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Hibiscus sabdariffa L. antimicrobial compounds for food applications: A bibliometric analysis

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Abstract:
The increasing demand for natural antimicrobial agents in food preservation has led to a growing interest in *Hibiscus sabdariffa* L. due to its antimicrobial properties. We conducted a bibliometric analysis to assess the scientific production of antimicrobial extracts and compounds from *H. sabdariffa*, identifying research trends, relevant applications in the food industry, and knowledge gaps. A structured search was performed in the Web of Science database, retrieving articles published between 1984 and 2025. Bibliometric indicators, including annual publication trends, most influential journals, research collaboration networks, and keyword co-occurrence, were analyzed using R and VOSviewer. The results indicated a yearly growth rate of 8.15% in *H. sabdariffa* antimicrobial research, with significant contributions from Mexico, Egypt, and India. Studies have demonstrated that *H. sabdariffa* extracts, particularly ethanolic and aqueous fractions, exhibit potent antibacterial activity against *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus*, attributed to phenolic compounds, flavonoids, and anthocyanins. Despite promising applications, challenges remain regarding the stability of *H. sabdariffa* compounds in food matrices, standardization of extraction methods, and regulatory approval for commercialization. Future research should optimize extraction techniques, develop nanoencapsulation strategies to enhance stability, and explore synergistic effects with other natural antimicrobials. Additionally, interdisciplinary studies combining food science, pharmacology, and biotechnology could further elucidate *H. sabdariffa*'s antimicrobial mechanisms and facilitate its integration into sustainable food preservation systems. This analysis provides valuable insights into the current research landscape and outlines strategic directions for advancing the application of *H. sabdariffa*-based antimicrobials in the food industry.

Keywords: Antimicrobial properties, phenolics, extraction standardization, natural food preservatives, encapsulated bioactives, shelf-life extension

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INTRODUCTION

Hibiscus sabdariffa L., a flowering plant native to Africa and cultivated in tropical and subtropical regions, is valued for its bright red calyces traditionally used in beverages, jams, and remedies for hypertension and diabetes [1, 2]. Rich in such bioactive compounds as anthocyanins, flavonoids, and organic acids (Table 1), *H. sabdariffa* exhibits nutritional, antioxidant, and antimicrobial properties [3, 4]. Delphinidin-3-sambubioside and cyanidin-3-sambubioside in its composition exhibit antimicrobial activity against pathogens such as *Escherichia coli* and *Staphylococcus aureus*. This makes *H. sabdariffa* a natural alternative to synthetic preservatives [5, 6] and a promising candidate for safer and more sustainable food preservation strategies [7, 8].

Antimicrobial compounds are essential for food preservation as they inhibit spoilage microorganisms, extend shelf life, and prevent disease by targeting pathogens. Natural alternatives, including plant extracts and essential oils, are increasingly recognized for their safety and efficacy in combating bacteria such as *Salmonella* and *E. coli* [9, 10]. These compounds disrupt

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microbial cell membranes or metabolic processes, causing cell death [11, 12]. For instance, carvacrol and cinnamaldehyde increase membrane permeability, leading to cellular leakage [13].

The consumer demand for healthier, minimally processed foods and tighter rules on synthetic additives accelerate the change toward natural antimicrobials [14, 15]. This trend highlights the possibilities of natural antimicrobials to satisfy both consumer expectations and legal criteria since it fits clean-label preferences and environmental goals [16]. Research on *H. sabdariffa* has shown that its extracts are highly effective in inhibiting the growth of harmful bacteria (Table 2). *H. sabdariffa* has proven effective in various food preservation strategies, particularly through its integration into edible films and coatings. These applications not only enhance food safety by inhibiting microbial growth but also help maintain sensory and nutritional properties [17, 18]. Notably, the development of antimicrobial biodegradable films incorporating *H. sabdariffa* extracts further highlights the plant's versatility and potential to extend shelf life across a broad range of food products. For example, maize starch films incorporating aqueous extracts of *H. sabdariffa* have shown notable antibacterial properties against *Listeria monocytogenes*, *S. aureus*, and *E. coli*, with inhibitory zones over 29 mm [19]. In addition, the inhibitory action of hibiscus acid on *Salmonella enterica* and *E. coli* has revealed its potential against bacteria resistant to antibiotics [20, 21]. Another example of its pragmatic use in food safety is rinsing beef with *H. sabdariffa* extracts to lower *L. monocytogenes* and methicillin-resistant *S. aureus* [22].

In another study, impregnating apple wedges with *H. sabdariffa* extracts boosted the contents of bioactive components and improved sensory acceptability [23]. The plant's anti-*E. coli* effects on animal products have

Table 1 Main phytochemicals found in *Hibiscus sabdariffa* L. flowers [24, 25]

Phenolic acids	Flavonoids	Anthocyanins	Other phenolic compounds
Citric acid Chlorogenic acid Cryptochlorogenic acid Hibiscus acid Hydroxycitric acid Hydroxybenzoic and Hydroxycinnamic acids Protocatechuic acid Pelargonidic acid	Hibiscitrin (Hibiscetin-3-glucoside) Quercetin (Quercetin-3-O-glucuronide) Kaempferol (Kaempferol 3-O-glucuronide) Syringetin-3-O-glucoside Luteolin (Luteolin-7-O-D-glucuronidemethylester) Sabdaritrine Gossypitrin Gossytrin Other glycosides of gossypetin Anthocyanins	Hibycin (Cyanidin-3-glucoside or Delphinidin-3-glucoside) Cyanidin-3-sambubioside Delphinidin-3-sambubioside	Eugenol Sterols: *β*-sitosterol Ergosterol

Table 2 Antimicrobial activity of *Hibiscus sabdariffa* L. extracts and compounds in *in vitro* and food systems

Compound or extract	*In vitro* antimicrobial activity	Application in food	Reference
Ethanol-hydrochloric acid extract	The roselle extract prepared by ultrasonic extraction showed antibacterial activity, with IC_{50} values ranging from 0.15 ± 0.05 mg/mL to 4.64 ± 0.07 mg/mL and MIC values from 1.66 ± 0.06 to 7.11 ± 1.05 mg/mL against various bacteria, particularly effective against gram-positive bacteria such as *Staphylococcus aureus* and *Streptococcus intermedius.*	The extract was not tested in food.	[26]
Acetone extract	The extract was not tested *in vitro*.	The addition of polyvinyl alcohol and extract enhanced the films' mechanical performance and reduced water vapor permeability, which is beneficial for food packaging applications. These results highlighted the potential of using *Hibiscus sabdariffa* L. extract in developing biodegradable materials that minimize environmental impact while maintaining food safety.	[27]
Aqueous extract	Aqueous extracts showed dose-dependent inhibitory effects against *Escherichia coli* O157:H7 and *Staphylococcus aureus*, with effective concentrations leading to increased lag phases and reduced growth rates of these bacteria in microbiological media.	The extract demonstrated antimicrobial effects in UHT milk, effectively inhibiting the growth of both pathogenic bacteria over a period of 7 days.	[28]

Continuation of Table 2

Compound or extract	*In vitro* antimicrobial activity	Application in food	Reference
Hibiscus acid	The compound exhibited antivirulence properties by reducing *Salmonella typhimurium*'s invasion of epithelial cells, demonstrating its potential as an anti-motility agent against this bacterium.	The compound was not tested in food.	[20]
Ethanolic-aqueous extract	The extract showed antimicrobial activity against *Salmonella typhimurium*, *Staphylococcus aureus*, *Escherichia coli,* and *Pseudomonas aeruginosa.*	The reduction of microorganisms on the surface of surimi was greater, ranging from 4 to 5 Log CFU/g, compared to the inner part, which showed a reduction of 2 to 4 Log CFU/g. Furthermore, the use of hibiscus extract improved the sensory qualities, such as appearance, smell and color, of surimi stored under cold conditions for 7 days, compared to the control sample without the extract.	[29]
Ethanolic extract	The extract showed significant antibacterial activity against food-borne pathogens such as *Escherichia coli, Salmonella enterica*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Bacillus cereus*.	The extract was effective as a natural preservative, extending the shelf-life of beef meat. Microbiological, color, and sensory analyses indicated improved preservation qualities when the extract was applied.	[22]
Hibiscus acid	This compound showed antimicrobial effect against multidrug-resistant *Salmonella* and *Escherichia coli*. Additionally, it affected the membrane permeability of *Escherichia coli* and *Salmonella*, showing its potential mechanism of action against these bacteria.	The compound was not tested in food.	[21]
Methanolic, acetonic, and ethyl acetate extracts	The extract was not tested *in vitro*.	Roselle calyx extracts significantly reduced ($p < 0.05$) the number of all food-borne bacteria on contaminated romaine lettuce, spinach, and coriander compared to sodium hypochlorite, colloidal silver, and acetic acid. Therefore, they could be a valuable addition to disinfection protocols for these leafy greens.	[30]
Acetone and methanol extracts	Both acetonic and methanolic extracts of *Hibiscus sabdariffa* L. had antimicrobial effects against five pathogenic microorganisms. Inhibition halos ranged from 15–21.3 mm for the acetonic extract and 12–15.59 mm for the methanolic extract. *Escherichia coli* was the most sensitive to the extracts, while *Shigella flexneri* was the least sensitive. The extract concentration was 10 mg/mL, and the highest antimicrobial effect was observed for the acetonic extract ($p < 0.05$).	The films made from potato starch, glycerol, and *Hibiscus sabdariffa* L. extracts effectively inhibited *Listeria monocytogenes*. The acetonic extract film reduced about 1 log CFU within the first 24 h, with a further decrease to 1.5 log CFU by the second day. Conversely, the methanolic extract film allowed for bacterial recovery, indicating ineffective transfer of the extract to the sausage and insufficient inhibition. Control sausages without the extracts exhibited continuous bacterial growth, underscoring the antimicrobial effectiveness of the extract-containing films.	[31]
Aqueous extract	The extract was not tested *in vitro*.	The extracts of *Hibiscus sabdariffa* L. demonstrated significant antibacterial activity against MRSA and *Listeria monocytogenes*. When applied at concentrations of 120 and 240 mg/mL, these extracts effectively reduced bacterial counts on hot dogs after rinsing for various durations (5, 15, 30, and 60 min) and subsequent storage (0 and 24 h).	[32]
Protocatechuic acid Aqueous extract	Protocatechuic acid and aqueous extract inhibited the growth of MRSA, *Klebsiella pneumoniae, Pseudomonas aeruginosa* and *Acinetobacter baumannii.* The compound showed a greater inhibitory effect compared to the roselle calyx extract.	The compound and the extract were not tested in food.	[33]

