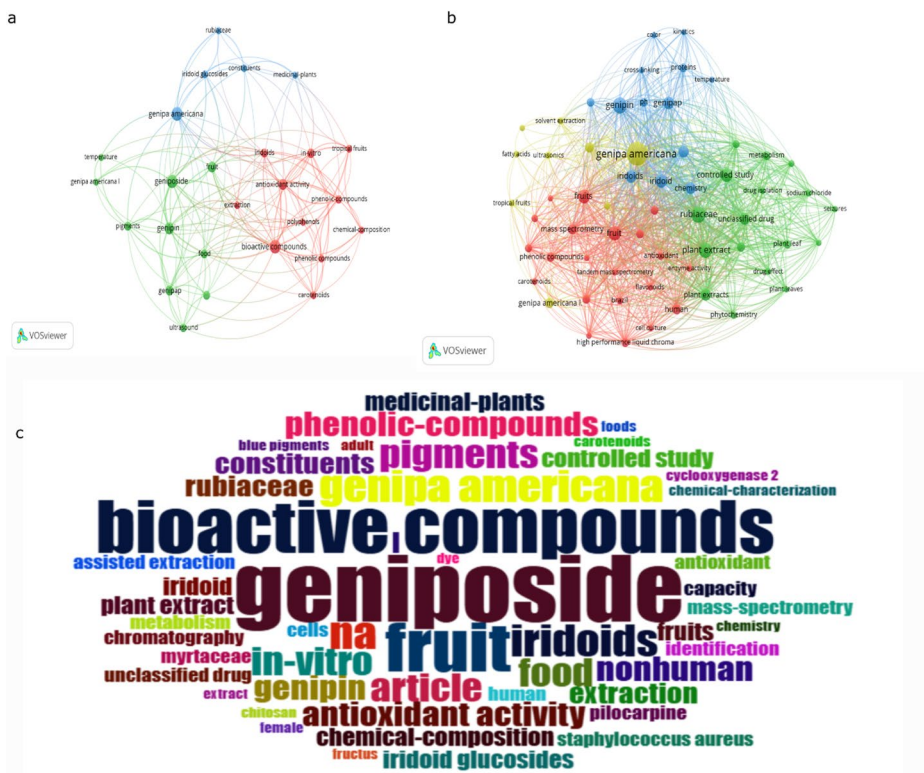


Fig. 3 Keyword co-occurrence network demonstrating the frequency and interconnections of key terms used in the analyzed publications, indicating major research trends. Source: Prepared by the authors with VOSviewer, R and biblioshiny, 2025

predominantly addressing aspects related to phytochemistry, metabolism, and the regulation of detected substances. The red cluster focuses on the relationship between genipap and its bioactive compounds, such as phenolics, flavonoids, antioxidants, and carotenoids. Within this group, analytical techniques for compound identification, including mass spectrometry and high-performance liquid chromatography (HPLC), are recurrently noted. The blue cluster pertains to the chemistry of specific genipap compounds, with emphasis on iridoids, as well as factors influencing the kinetics of the fruit-derived pigment and the activity of present proteins. Finally, the yellow cluster, the smallest among the four, is associated with ultrasound-assisted extraction techniques and the solvents employed in these procedures.

Figure 3c, the keyword cloud generated through data processing in RStudio, using the Biblioshiny package, is presented. In this visualization, the most frequently occurring terms are highlighted. The most prominent word is geniposide, one of the main bioactive constituents of genipap (*Genipa americana* L.). Geniposide is classified as an iridoid, a type of bioactive compound that plays a central role in the reaction responsible for the formation of the blue pigment obtained from genipap. The second most salient expression is bioactive compounds, a category that includes, among others, phenolic compounds, iridoids, and carotenoids. The antioxidant activity of these compounds is also widely addressed in the studies analyzed. However, keywords related to large-scale optimization were not identified, suggesting that the current literature largely confines studies to the characterization of bioactive compounds. This highlights a significant scientific gap and presents a relevant opportunity for future research focused on process optimization and industrial application. These findings underscore the importance of genipap, particularly its by-products, as promising sources of bioactive compounds, while simultaneously emphasizing the need for advances in studies aimed at their industrial and biotechnological application.