also demonstrated its natural preservation value in the meat sector [2]. This underscores the versatility and potential of *H. sabdariffa* as a natural antimicrobial agent in food applications.

Despite the growing interest in the antimicrobial applications of *H. sabdariffa*, several knowledge gaps limit the full exploitation of its potential. Although various bioactive compounds – such as anthocyanins, flavonoids, and organic acids – have been identified, their specific roles and mechanisms of action remain poorly understood. For example, it is still under investigation how anthocyanins disrupt bacterial membranes, or how quercetin inhibits enzymes such as DNA gyrase [34]. In contrast, some compounds such as hibiscus acid have demonstrated specific mechanisms of action against certain bacterial strains [20, 21]. Additional challenges include the stability of these compounds during food processing and storage, as thermal treatments can reduce their antimicrobial efficacy [4, 35]. Another challenge is that the scalability of *H. sabdariffa* extracts is hindered by the absence of optimized extraction techniques and standardized production protocols [36].

Variability in extraction methods and geographic origin further complicates the consistent application of *H. sabdariffa*. Different techniques, such as hot versus cold water extraction, affect bioactive compound levels, as does the phytochemical composition tied to geographic origin [37, 38]. While *H. sabdariffa* is generally safe, concerns about its extract's toxicity in clinical and food applications require further studies [39]. Addressing these issues through standardization and comprehensive evaluations could optimize *H. sabdariffa* as a natural antimicrobial agent.

A bibliometric analysis can provide valuable insights into research trends, knowledge gaps, and future directions for utilizing *H. sabdariffa* as a natural antimicrobial agent in food applications. It can also uncover opportunities for interdisciplinary collaboration, such as integrating food science and pharmacology to develop functional foods or synergistic natural antimicrobials [38, 40], thereby advancing strategies for optimized food preservation and safety.

In view of the above, we aimed to analyze the scientific production of antimicrobial extracts and compounds from *H. sabdariffa* through a bibliometric study identifying research trends, current applications in the food industry, and knowledge gaps. As a result, we sought to propose key areas for future studies, emphasizing their relevance to developing safer and more sustainable food products.

STUDY OBJECTS AND METHODS

The methodology for this bibliometric analysis was designed to systematically investigate the scientific literature on antimicrobial extracts and compounds derived from *Hibiscus sabdariffa* L. The research was conducted using the "Advanced Search" feature on the Web of Science (WoS) database on January 28, 2025. A specific logical search function was employed to retrieve relevant publications. The search query was structured as follows: 'TS=("*Hibiscus sabdariffa*" AND ("extract*" OR "bioactive compound*" OR "natural product*" OR "polyphenol*" OR "flavonoid*") AND ("antimicrobial*" OR "antibacterial*" OR "antifungal*" OR "food preserv*" OR "food application*" OR "food safety"))'.

This logical function was designed to capture studies focusing on *H. sabdariffa* and its antimicrobial properties, including its extracts, bioactive compounds, and their food preservation and safety applications. The asterisks (*) were used as wildcards to account for variations in the terms, ensuring a comprehensive retrieval of relevant literature. The search results were refined using specific filters to enhance precision. Only documents classified as "Article" were included, and the publication years were restricted to the period between 1984 and 2025, with specific years selected to align with the research objectives.

The refined search results were downloaded in two file formats, "savedrecs.bib" and "savedrecs.ris", using the "Full Record" option to ensure that all available metadata for each publication was included. These files were stored for subsequent analysis. The bibliometric analysis was performed using the "savedrecs.ris" file, which was loaded into the graphical interface of the bibliometrix package (version 4.3.0) in R. The R programming language (version 4.3.3, "Angel Food Cake") was utilized for this analysis, running on a 64-bit Linux Mint 22 Wilma system based on Ubuntu 24.04 Noble. The system specifications included a 6.8.0-52-generic kernel, x86_64 architecture, and GCC compiler version 13.3.0. This computational environment ensured the accuracy and reproducibility of the analysis.

The "savedrecs.ris" file was processed using VOSviewer software (version 1.6.20) to analyze the authors' keywords. A map was created based on bibliographic data, and the data source was selected from reference manager files. The RIS file was uploaded, and a co-occurrence analysis was performed with keywords as the unit of analysis and full counting as the counting method. A thesaurus file in ".txt" format, containing two columns labeled "label" and "replace by", was used to standardize terminology. In this file, the terms "*Hibiscus-sabdariffa* l.", "*Hibiscus-sabdariffa*", "*Hibiscus sabdariffa* l", "*Hibiscus sabdariffa* l.", "roselle calyx", "roselle", "hibiscus", "l.", "l", "leaves", and "calyxes hibiscus" were replaced by "*Hibiscus sabdariffa*" to ensure consistency in keyword mapping.

A minimum threshold of five occurrences per keyword was set, and out of 1021 keywords, 47 met this criterion. These 47 keywords were selected for further analysis. Once the processing was completed, the resulting network, overlay, and density visualizations were saved in the PNG format.

RESULTS AND DISCUSSION

Scientific production from 1984 to 2024. The bibliometric analysis provided a detailed overview of the research landscape surrounding antimicrobial extracts

and compounds derived from *Hibiscus sabdariffa* L., as can be seen in Table 3. The data spanned from 1984 to 2024, covering 166 documents from 129 distinct sources. This indicated a broad and diverse range of publications, reflecting the multidisciplinary interest in *H. sabdariffa* as a natural resource for antimicrobial applications in the food industry.

The annual growth rate of 8.15% demonstrated a steady increase in research interest over the years. This growth suggested the field was gaining momentum, likely driven by the increasing demand for natural and sustainable food preservation methods. The average age of the documents was 6 years, which indicated that much of the research was relatively recent. This was further supported by the high average citation count of 22.17 per document, suggesting that the research is active and highly influential within the scientific community.

The analysis of document contents revealed a rich array of keywords, with 588 Keywords Plus (ID) and 577 Author's Keywords (DE). This diversity in keywords highlighted the multidisciplinary nature of the research, encompassing topics such as bioactive compounds, polyphenols, flavonoids, and food safety. The large number of keywords suggested that the studies explored various applications and mechanisms related to *H. sabdariffa*, from its antimicrobial properties to its potential use in food preservation.

Regarding authorship, the data showed that 864 authors contributed to 166 documents, with an average of 5.96 co-authors per document. This indicated a high level of collaboration among researchers, further supported by the 22.29% rate of international co-authorships. Such partnership allows for advancing the field and exchanging ideas and resources across different regions and institutions. The presence of only three single-authored documents underscored the collaborative nature of this research area.

Table 3 Bibliometric characteristics of research on antimicrobial extracts from *Hibiscus sabdariffa* L. (1984–2024)

Description	Results
Main information about data	
Timespan, years	1984–2024
Sources (journals, books, etc.)	129
Documents	166
Annual growth rate, %	8.15
Document average age, year	6
Average citations per doc	22.17
Document contents	
Keywords Plus (ID)	588
Author's Keywords (DE)	577
Authors	
Authors	864
Authors of single-authored documents	3
Authors collaboration	
Single-authored documents	3
Co-authors per document	5.96
International co-authorships, %	22.29
Document types	
Article	160
Article; book chapter	2
Article; early access	2
Article; proceedings paper	1
Article; retracted publication	1

The document types were predominantly articles (160), with a few other types, such as book chapters, early access articles, and proceedings papers. This distribution reflected the primary focus on peer-reviewed journal articles, the main vehicle for disseminating scientific findings. Including a retracted publication served as a reminder of the importance of rigorous peer review and the need for continuous quality control in scientific research.

Future research should address the identified knowledge gaps, such as the stability of bioactive compounds during food processing and the standardization of extraction methods, to fully harness the potential of *H. sabdariffa* as a natural antimicrobial agent.