The evolution of scientific production over the last two decades regarding studies on genipap is shown in Fig. 4a. In the early 2000s, the number of publications was at its lowest recorded level. Beginning in 2004, a slight increase was observed, which persisted with low-intensity fluctuations until 2010. In 2012, the first significant peak in global scientific output occurred, followed by a decline and, subsequently, a modest increase. This oscillatory pattern continued in the following years. Around 2018, scientific production experienced a marked increase, reaching approximately twice the level of the initial 2012 peak. In 2020, the highest volume of publications of the past two decades was recorded. After this period, there was a sharp decline, possibly associated with the SARS-CoV-2 pandemic, characterized by mobility restrictions and reduced productivity across multiple sectors. Only in 2022 did production resume growth, culminating in the second-highest peak observed in 2024. Regarding the current year, considering only the first half of 2025, scientific output is slightly higher than that recorded in 2022.

According to Fig. 4b, Brazil stands out as the leading producer of studies on genipap (*Genipa americana* L.) and its residues. Although multiple countries have contributed to some publications, more than 80% of Brazilian output consists of exclusively national authorship. Mexico, the second-largest producer, exhibits international collaboration in approximately half of its publications. It is noteworthy that only Argentina, Japan, Peru, and the United States display independent production without the involvement of other countries. Even when aggregating all publications from the remaining nations, their combined output does not surpass that of Brazil. These findings reinforce the country's leading position in research on genipap, its residues, and derivatives.