Figure 1 provides a bibliometric overview of research on antimicrobial extracts and compounds derived from *H. sabdariffa*. The analysis covers publication trends, geographic contributions, main sources of publication, journal impact, and disciplinary classifications. These visualizations collectively highlight the growing interest in *H. sabdariffa* as a natural antimicrobial agent and its multidisciplinary research impact across food science, microbiology, pharmacology, and chemistry.

The temporal distribution of publications from 1984 to 2024 (Fig. 1a) reveals a clear shift in research interest toward *H. sabdariffa* and its antimicrobial properties. The first recorded study in 1984 was followed by more than a decade of inactivity, suggesting that the potential of *H. sabdariffa* as a natural antimicrobial agent was largely unexplored during this period. It was not until 1999 that another study emerged, marking the beginning of sporadic research activity.

A steady, but slow increase in publications began in the mid-2000s, aligning with a growing scientific interest in natural antimicrobials and food safety applications. The number of articles per year remained relatively low until 2015 when research on *H. sabdariffa*'s antimicrobial compounds gained traction. This period coincides with the broader scientific trend toward sustainable food preservation solutions and the increasing demand for clean-label products.

A turning point occurred after 2016, when publication output rose sharply, peaking at 23 articles in 2024. The most notable surge occurred between 2018 and 2024 when research output consistently exceeded ten articles yearly. This rapid growth may be attributed to advances in analytical techniques, increased awareness of antimicrobial resistance, and regulatory shifts favoring natural preservatives in food formulations. The post-2020 acceleration further suggests that the COVID-19 pandemic may have intensified interest in food safety and alternative antimicrobial strategies, leading to increased research output.

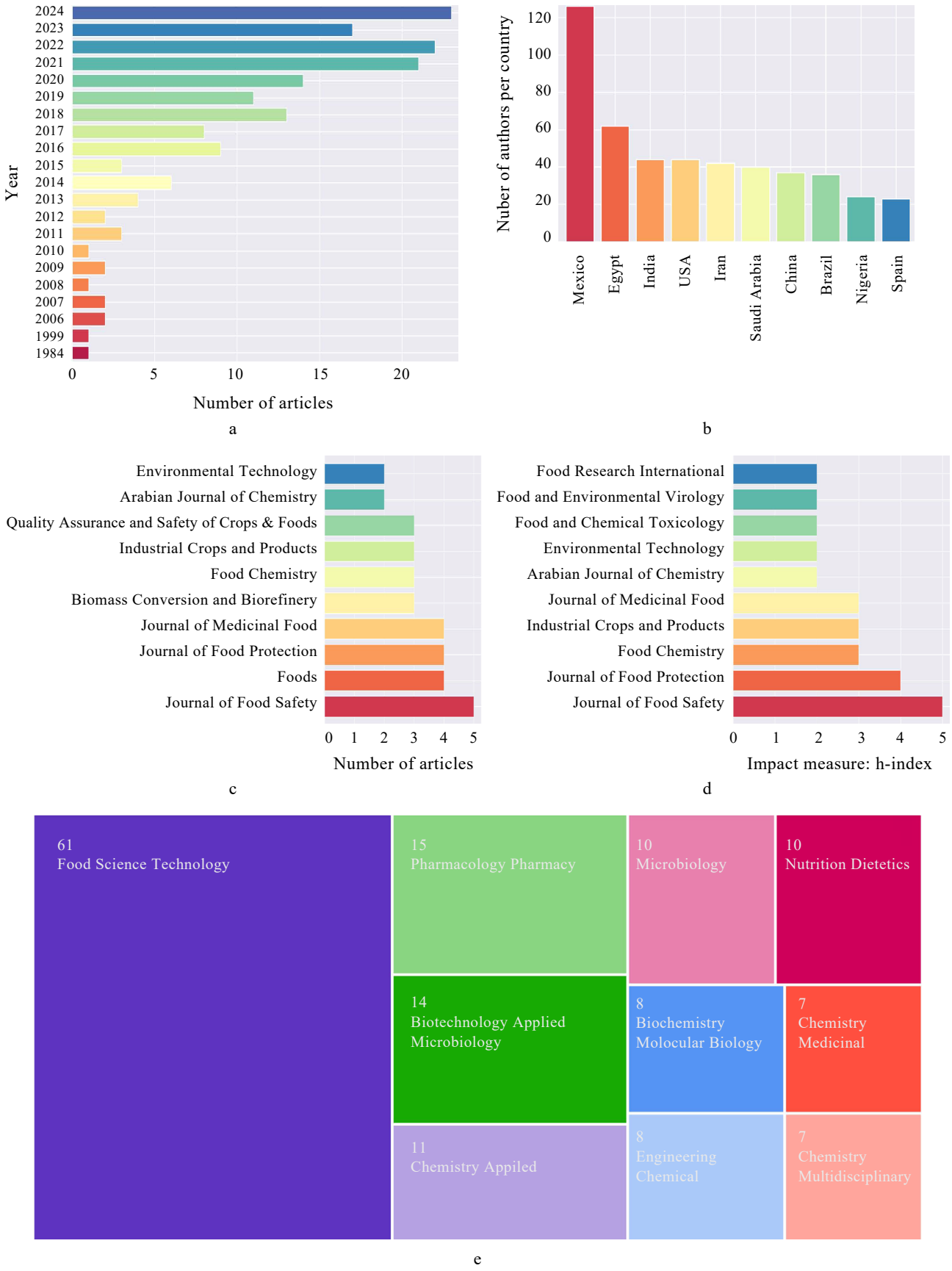


Figure 1 Bibliometric analysis of research on antimicrobial extracts and compounds from *Hibiscus sabdariffa* L.: (a) annual scientific production from 1984 to 2024, showing the number of articles published per year; (b) geographic distribution of research, presenting the number of articles by country; (c) most relevant sources, displaying the number of articles published in each journal; (d) journal impact analysis based on the h-index of the most influential sources; and (e) Web of Science category distribution, illustrating the main research areas related to *Hibiscus sabdariffa* L. antimicrobial studies

The geographic distribution of research on *H. sabdariffa* antimicrobial extracts and compounds, illustrated in Fig. 1b, reveals an intense concentration of scientific production in a few important countries. Mexico leads with 126 publications, more than double the contributions from the second-ranking country, Egypt (62 publications). This dominance may be attributed to Mexico's longstanding interest in *H. sabdariffa* as a medicinal and food ingredient and the country's rich biodiversity and traditional use of *H. sabdariffa*-based products. Additionally, major research institutions focusing on natural antimicrobials and functional foods may have further propelled Mexico's leadership in this field.

Following Mexico, Egypt, India, the USA, Iran, and Saudi Arabia contribute 40 to 62 publications each, reflecting a diverse but concentrated research effort. Egypt and India have well-established traditions in medicinal plant research, and their contributions likely stem from an interest in bioactive compounds for pharmaceutical and food applications. The USA's presence in the top four suggests a growing global interest in natural antimicrobials, possibly driven by food safety regulations and consumer demand for clean-label products.

China, Brazil, Nigeria, and Spain also make notable contributions, albeit on a lower scale. China (37) and Brazil (36) are emerging players in this research area, likely due to government initiatives supporting functional food development and the global push toward sustainable food preservation. Nigeria's representation (24 publications) highlights Africa's growing interest in plant-based antimicrobials, while Spain's (23 publications) contribution suggests European involvement in *H. sabdariffa*-related research, potentially linked to food innovation and dietary applications.

The distribution of publications across scientific journals, as depicted in Fig. 1c, highlights the primary sources contributing to research on *H. sabdariffa* antimicrobial extracts and compounds. The Journal of Food Safety emerges as the most prolific source, with five articles underscoring the strong connection between *H. sabdariffa* research and food safety applications. This aligns with the increasing interest in natural antimicrobials as alternatives to synthetic preservatives, reinforcing the role of *H. sabdariffa* in enhancing food safety and shelf-life stability.

Following closely, Foods, the Journal of Food Protection, and the Journal of Medicinal Food contributed four articles each, reflecting the multidisciplinary nature of this research field. While the Journal of Food Protection focuses on food-borne pathogen control and risk management, the Journal of Medicinal Food suggests a broader exploration of *H. sabdariffa*'s bioactive properties, including medicinal and functional food applications. The presence of Foods further indicates an interest in food formulation and technological advancements involving *H. sabdariffa*-derived antimicrobials.

The journals such as Biomass Conversion and Biorefinery, Food Chemistry, Industrial Crops and Products, and Quality Assurance and Safety of Crops & Foods published three articles each, demonstrating an increasing focus on bioprocessing, food chemistry, and industrial applications of *H. sabdariffa* extracts. This suggests that *H. sabdariffa* antimicrobial research food preservation is being explored for biorefinery applications, sustainability, and industrial scalability.

Lastly, the Arabian Journal of Chemistry and Environmental Technology contributed two articles each, signaling the use of *H. sabdariffa* antimicrobial compounds in applied chemistry and environmental science. This may reflect investigations into green extraction techniques, chemical characterization, and potential ecological benefits of *H. sabdariffa*-based antimicrobials.

The impact analysis of the journals publishing research on *H. sabdariffa* antimicrobial extracts and compounds, as depicted in Fig. 1d, provides insights into the scientific influence of various sources. The Journal of Food Safety has the highest h-index (5), indicating that at least five articles on this topic have received five or more citations. This suggests that the research published in this journal has maintained consistent citation impact, likely due to its focus on food safety, which aligns with the increasing interest in natural antimicrobial solutions. It has five published articles on this topic, accumulating 69 citations, with a mean citation rate of approximately 13.8 citations per article.

The Journal of Food Protection follows with a h-index of 4, reflecting its role in disseminating research on food-borne pathogen control and antimicrobial strategies. It has four publications in this field, accumulating 65 citations and a g-index of 4, suggesting a balanced distribution of citations across its publications. The Journal of Medicinal Food has four publications but an h-index of 3, indicating a slightly lower citation impact. However, its earliest publication dates back to 2011, making it one of the longest-standing contributors to *H. sabdariffa* research.

Food Chemistry and Industrial Crops and Products have a h-index of 3, but their citation counts differ significantly. Food Chemistry has received 82 citations from three publications, while Industrial Crops and Products has amassed 191 citations from three publications, giving it the highest total citation count among all sources. This suggests that the studies published in Industrial Crops and Products have been particularly influential despite relatively few articles.

The journals such as the Arabian Journal of Chemistry, Environmental Technology, Food and Chemical Toxicology, Food and Environmental Virology, and Food Research International have a h-index of 2, indicating that their research contributions have had a more moderate impact. However, Food Research International stands out with 155 citations from two publications, suggesting that while its number of articles is limited, the research published there has been highly cited. In contrast, Food and Chemical Toxicology has a long publication history on this topic, with its earliest relevant study appearing in 1999.

The m-index, which accounts for the impact rate over time, highlights that the Arabian Journal of Chemistry and the Journal of Food Safety have the highest values of 0.5. Although their total number of publications may not be the highest, their research impact has grown rapidly in recent years.

The treemap chart in Fig. 1e illustrates the distribution of scientific research on *H. sabdariffa* antimicrobial extracts and compounds across different WoS categories. The most prominent category is Food Science Technology, accounting for 36.75% of the total records. This dominance aligns with previous findings in Fig. 1a–1c, emphasizing the strong association between *H. sabdariffa* research and food safety, preservation, and technological applications. The high presence of this category suggests that *H. sabdariffa* is primarily studied for its potential in food formulation and antimicrobial protection.

The second most represented category is Pharmacology Pharmacy, with 9.04% of the records. This indicates that a substantial portion of the research explores the pharmacological and therapeutic properties of *H. sabdariffa* beyond its food applications. This is consistent with the presence of journals such as the Journal of Medicinal Food (Fig. 1c) as the main source of publication. Similarly, Biotechnology & Applied Microbiology represents 8.43% of the research, suggesting that its studies focus on microbial interactions, fermentation processes, and biotechnological applications of *H. sabdariffa* compounds.

Several chemistry-related categories, including Applied Chemistry, Biochemistry Molecular Biology, Chemistry Medicinal, and Chemistry Multidisciplinary, collectively represent a significant portion of the research. This finding is consistent with Fig. 1d, where the journals such as Food Chemistry and Industrial Crops and Products demonstrated a strong citation impact in the field. The presence of Microbiology (6.02%) also aligns with Fig. 1c, where the journals related to food protection and pathogen control were identified among the most relevant sources.

Interestingly, Nutrition Dietetics (6.02%) appears as a relevant category, reinforcing that *H. sabdariffa* is investigated for its antimicrobial properties, nutritional benefits, and potential role in functional foods. This observation complements the previous results, particularly the growing research output seen in Fig. 1a over the past decade, which could be driven by the increasing consumer demand for healthier, natural alternatives in food products.

Other categories, such as Engineering Chemical and Environmental Sciences, highlight the interdisciplinary nature of this research. Environmental Sciences (4.21%) suggests interest in sustainable extraction methods and eco-friendly applications, while Engineering Chemical (4.82%) may indicate efforts to optimize the processing and formulation of *H. sabdariffa*-based antimicrobial compounds.

The bibliometric analysis presented in Fig. 1 highlights the expanding research landscape on *H. sabdariffa* antimicrobial extracts and compounds, particularly in food preservation and safety. While the field has grown, regional disparities, fragmented journal distribution, and the need for standardized methodologies remain among its challenges. Strengthening interdisciplinary collaboration and global research networks could enhance the scalability and practical applications of *H. sabdariffa* antimicrobials, ultimately supporting their broader adoption in the food industry and related fields.

Table 4 presents the top-cited publications, including their respective authors, journal sources, digital object identifiers (DOIs), total citations, annual citation rate, and normalized citation count. Gonelimali *et al.* [41] published a paper with the highest citation count (416 citations) in Frontiers in Microbiology, highlighting its impact on the field. Other highly cited studies include those by Borrás-Linares *et al.* [34] in Industrial Crops and Products (174 citations) and Soto-Robles *et al.* [42] in Results in Physics (146 citations). The citation distribution indicated that the foundational works on antimicrobial applications of *H. sabdariffa* have gained recognition across different disciplines, particularly in microbiology, food science, and materials research.

The annual citation rate varied across the publications, with the most frequently cited study receiving an average of 52 citations per year, suggesting sustained interest over time. Normalized citation counts were included to adjust for differences in publication years, offering a more accurate comparison of each document's impact. These results underscore the growing scientific interest in *H. sabdariffa*'s antimicrobial potential and relevance across multiple research domains. The presence of diverse publication sources and disciplines indicates the interdisciplinary nature of this research field, supporting further exploration of its applications in food preservation, microbiology, and material sciences.

The comparative analysis of the ten most cited articles on *H. sabdariffa* antimicrobial extracts and compounds (Table 5) highlights the diverse research directions and applications of this plant. Several studies focused on its antibacterial properties, demonstrating its effectiveness against food-borne pathogens and spoilage microorganisms. Ethanolic extracts exhibited more potent antimicrobial activity than aqueous extracts, with mechanisms involving bacterial membrane disruption and changes in cytoplasmic pH [41]. The antibacterial potential was also linked to its phenolic and anthocyanidin content, which varied among 25 Mexican varieties, emphasizing the importance of proper varietal characterization in research [34].

Beyond direct antimicrobial effects, *H. sabdariffa* extracts have been used as natural reducing agents in the green synthesis of zinc oxide nanoparticles, demonstrating vigorous photocatalytic activity and environmental applications [42]. The plant has also been incorporated into biopolymer matrices, such as chitosan/polyvinyl alcohol blends, where it enhanced antimicrobial efficacy against *Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus*, *B. subtilis*, and

Candida albicans [5]. Similarly, its extract was used to develop bio-nanocomposite cheese coatings, reducing microbial growth and extending shelf-life while maintaining product quality [43].

Regarding food preservation, *H. sabdariffa* ethanol extracts and protocatechuic acid effectively inhibited bacterial growth in ground beef and apple juice, suggesting their potential as natural food preservatives [44]. The plant's multifunctionality extends to nutritional applications, as it contains high levels of anthocyanins, antioxidants, and bioactive compounds, reinforcing its value as a natural food colorant and bioactive ingredient [45]. In addition, a study exploring its cytotoxic effects showed its dose-dependent antibacterial activity against multiple pathogens and potential anticancer properties [46].

In a broader therapeutic context, *H. sabdariffa* polyphenols were investigated for their role in age-related disease management, modulating oxidative stress, inflammation, mitochondrial function, and metabolic pathways [47]. Additionally, its potential to enhance antibiotic efficacy against resistant *E. coli* strains was examined, showing that some plant extracts improved antibiotic action while others had no significant effect [48].

Thus, the bibliometric analysis of these highly cited articles underscores *H. sabdariffa* as a multifunctional plant with applications in antimicrobial preservation, food technology, biomedical materials, and therapeutic interventions. Future research should focus on optimizing extraction methods, improving bioavailability, and standardizing its applications to maximize its industrial and pharmaceutical potential.

Authors' keywords analysis. Figure 2 presents the most relevant research topics related to *H. sabdariffa*, highlighting the key themes based on the authors' keywords. The figure includes a word cloud (Fig. 2a) that visualizes the most frequently used terms and a thematic

Table 4 Major globally-cited documents on antimicrobial compounds from *Hibiscus sabdariffa* L.