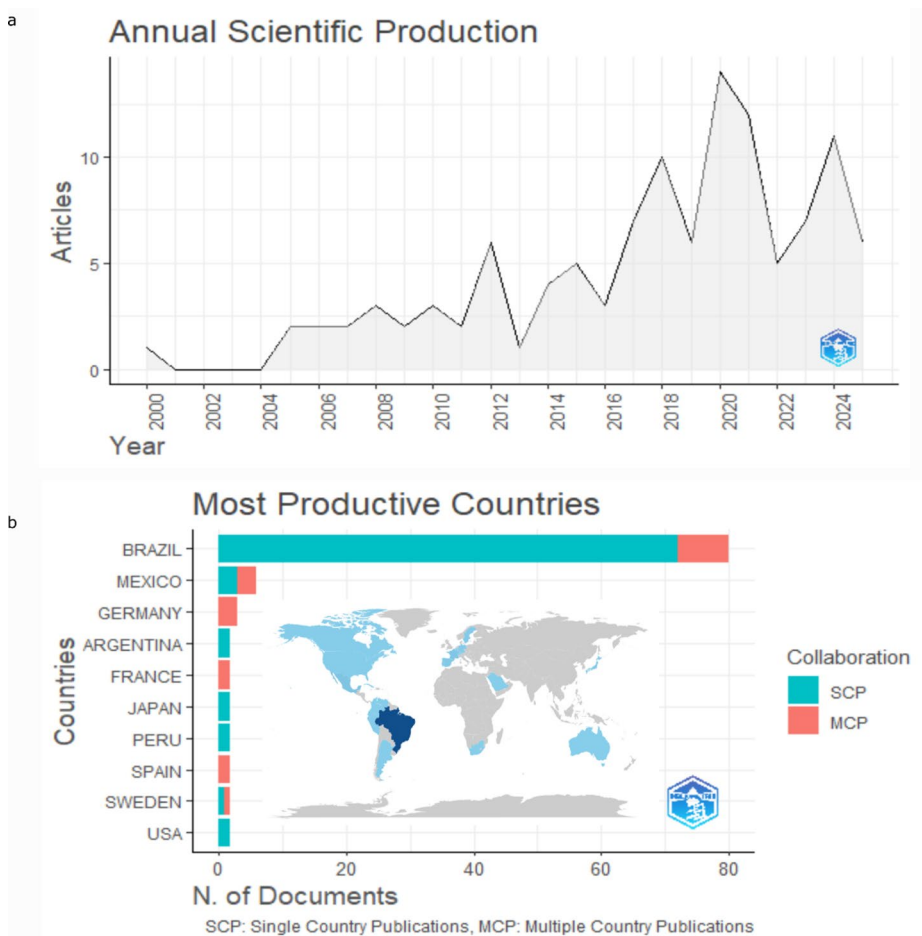


Fig. 4 Temporal trend of global scientific production over the last two decades, showing the annual number of publications and growth patterns in the studied research area. Source: Prepared by the authors with R and biblioshiny, 2025

Figure 5 presents the main journals that published studies on genipap and/or its residues between Jan/2004 and July/2025.

The data on publications indicate a broad research approach. Food Research International, the journal with the highest number of related publications, focuses on high-impact studies in the fields of food science, technology, and engineering, as well as nutrition. Its output is two to five times greater than that of other journals, reflecting the strong interest in the bioactive compounds present in genipap (*Genipa americana* L.) and their potential applications in health-promoting products. Food Chemistry, ranking second in publication volume, publishes studies that investigate food constituents, particularly bioactive compounds, the effects of processing on foods, and the chemistry associated with metabolism and toxicology of food additives. These findings reinforce the relevance of genipap as a promising source of bioactive compounds.

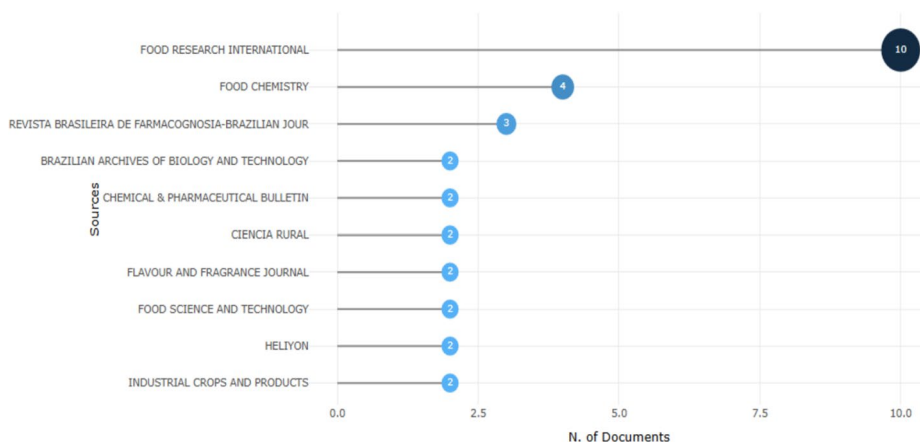


Fig. 5 Distribution of articles across journals, indicating the most frequently publishing sources and their relative contributions to the field. Source: Prepared by the authors with R and biblioshiny, 2025

The Revista Brasileira de Farmacognosia – Brazilian Journal of Pharmacognosy, although encompassing another area, emphasizes studies of plants, such as genipap, as natural sources of bioactive compounds, highlighting both pharmaceutical and food-related applications. The Brazilian Archives of Biology and Technology addresses the integration of biology and technology, underscoring the value of genipap as a whole and promoting the integral utilization of the fruit. Similarly, the Chemical and Pharmaceutical Bulletin investigates genipap from an interdisciplinary perspective.

The remaining journals listed address similar aspects, with particular emphasis on studies of the blue pigment extracted from genipap [29], its major compounds [26] and its antioxidant properties [30]. Despite these advances, few studies have specifically investigated genipap processing residues. However [31], conducted the extraction of bioactive compounds from residues of several fruits, including genipap, yielding promising results. Their findings revealed the presence of individual polyphenols, high sugar content, and elevated sucrose levels. They also proposed optimized extraction conditions for genipap, further supporting the feasibility of utilizing these compounds across diverse industrial sectors.