Paper	Total citations	Citations per year	Normalized total citations
Gonelimali FD, Lin J, Miao W, Xuan J, Charles F, *et al*. Antimicrobial properties and mechanism of action of some plant extracts against food pathogens and spoilage microorganisms. Frontiers in Microbiology. 2018;9:1639. https://doi.org/10.3389/fmicb.2018.01639	416	52	9
Borrás-Linares I, Fernández-Arroyo S, Arráez-Roman D, Palmeros-Suárez PA, Del Val-Díaz R, *et al*. Characterization of phenolic compounds, anthocyanidin, antioxidant and antimicrobial activity of 25 varieties of Mexican Roselle (*Hibiscus sabdariffa*). Industrial Crops and Products. 2015;69:385–394. https://doi.org/10.1016/j.indcrop.2015.02.053	174	15.82	2.26
Soto-Robles CA, Luque PA, Gómez-Gutiérrez CM, Nava O, Vilchis-Nestor AR, *et al*. Study on the effect of the concentration of *Hibiscus sabdariffa* extract on the green synthesis of ZnO nanoparticles. Results in Physics. 2019;15:102807. https://doi.org/10.1016/j.rinp.2019.102807	146	20.86	3.16
Abdelghany AM, Menazea AA, Ismail AM. Synthesis, characterization and antimicrobial activity of Chitosan/Polyvinyl Alcohol blend doped with *Hibiscus Sabdariffa* L. extract. Journal of Molecular Structure. 2019;1197:603–609. https://doi.org/10.1016/j.molstruc.2019.07.089	140	20	3.03
Chao CY, Yin MC. Antibacterial effects of roselle calyx extracts and protocatechuic acid in ground beef and apple juice. Foodborne Pathogens and Disease. 2009;6(2):201–206. https://doi.org/10.1089/fpd.2008.0187	129	7.59	1.93
Jabeur I, Pereira E, Barros L, Calhelha RC, Soković M, *et al*. *Hibiscus sabdariffa* L. as a source of nutrients, bioactive compounds and colouring agents. Food Research International. 2017;100(Part 1):717–723. https://doi.org/10.1016/j.foodres.2017.07.073	118	13.11	4.72
El-Sayed SM, El-Sayed HS, Ibrahim OA, Youssef AM. Rational design of chitosan/guar gum/zinc oxide bionanocomposites based on Roselle calyx extract for Ras cheese coating. Carbohydrate Polymers. 2020;239:116234. https://doi.org/10.1016/j.carbpol.2020.116234	101	16.83	4.27
Olaleye MT. Cytotoxicity and antibacterial activity of methanolic extract of *Hibiscus sabdariffa.* Journal of Medicinal Plants Research. 2007;(1):9–13.	93	4.89	1.81
Barrajón-Catalán E, Herranz-López M, Joven J, Segura-Carretero A, Alonso-Villaverde C, *et al*. Molecular promiscuity of plant polyphenols in the management of age-related diseases: Far beyond their antioxidant properties. In: Camps J, editor. Oxidative stress and inflammation in non-communicable diseases – molecular mechanisms and perspectives in therapeutics. Advances in Experimental Medicine and Biology. Cham: Springer; 2014;824:141–159. https://doi.org/10.1007/978-3-319-07320-0_11	83	6.92	2.23
Darwish RM, Aburjai TA. Effect of ethnomedicinal plants used in folklore medicine in Jordan as antibiotic resistant inhibitors on *Escherichia coli*. BMC Complementary and Alternative Medicine. 2010;10:9. https://doi.org/10.1186/1472-6882-10-9	80	5	1

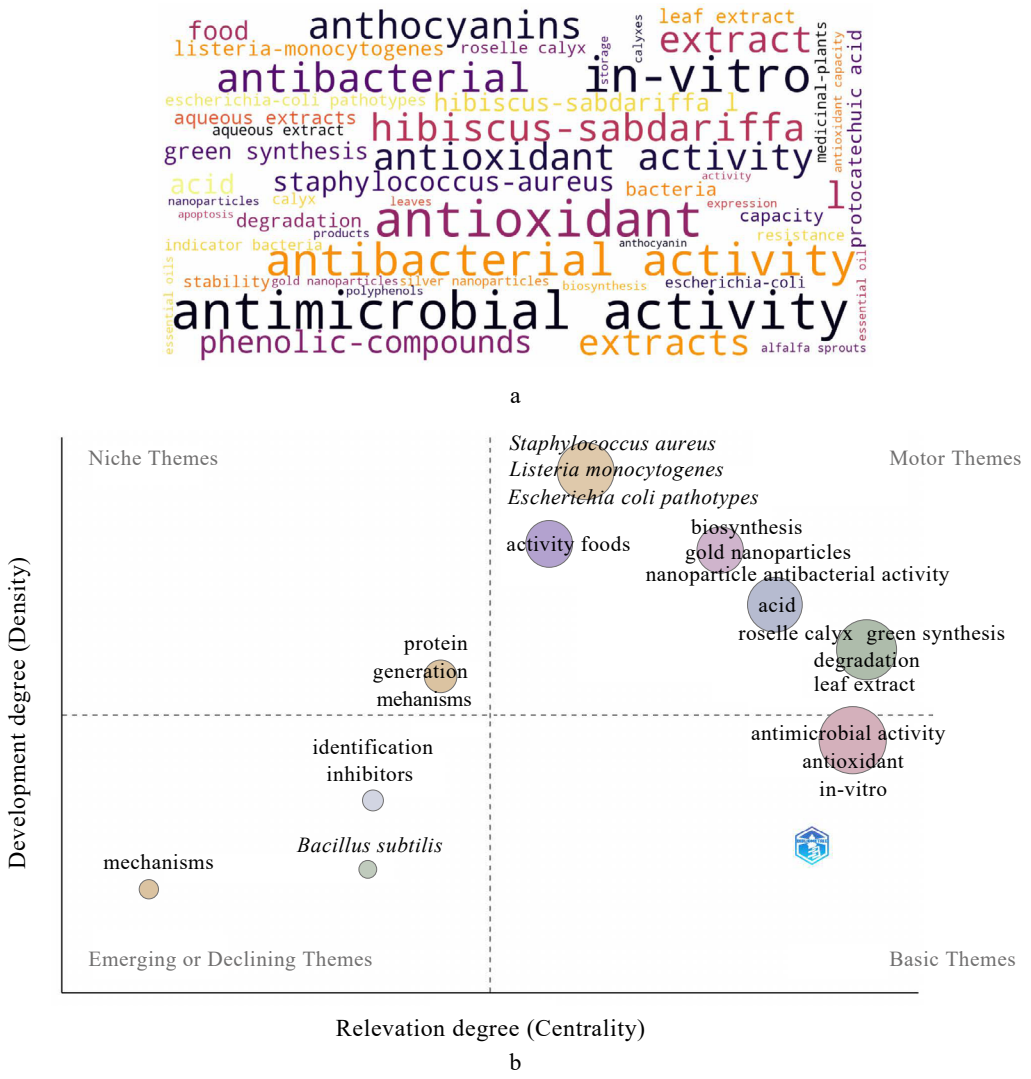
Table 5 Comparative analysis of the 10 most cited articles on *Hibiscus sabdariffa* L. antimicrobial extracts and compounds

Problem Addressed	General Objective	Results	Conclusion	Reference
Antimicrobial potential and mechanisms of plant extracts against food-borne pathogens	To evaluate the antimicrobial activity and mechanism of *Hibiscus sabdariffa* L. and other plant extracts	Ethanolic extracts exhibited stronger antibacterial and antifungal effects, disrupting bacterial membrane integrity	*Hibiscus sabdariffa* L. extracts can serve as natural food preservatives and alternatives to synthetic antimicrobials	[41]
Characterization of phenolic and anthocyanidin compounds and their bioactivity	To analyze 25 *Hibiscus sabdariffa* L. varieties for phenolic content, antioxidant capacity, and antimicrobial activity	Significant variability in polyphenol content, strong antibacterial effects against Gram-positive bacteria	Proper varietal identification is necessary for maximizing *Hibiscus sabdariffa* L.'s potential in food and pharmaceutical applications	[34]
Green synthesis of ZnO nanoparticles using *Hibiscus sabdariffa* L. extract	To investigate how extract concentration influences ZnO nanoparticle synthesis and photocatalytic efficiency	Higher extract concentrations led to smaller nanoparticles and enhanced photocatalytic degradation of methylene blue	*Hibiscus sabdariffa* L. extract is a sustainable alternative for ZnO nanoparticle synthesis with environmental applications	[42]
Development of antimicrobial biopolymer films incorporating *Hibiscus sabdariffa* L. extract	To synthesize chitosan/polyvinyl alcohol films doped with *Hibiscus sabdariffa* L. extract for antimicrobial applications	Improved mechanical properties and significant antibacterial activity against *Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus*, and *Candida albicans*	*Hibiscus sabdariffa* L. enhances biopolymer films, making them suitable for food packaging and biomedical uses	[49]
Effectiveness of *Hibiscus sabdariffa* L. extracts and protocatechuic acid in food systems	To test antimicrobial properties in ground beef and apple juice	Ethanol extracts were more effective than aqueous ones, and protocatechuic acid remained stable under heat	*Hibiscus sabdariffa* L. extracts can be used as natural preservatives in food systems	[44]
Nutritional, antioxidant, and antimicrobial properties of *Hibiscus sabdariffa* L.	To evaluate its bioactive components and safety for food applications	High anthocyanin content, strong antioxidant properties, and antimicrobial activity without cytotoxic effects	*Hibiscus sabdariffa* L. is a multifunctional ingredient for food and pharmaceutical use	[45]
Development of bio-nanocomposites for cheese coating using *Hibiscus sabdariffa* L.	To enhance Ras cheese preservation using a chitosan/guar gum/zinc oxide system	Coated cheese exhibited reduced microbial growth and better sensory attributes	*Hibiscus sabdariffa* L.-based biofilms offer a sustainable solution for extending cheese shelf-life	[43]
Cytotoxic and antibacterial properties of methanolic *Hibiscus sabdariffa* L. extract	To test its antibacterial spectrum and potential anticancer properties	Significant activity against Gram-positive and Gram-negative bacteria; cytotoxic effects in brine shrimp assays	*Hibiscus sabdariffa* L. has therapeutic potential for bacterial infections and cancer treatment	[46]
Mechanisms of polyphenols in managing age-related diseases	To explore polyphenols' effects on oxidative stress, inflammation, and metabolic pathways	Polyphenols modulate AMPK/mTOR pathways and influence mitochondrial function	*Hibiscus sabdariffa* L. polyphenols may contribute to aging-related disease prevention	[47]
Antibiotic resistance in *Escherichia coli* and potential plant-based inhibitors	To evaluate 19 Jordanian plant extracts, including *Hibiscus sabdariffa* L., as antibiotic resistance modifiers	Some extracts enhanced antibiotic efficacy, while others showed no significant effect	Certain plant extracts may improve antibiotic treatment outcomes for resistant *Escherichia coli* strains	[48]

map (Fig. 2b) that categorizes research trends according to their centrality and development. These visualizations help identify dominant topics, emerging areas, and specialized fields within *H. sabdariffa*'s antimicrobial and bioactive applications.