Some studies indicate that the pulp yield of genipap ranges between 48% and 73.81% [12, 32]. Other research reports the use of genipap peels in the development of by-products, particularly through drying to produce flour and in the preparation of sweets [9]. Nevertheless, a considerable amount of residue is generated during genipap processing, which, depending on the fruit, may represent approximately 30% to 50% of the total weight [12, 32]. Although the current reuse of these residues remains limited and the number of studies scarce, it is important to emphasize their substantial potential as agro-industrial by-products, particularly due to the significant quantities generated.

Agro-Industrial Residues

Brazil has an economy strongly based on agriculture and ranks among the world's ten largest agro-industrial producers, occupying third place globally. In the early 2000s, the country exported approximately USD 20 billion in products; this figure increased substantially,

reaching USD 160 billion in 2022. Productivity gains recorded over the past three decades have been remarkable, supporting estimates that by the end of this decade Brazil may lead the global market in at least nine commodities. Alongside this high annual agricultural output, the country also faces the challenge of managing the agro-industrial residues generated by such overproduction, which directly influences the scale of waste production [33].

Agro-industrial residues are defined as all waste generated from the production of agricultural or animal-based products. Many of these by-products arise from the food industry, including breweries, sugar production, fruits, cereals, vegetables, and dairy. Agricultural activities also play a significant role in residue generation. Even whey and wastewater derived from agro-industrial processes are classified as agro-industrial residues. Some of these by-products are rich in fibers, carbohydrates, antioxidants, minerals, proteins, and sugars, and are primarily composed of lignocellulosic materials [34].

Regarding the residue derived from genipap, studies reported in the literature show limitations in quantitative data on its lignocellulosic composition. Nevertheless, these residues are expected to comprise a matrix of cellulose, hemicellulose, and lignin due to their plant origin [35, 20]. Supporting this interpretation, additional studies highlight the high carbohydrate content of genipap residues, exceeding 70% on a dry weight basis, as well as the elevated levels of insoluble fiber, indicative of a typical lignocellulosic material profile [36]. In general, fruit residues tend to exhibit lower lignin contents compared to other biomasses, suggesting improved efficiency in the extraction of their bioactive compounds [34].

A considerable share of food intended for human consumption is wasted during processing and throughout the production chain, further increasing the amount of available residue. Industries have focused on minimizing the environmental impact of untreated waste disposal. Given that this material has characteristics with high potential for the development of new products, the valorization of residues has emerged as a strategy to mitigate environmental damage [37–39] emphasize the potential of these residues, as they are composed of high-value substances, highlighting promising alternatives for residues from the vegetable industry: food ingredients for incorporation into fruit juices and bakery products, substrates for generating fruit flavors, and bioadsorbents for wastewater treatment.

The full utilization of foods represents a viable strategy for the reuse of residues generated during production. This approach operates on two fronts: it contributes to food security by using residues as raw materials to enhance the nutritional profile of various products, and it mitigates environmental impacts by providing safe and appropriate destinations for such residues [40].

Description and Utilization of Agro-Industrial Residues

Commonly and erroneously classified as industrial “waste,” residues differ from actual waste because they possess added economic value and can be reutilized either within the same production process or in distinct processes [41]. The food industry generates a wide variety of residues with characteristics suitable for use as raw materials in multiple processes.

Industries processing fruits and vegetables work with highly perishable raw materials, and the processing required to extend their shelf life generates large volumes of by-products. Most of the residues generated consist of peels, pomace, and seeds. In juice and pulp processing, approximately 40% of the raw material results in residues. Several studies

have demonstrated the nutritional richness of fruits, including high levels of phenolic compounds, vitamin C, vitamin E, dietary fiber, carotenoids, and antioxidants [42, 43].