The word cloud in Fig. 2a highlights the most frequently used authors' keywords, reflecting relevant research themes in *H. sabdariffa* studies. The most recurrent term, "antimicrobial activity" (33 occurrences), underscores the strong scientific interest in the plant's antimicrobial potential. Similarly, "antioxidant" (31 occurrences) and "antioxidant activity" (17 occurrences) indicate a significant focus on the plant's bioactive properties, particularly its capacity to neutralize oxidative stress. The keyword "in-vitro" (29 occurrences) suggests that most studies have been conducted in controlled laboratory settings, emphasizing mechanistic evaluations rather than applied or clinical research.

The presence of "antibacterial activity" (25 occurrences) and "antibacterial" (20 occurrences) further sup-



a

b

Figure 2 Analysis of authors' keywords in *Hibiscus sabdariffa* L. research: (a) word cloud of the most frequently used keywords, highlighting dominant research topics; (b) thematic map categorizing research trends based on centrality and density, identifying motor, basic, niche, and emerging themes

ports the idea that *H. sabdariffa* has been extensively investigated for its potential to combat bacterial pathogens. Among the specific bacteria mentioned, "*Staphylococcus aureus*" (11 occurrences), "*Listeria monocytogenes*" (9 occurrences), and "*Escherichia coli*" (6 occurrences) represent common food-borne pathogens, highlighting the relevance of *H. sabdariffa* extracts in food safety applications. Additionally, "phenolic compounds" (15 occurrences) and "anthocyanins" (18 occurrences) suggest that the research has focused on the plant's phytochemical composition and its role in antimicrobial and antioxidant activities.

The keyword "extract" (17 occurrences) and related terms such as "aqueous extracts" (8 occurrences) and "leaf extract" (8 occurrences) indicate a significant emphasis on extraction methods, with aqueous extraction being a commonly explored technique. The presence of "green synthesis" (9 occurrences), "silver nanoparticles" (6 occurrences), and "gold nanoparticles" (5 occurrences) suggests a growing interest in sustainable nanotechnology approaches using *H. sabdariffa* as a reducing agent. This aligns with the trend of using plant-based extracts for biosynthesis (5 occurrences) of nanoparticles with antimicrobial and catalytic properties.

Furthermore, the inclusion of "resistance" (6 occurrences) and "indicator bacteria" (6 occurrences) suggests that some studies have investigated the effects of *H. sabdariffa* against antibiotic-resistant bacterial strains, reinforcing its potential as an alternative antimicrobial agent. Additionally, the terms such as "capacity" (7 occurrences), "stability" (7 occurrences), and "storage" (5 occurrences) highlight considerations regarding the shelf-life and functional stability of *H. sabdariffa*-based products.

The thematic map in Fig. 2b categorizes the most relevant research topics in *H. sabdariffa* studies based on their degree of development (density) and centrality. The analysis reveals distinct clusters representing well-established areas, emerging trends, and niche themes.

The upper-right quadrant (motor themes) shows such important topics as "antibacterial activity", "acid", "bio-

synthesis", "gold nanoparticles", "green synthesis", and "degradation". These themes are highly developed and central to the field, indicating their importance in driving research on *H. sabdariffa*. The presence of terms related to nanotechnology, such as "gold nanoparticles" and "biosynthesis", suggests a growing interest in applying *H. sabdariffa* extracts in green synthesis for antimicrobial and environmental purposes.

The lower-right quadrant (basic themes) includes "antimicrobial activity", "antioxidant", and "*in-vitro*", which represent fundamental and widely studied research areas. These topics are well-connected to other themes, highlighting their foundational role in the field. The emphasis on antioxidant and antimicrobial activity aligns with previous bibliometric findings, confirming that these are the core research focuses in *H. sabdariffa* studies.

The upper-left quadrant (niche themes) contains terms such as "*Staphylococcus aureus*", "*Listeria monocytogenes*", and "*Escherichia coli* pathotypes". These topics are highly specialized but less central, indicating the research focus on the antimicrobial effects of *H. sabdariffa* against specific food-borne pathogens. The presence of "foods" in this category suggests that these studies are often linked to food safety applications.

The lower-left quadrant (emerging or declining themes) features terms such as "*Bacillus subtilis*", "mechanisms", "identification", and "inhibitors". These topics are less developed and have limited centrality, suggesting either an emerging trend or a research area losing relevance. Including the mechanisms and inhibitors indicates that the studies investigating the molecular pathways underlying *H. sabdariffa*'s bioactivity are still underexplored.

Figure 3 provides a comprehensive thematic analysis of *H. sabdariffa* research, identifying important scientific areas, their interconnections, and the evolution of research focus over time. The network visualization in Fig. 3a illustrates the main study topics associated with *H. sabdariffa*. It reveals five distinct clusters that categorize the plant's scientific relevance. Each cluster represents a core research focus connected through co-occurrence relationships, emphasizing *H. sabdariffa*'s role in various applications, from food preservation to nanotechnology.

Cluster 1: Phytochemical composition and antioxidant properties (Red, RGB: 225, 131, 47). This cluster is centered on the bioactive molecules in *H. sabdariffa* that confer its antioxidant and medicinal effects. The most common terms are polyphenols (6 occurrences), phenolic compounds (15 occurrences), and anthocyanins (22 occurrences). These molecules are intimately linked with antioxidant capacity (6 occurrences) and activity (24 occurrences). The central location of *H. sabdariffa* (111 occurrences) inside this cluster emphasizes the great body of study on its phytochemical profile and possible medical advantages.

Cluster 2: Food-borne pathogens and antibacterial effects (Green, RGB: 162, 152, 223). This cluster focuses on *H. sabdariffa* antibacterial properties and applications in food safety. The most prominent terms include antibacterial activity (35 occurrences), *Listeria monocytogenes* (9 occurrences), and *Escherichia coli* pathotypes (7 occurrences). The presence of indicator bacteria (7 occurrences) and alfalfa sprouts (6 occurrences) suggests a strong focus on preventing food-borne illnesses. The earlier publication years for these terms indicate that this area has been well-established, though ongoing research continues to optimize the use of *H. sabdariffa* in antimicrobial applications.

Cluster 3: Antimicrobial activity and traditional medicine (Blue, RGB: 204, 65, 192). This cluster explores *H. sabdariffa*'s broader antimicrobial properties and applications in traditional medicine. Notable terms include antimicrobial activity (47 occurrences), essential oils (5 occurrences), and medicinal plants (5 occurrences). The connection to methanolic extract (5 occurrences) and expression (5 occurrences) suggests a growing interest in mechanistic studies that explore how bioactive compounds exert their antimicrobial effects.

Cluster 4: Green synthesis and nanotechnology applications (Yellow, RGB: 229, 255, 67). This cluster is associated with the nanotechnology applications of *H. sabdariffa*, particularly its role in the green synthesis of nanoparticles. Key terms include silver nanoparticles (12 occurrences), gold nanoparticles (6 occurrences), and green synthesis (11 occurrences). Other closely related terms, such as biosynthesis (8 occurrences) and reduction (5 occurrences), reinforce the plant's role in eco-friendly material science applications.