Genipap, a raw material used by the fruit and vegetable industries, exhibits significant antioxidant activity in its residues, such as peels and seeds [36]. reported values of 803.32 EC₅₀ (mg/mL) by the DPPH method and 304.56 mol Fe₂SO₄·g⁻¹ by the FRAP method in genipap peels; and 2,357.94 EC₅₀ (mg/mL) by DPPH and 245.12 mol Fe₂SO₄·g⁻¹ by FRAP in the seeds. DPPH values are expressed as EC₅₀, representing the concentration required to reduce 50% of the free radical, while FRAP results indicate the reducing capacity of the extracts. However, the expression of FRAP results reported by [36] in mol Fe₂SO₄·g⁻¹ differs from the more commonly used literature standard, which expresses these values as Fe²⁺ equivalents (μmol/g), a factor that should be considered when interpreting the data.

[31] obtained values ranging from 1,617.23 to 6,583.10 μmol Fe₂SO₄·100 g⁻¹ by the FRAP method, and from 2,074.67 to 2,344.91 μmol Trolox·100 g⁻¹ by DPPH, considering the combined analysis of the residues. Direct comparison of these results is limited due to methodological heterogeneity among studies, including differences in the assays employed, units of measurement, quantification bases, and extraction protocols. While [36] used maceration and Soxhlet extraction with 80% ethanol and hexane [31], employed shaker and ultrasound-assisted extraction with ethanol, methanol, and acetone (80%). Consequently, data analysis was conducted qualitatively, considering general trends in antioxidant activity without performing direct quantitative comparisons, to avoid misinterpretation arising from the lack of experimental standardization.

[26] applied pressurized liquid extraction with 99% ethanol to determine the antioxidant activity of genipap peels and seeds. Values for the peels ranged from 5.2 to 15.4 μmol Trolox/g by the FRAP method and from 1.8 to 3.8 μmol Trolox/g by DPPH. Compared to other studies, these results may reflect differences in operational conditions and solvent polarity, preventing direct inference regarding the superiority or inferiority of the employed technique.

According to [36], DPPH results indicated that the seeds exhibited antioxidant activity approximately four times higher than that of the peels, whereas FRAP results showed slightly higher values for the peels. This discrepancy may be attributed to the distinct mechanisms of the assays, as DPPH is associated with hydrogen atom donation capacity, whereas FRAP evaluates electron transfer. Thus, the results suggest differences in the chemical composition between peels and seeds, particularly in the distribution of phenolic compounds and other antioxidants with distinct modes of action.

Considering the findings reported by [31], the combined utilization of residues (peels and seeds) appears to be a promising strategy, as it may exploit the complementarity of antioxidant compounds, thereby enhancing the potential for application in the development of novel products.

A study by [44] on antioxidant activity in residues of pineapple, cashew, passion fruit, and mango indicated that all residues presented satisfactory antioxidant content, supporting their incorporation into other products as natural antioxidant sources [45]. reported that seeds of orange, guava, passion fruit, and tomato are excellent and viable raw materials for the production of edible oils.

[46] found that incorporating mango peel powder into cake formulations as a substitute for bread crumbs resulted in products with good sensory acceptance. Since mango peel powder did not negatively affect the final product's sensory profile, it contributed to enhanc-

ing its nutritional composition. Similarly [47], demonstrated that adding pumpkin residue flour to gluten-free bread formulations is a promising alternative due to its positive nutritional outcomes, as well as improved quality and consumer acceptance [48]. showed that incorporating beet residue syrup into yogurt increased antioxidant capacity and calcium and potassium content without altering product quality or identity standards.

[49] reported that rice husks and corn cobs used for bio-oil production yielded bio-oils with lower viscosity and greater acidity from corn cobs, although both showed similar reactivity and represent biomass sources of high-value compounds. According to [50], these plant residues have substantial potential for energy generation [51]. also emphasized the importance of cereal industry residues for the biotechnological production of xylitol.

In the sugar industry, most residues can be reused, transformed, and incorporated into new processes. Sugarcane bagasse and straw form a biomass with high lignocellulosic content, widely applied in energy production, representing a renewable source with significant economic and environmental viability [52, 53]. Another use of sugarcane bagasse, according to [54], is as ruminant feed, where protein content increased from 2.3% to 7.2% when the bagasse was cultured with *Spirulina platensis* [55]. identified filter cake as a potential fertilizer due to its high potassium, calcium, and nitrogen content [56]. reported that incorporating sugarcane bagasse ash into mortar produced properties comparable to sand, with satisfactory resistance parameters.

Honey cakes enriched with fibers derived from brewing residues, as investigated by [57], were classified as “high in fiber” and achieved satisfactory sensory acceptance. Similarly, yeast residues, like brewers’ spent grain, are notable for their protein content and high nutritional value [58]. These findings further highlight the importance of exploring and developing strategies to valorize such materials, ensuring they are directed toward beneficial uses and preventing the generation of additional environmental burdens.

Bioactive Compounds

Given the growing demand for improvements in quality of life, reflected in the maintenance of health and the adoption of healthier dietary habits, consumers have increasingly valued and preferred foods that provide specific health benefits upon consumption [59, 60, 61]. These characteristics are inherent to functional foods. According to the Brazilian Health Regulatory Agency [62], a functional food is defined as a food or ingredient that, in addition to fulfilling its basic nutritional functions, produces beneficial effects on health, is safe for consumption, and does not require medical supervision. Such foods contain bioactive compounds responsible for promoting health benefits.

Potential of Bioactive Compounds

Bioactive compounds play a crucial role in the food, pharmaceutical, and cosmetic industries. Consequently, studies such as those conducted by [63, 64] and [65] have increasingly focused on the economic, safe, and readily available extraction of these compounds, as well as their effects on human health, oxidative stress mitigation, and functional properties necessary for their application.

One promising approach for obtaining bioactive compounds is through the valorization of residues, which adds value to products [66]. explored this strategy using tomato

residues to extract phenolic compounds and evaluate antioxidant capacity. They employed conventional and ultrasound-assisted extraction techniques. Tomato residues yielded 584.63 ± 1.78 mg GAE/g of phenolic compounds and antioxidant capacities of $700.67 \mu\text{mol TE/g}$ (ORAC) and $186.98 \mu\text{mol TE/g}$ (ABTS). The phenolic content obtained was within the range reported in the literature for by-products of different tomato varieties. Ultrasound-assisted extraction resulted in higher phenolic recovery and shorter extraction times. Additionally, 21% of the phenolic compounds from these residues were flavonoids in both extraction methods. This study enabled the quantification of bioactive compounds in tomato processing residues, highlighting significant levels for potential applications, particularly of flavonoids.

[67] presented a review of agro-industrial residues as sources of bioactive compounds and their potential applications. Their work emphasizes the diversity of residues containing secondary metabolites with antioxidant and antimicrobial activities, useful for preventing contamination in ethanol production. Fruit residues were particularly noted, with studies demonstrating that residues from grape, avocado, mango, orange, lemon, jaboticaba, apple, banana, and tangerine can be used to obtain natural bioactive compounds, which exhibit similar properties to synthetic counterparts while offering advantages for food industry applications.

[68] highlighted the importance of investigating bioactive compounds derived from fruit residues. They characterized oils extracted from seeds of various orange varieties for carotenoids, tocopherols, phytosterols, total phenolics, and antioxidant activity. Total carotenoids ranged from 11.64 to 26.69 mg/kg, total phenolic compounds from 3.79 to 4.91 g/kg, tocopherols from 134.07 to 137.43 mg/kg, and total phytosterols from 1,288.5 to 1,334.0 mg/kg. Antioxidant capacity ranged from 56% to 70.2%. Differences in values were attributed to variations in orange varieties. Nevertheless, all oils from the studied seeds contained considerable bioactive compounds and antioxidant activity, making them suitable for incorporation into nutritionally balanced diets.