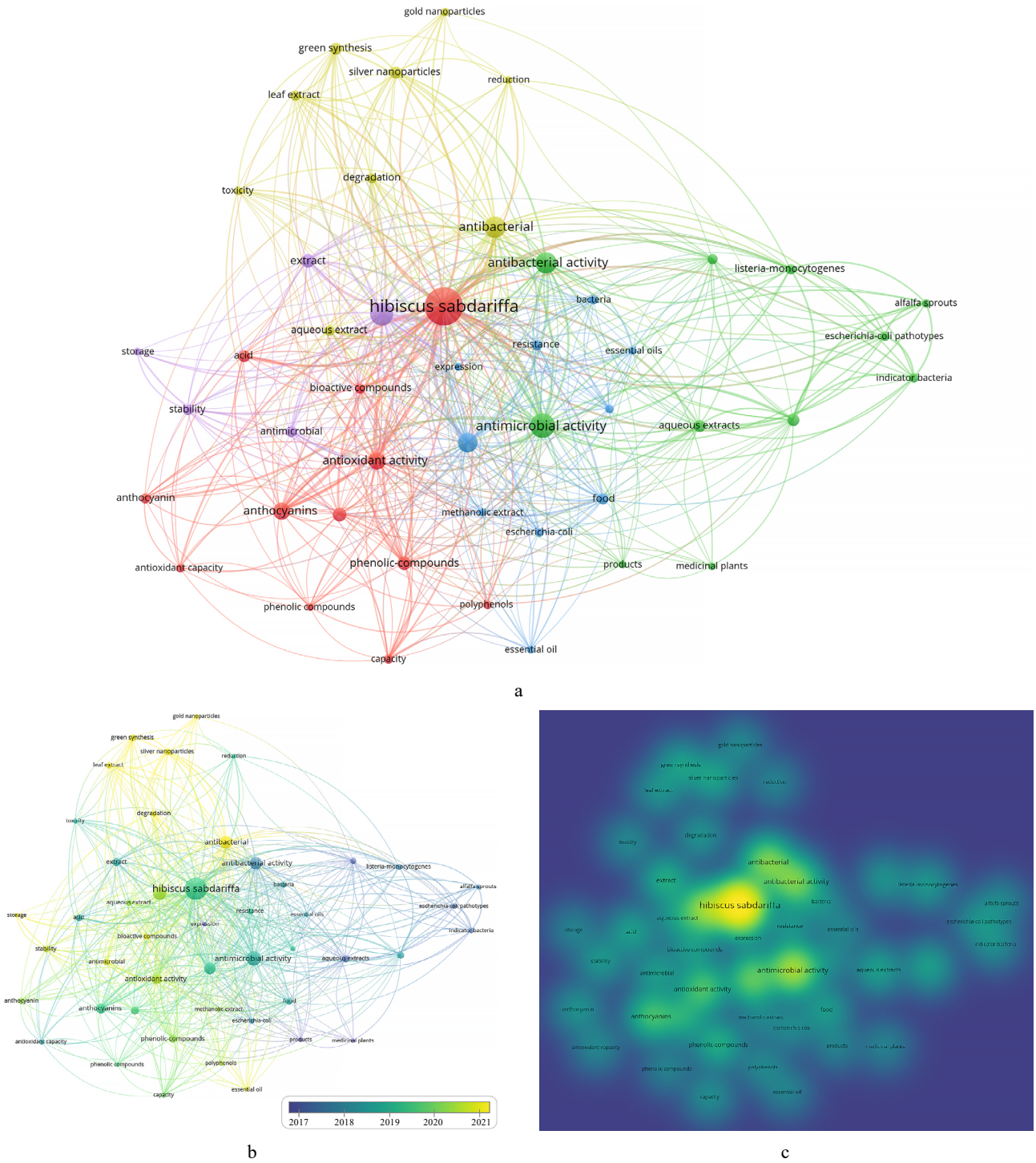
Cluster 5: Food preservation and stability (Purple, RGB: 3, 60, 96). This cluster addresses food product preservation and stabilization using *H. sabdariffa*-based coatings and additives. Important words are storage (5 occurrences), stability (9 occurrences), and toxicity (6 occurrences).

The overlay visualization (Fig. 3b) reveals the temporal evolution of research topics related to *H. sabdariffa*, with colors representing the average publication year for each term. Older topics, shown in blue, include "antibacterial activity" (2017.8571), "aqueous extracts" (2017.3636), and "*Staphylococcus aureus*" (2018.3636), indicating an early research focus on the antimicrobial properties and traditional extraction methods of *H. sabdariffa*. Similarly, the terms such as "*Listeria monocytogenes*" (2017.7778) and "*Escherichia coli* pathotypes" (2017.4286) suggest that the initial studies primarily examined *H. sabdariffa*'s efficacy against food-borne pathogens.

In contrast, more recent topics, represented in yellow-green, highlight a growing interest in advanced applications. The terms such as "silver nanoparticles" (2021.9167), "gold nanoparticles" (2021), and "green synthesis" (2021.0909) suggest a shift towards nanotechnology-based research and sustainable material development. The term "degradation" (2021.625) further supports this transition, indicating an emerging focus on environmental applications. Furthermore, the terms "antibacterial" (2021.4) and "bioactive compounds"

(2021.1111) remain relevant, reflecting the continuous exploration of *H. sabdariffa* for its antimicrobial and functional properties.

The overlay visualization (Fig. 3b) aligns with the thematic map (Fig. 2b), particularly in the evolution of research priorities. Thematic motor topics, such as "antimicrobial activity", "antioxidant activity", and "*in-vitro*" applications, correspond to the most frequently occurring and recently published terms in Fig. 3b, reinforcing their central role in *H. sabdariffa* research. Additionally, the emerging trends in green synthesis, degradation, and leaf extraction (classified as motor themes) are among the latest investigated topics (2021+), further validating the transition toward nanotechnology and sustainable applications. In contrast, the niche themes such as "*Staphylococcus aureus*", "*Listeria monocytogenes*", and "*Escherichia coli* pathotypes" reflect earlier research efforts focused on traditional antibacterial testing, as seen



a

b

c

Figure 3 Thematic analysis of *Hibiscus sabdariffa* L. research: (a) network visualization of thematic clusters; (b) overlay visualization representing temporal evolution; and (c) density visualization indicating influence density

in the older publication scores (Fig. 3b). This connection underlines a shift from pathogen-targeted studies toward broader, interdisciplinary applications, positioning *H. sabdariffa* as a versatile bioactive resource for food and pharmaceutical innovations.

The density visualization (Fig. 3c) highlights the intensity of research focus on specific terms related to *H. sabdariffa* by using a heat-map representation. The brightest yellow regions correspond to the most frequently co-occurring terms, indicating the core research themes. Notably, "*Hibiscus sabdariffa*", "antimicrobial activity", "antioxidant activity", and "antibacterial activity" emerge as the central topics, reflecting the extensive scientific interest in the bioactive potential of this plant. The green and blue areas represent less frequent but still relevant concepts, such as "green synthesis", "silver nanoparticles", and "phenolic compounds", which align with the emerging trends in nanotechnology and phytochemistry. The presence of "bacteria", "*Staphylococcus aureus*", and "*Escherichia coli*" in moderately dense areas suggests ongoing investigations into the antimicrobial properties of *H. sabdariffa*. Meanwhile, the lower-density zones, including "storage", "stability", and toxicity, indicate less explored but potentially valuable research directions.

The visualizations presented in Fig. 3a–3c provide a comprehensive perspective on the evolution and interdisciplinary nature of *H. sabdariffa* research. The network visualization (Fig. 3a) highlights strong interconnections between important research areas, emphasizing *H. sabdariffa*'s role in phytochemistry, microbiology, nanotechnology, and food science. The overlay visualization (Fig. 3b) reveals the chronological progression of the research focus, showing a transition from traditional microbiological studies to modern interdisciplinary approaches incorporating green synthesis and nanotechnology. Finally, the density visualization (Fig. 3c) effectively identifies the most frequently explored topics while pointing to emerging areas requiring further investigation. Together, these analyses suggest that future research should continue integrating diverse scientific fields to optimize *H. sabdariffa*'s industrial applications, enhance its bioactive potential, and develop innovative formulations for food preservation, pharmaceuticals, and sustainable antimicrobial materials.

Factorial analysis approach. Multiple Correspondence Analysis was performed to identify the thematic organization of *H. sabdariffa* research, as illustrated by a conceptual structure map in Fig. 4. The first dimension (Dim 1), which accounts for 41.81% of the variance, primarily differentiates the studies related to microbiological aspects on the negative axis (e. g., "*Escherichia coli* pathotypes", "*Staphylococcus aureus*", "*Listeria monocytogenes*", "indicator bacteria", and "alfalfa sprouts") from the studies associated with phytochemical and nanotechnological applications on the positive axis (e. g., "green synthesis", "gold nanoparticles", "silver nanoparticles", "biosynthesis", and "leaf extract"). This separa-