[69] reported that beer production residues also serve as a source of bioactive compounds. They identified and quantified phenolic compounds in malt residues and determined their antioxidant capacity. Total phenolics were 1.06 ± 0.54 mg GAE/g, flavonoids 0.24 ± 0.07 mg QE/g, gallic acid 2.43 ± 0.04 mg/g extract, and p-coumaric acid 0.16 ± 0.01 mg/g extract. These compounds exhibited antioxidant activity exceeding literature reports, suggesting that bioactive compounds from malt residues could substitute synthetic compounds and serve as natural preservatives in foods.

Regarding genipap [70], reported multiple bioactive compounds present in different parts of the fruit. In juice and pulp processing by-products, studies have identified genipin and geniposide [26]; tannins, steroids, and saponins [71]; phenolic compounds [36]; phenolics and carotenoids [72]; phenolics and flavonoids [31]; and phenolics and triterpenes [73]. These studies indicate that phenolic compounds and iridoids, predominant in these residues, are mainly responsible for the observed antioxidant activity.

Additionally, iridoids such as genipin and geniposide have been associated with anti-inflammatory mechanisms mediated by the inhibition of the NF- κ B signaling pathway and the activation of antioxidant response factors, such as Nrf2, resulting in reduced production of pro-inflammatory cytokines and increased expression of antioxidant enzymes. These compounds also play a role in modulating oxidative stress and maintaining cellular integrity, contributing to hepatoprotective and cytoprotective effects described in the literature

[74]. According to Bentes and Mercadante [6], the chemical composition of genipap, particularly regarding iridoids and phenolic compounds, is directly related to the fruit's stage of maturation. In this context, iridoids such as geniposide are more abundant during early developmental stages and progressively decrease as the fruit matures, a pattern associated with their role as plant defense metabolites.

Ethnopharmacological studies report the use of genipap seeds and peels for various medicinal purposes, including the treatment of alopecia, hemorrhages, and fungal infections [75–77]. These applications may be related to the presence of bioactive compounds with antioxidant and anti-inflammatory properties, although most evidence to date derives from experimental and preclinical studies.

The presence of phenolic compounds in genipap peels and seeds, as reported in several studies [73, 36, 31], is associated with multiple health benefits. However, the levels of these compounds vary according to the fruit's maturation stage. For instance, iridoids exhibit significantly higher concentrations in unripe fruits (128.07 ± 1.09 mg/g) compared to ripe fruits (0.25 ± 0.00 mg/g) [6], reflecting a reduction of over 90% during maturation. This variation is related to decreased biosynthesis of defense compounds throughout fruit development [6]. Nevertheless, studies evaluating this dynamic specifically in residues such as peels and seeds, typically obtained from mature fruits, remain scarce.

The analyzed studies indicate that variations in bioactive compound content are influenced by multiple factors, including extraction techniques, solvents used, and operational conditions. Differences in methodology can significantly impact the efficiency of compound recovery, preventing the identification of a universally superior extraction method. Among the most commonly used solvents for bioactive compound extraction are ethanol, methanol, and acetone, each with distinct polarities and consequently differing effects on extraction efficiency.

Regarding genipap production by-products, there is a paucity of studies exploring their application, despite the high potential of available bioactive compounds. Growing interest in agro-industrial residues as sources of bioactive compounds has promoted the utilization of material normally considered waste as a raw material for high-value compounds [31].

However, large-scale application feasibility depends on the optimization and standardization of extraction processes, considering both efficiency and economic viability, as well as on investigations into the stability of bioactive compounds, solvent regulatory compliance, and extract safety, representing significant scientific gaps. Genipap residues possess relevant functional properties, and their utilization could generate economic and environmental benefits for industry, while representing a promising alternative for the development of novel products.

Final Considerations

According to scientometric data, Brazil stands out as the leading country in global scientific production on genipap and its derivatives. There is a clear predominance of research focused on bioactive compounds, in addition to the blue dye extracted from genipap. Worldwide production on the topic has shown oscillatory yet increasing trends when comparing the two decades. Interdisciplinarity is also observed among the journals publishing the most articles on the subject, although the fields of food science and chemistry are particularly prominent.

In this context, the full utilization of genipap, particularly its agro-industrial residues such as peels and seeds, emerges as a promising strategy for obtaining naturally derived bioactive compounds. These residues have potential applications across various industrial sectors, contributing to the valorization of production chains and the reduction of environmental impacts associated with improper disposal.

However, translating this potential into effective industrial applications still requires significant advances. Issues related to the chemical stability of bioactive compounds, the need for efficient extraction, purification, and standardization processes, as well as compliance with regulatory and safety requirements, represent critical challenges. Additionally, factors such as process scalability, extract reproducibility, and economic feasibility must be considered to consolidate these applications.

In summary, future studies should prioritize not only the chemical characterization of compounds but also the development and optimization of technological processes, including stabilization strategies, shelf-life assessment, and validation at pilot and industrial scales. Such efforts will enable the effective incorporation of genipap residues as raw materials in sustainable, high-value-added production systems.

Appendix

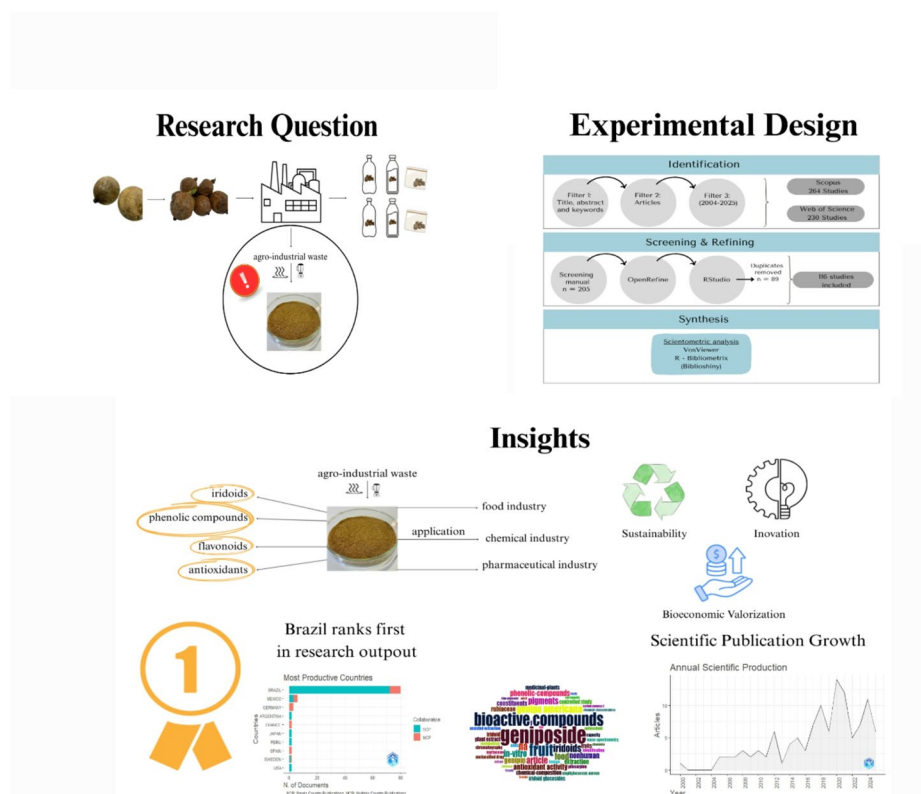


Fig. 6 Graphical abstract

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s43615-026-00949-5>.

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Declarations

Declaration of Interest Statement The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

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