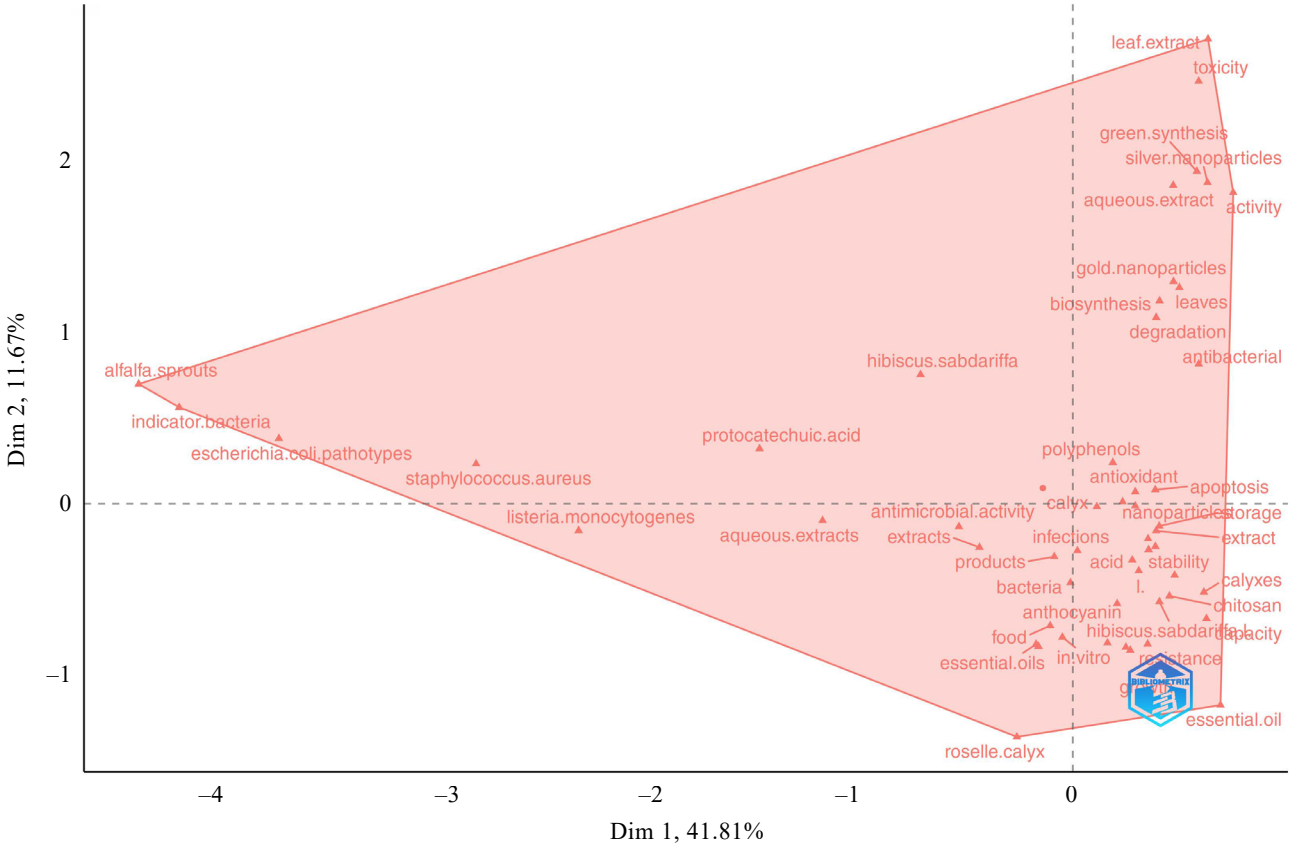


Figure 4 Conceptual structure map of *Hibiscus sabdariffa* L. research based on multiple correspondence analysis

tion suggests that *H. sabdariffa* research spans from food-borne pathogen control to applications in green chemistry and nanotechnology.

The second dimension (Dim 2) captures 21.67% of the variance and distinguishes between the topics related to antibacterial and antimicrobial research (e. g., "antimicrobial activity", "protocatechuic acid", "antibacterial activity") on the lower axis and the studies focusing on phytochemical properties and toxicity (e. g., "leaf extract", "toxicity", "biosynthesis", and "green synthesis") on the upper axis. This highlights a research dichotomy where *H. sabdariffa* is investigated both for its role in pathogen inhibition and its potential as a source of bioactive compounds in emerging technologies.

Thus, the Multiple Correspondence Analysis underscores the interdisciplinary nature of *H. sabdariffa* research, showing strong connections between microbiology, phytochemistry, and nanotechnology. The clustering of the terms suggests that the research trends are shifting towards integrating phytochemical and nanotechnology applications while maintaining a strong foundation in antimicrobial and food safety studies.

The conceptual structure map in Fig. 4 and the network visualization in Fig. 3a together highlight the underlying relationships and thematic organization within *H. sabdariffa* research. While Fig. 3a reveals the clustering of the interconnected research areas, Fig. 4 further refines these connections by positioning the topics along two principal dimensions. Dim 1 differentiates between microbiological aspects and phytochemical components, while Dim 2 distinguishes between research on antimicrobial activity and studies emphasizing extraction, synthesis, and functional applications. This alignment suggests that the interdisciplinary nature of *H. sabdariffa* research, as seen in Fig. 3a, is structurally supported by the conceptual differentiation in Fig. 4. The overlap between antimicrobial and antioxidant research reinforces *H. sabdariffa*'s dual functionality as a bioactive and food-preserving agent, making it as a promising subject for further exploration in functional food development and pharmaceutical applications.

Challenges. ***Variability in bioactive compounds.*** Geographic, environmental, and processing variability influences the concentration and efficacy of antimicrobial compounds in *H. sabdariffa* extracts. Different regions may have distinct soil compositions, climates, and cultivation practices that affect the growth and chemical composition (phenolic content, including anthocyanins and flavonoids) of the plant [37, 38]. Specific compounds such as protocatechuic acid and anthocyanins have been linked to the antimicrobial efficacy against various pathogens, including *E. coli* and *S. aureus* [20, 28, 37].

Environmental factors, including temperature, humidity, and light exposure, also influence the phytochemical composition of *H. sabdariffa*. Variations in these environmental conditions can lead to differences in the synthesis of secondary metabolites, which are responsible for the antimicrobial properties of the extracts [38, 50]. Furthermore, the extraction method can impact the yield and potency of these compounds. Aqueous extracts have been shown to exhibit varying degrees of antimicrobial activity depending on the extraction conditions, such as temperature and solvent ratios [19, 29].

Processing variability, including the method of extraction and preparation of the extracts, further affects the concentration and efficacy of antimicrobial compounds. For example, utilizing various solvents such as ethanol, methanol, or water can result in the extraction of distinct phytochemical profiles, which can either enhance or diminish antimicrobial activity [51–53]. The preparation method, including whether the plant material is utilized in a dried or fresh state, can significantly affect the bioactivity of the extracts. For example, fresh extracts might exhibit greater antimicrobial activity than their dried counterparts due to the retention of volatile compounds and elevated levels of active ingredients [28, 54, 55].

Efficacy in complex food matrices. Preserving antimicrobial efficacy of natural extracts incorporated into actual food systems – such as dairy, meat, or beverages – can face numerous difficulties. These difficulties arise from the complicated interactions between antimicrobial agents and food matrices, the stability of antimicrobial compounds, and the possibility of sensory changes in the food products.

One of the primary challenges is the solubility and stability of antimicrobial compounds in food systems. Many natural extracts exhibit poor solubility in aqueous environments, which can limit their effectiveness when added to food products [56]. For instance, essential oils can lose their bioactivity when exposed to varying conditions in food matrices, necessitating higher concentrations for the desired antimicrobial effect [57, 58]. This degradation can reduce their efficacy and complicate their application in food preservation.

Moreover, the interaction of antimicrobial agents with food components can alter their effectiveness. Such compounds as fats, proteins, and carbohydrates can bind to antimicrobial agents, reducing their availability and activity against pathogens [58, 59]. This interaction is particularly relevant in complex food systems where the presence of multiple components can lead to unpredictable outcomes regarding antimicrobial efficacy [58, 60].

Another critical aspect to consider is the sensory impact of incorporating antimicrobial extracts into food products. Many natural antimicrobials, such as essential oils, possess strong flavors or odors that can adversely affect the sensory qualities of the food [61]. This can lead to consumer rejection of the products that do not meet their taste preferences, despite their potential safety benefits. Therefore, balancing antimicrobial efficacy with sensory acceptability is a significant hurdle in the development of food products that utilize natural extracts [61].

To address these challenges, innovative delivery systems have been proposed to enhance the stability and efficacy of antimicrobial compounds in food applications. Techniques such as nanoencapsulation can

protect antimicrobial agents from degradation and improve their bioavailability, allowing for more effective and controlled release in food systems [57, 62]. Additionally, the use of active packaging systems that incorporate antimicrobial agents can provide a means to maintain their efficacy without directly altering the food's sensory properties [63, 64].

Stability during storage. There are several barriers to the long-term stability of antimicrobial activity in food products containing *H. sabdariffa* extracts. These barriers are primarily due to the inherent properties of the extracts, their interactions with food matrices, and the challenges associated with packaging technologies. Firstly, the variability in the composition of *H. sabdariffa* extracts can affect their antimicrobial efficacy [65]. This variability can lead to inconsistent antimicrobial activity across different batches, complicating food application quality control and standardization efforts [66].

Furthermore, lipids, proteins, and carbohydrates present in food products can bind to the antimicrobial substances, lowering their bioavailability and efficacy [67]. Finally, the fast spread of antimicrobial drugs added directly to food can lead to a rapid loss of efficacy since the interactions between the food components might cause these agents to become inactive [68].

Novel packaging options have been suggested to help with these problems. Effective concentrations throughout time can be maintained with active packaging technologies that allow the controlled release of antimicrobial drugs [69]. For example, films containing *H. sabdariffa* extracts could be made to release their antibacterial compounds progressively, thus extending their usefulness [70]. Nevertheless, the creation of such packaging materials calls for a comprehensive knowledge of the release kinetics and the interactions between the packaging materials and the food products [71].

Integrating nanotechnology in food packaging has also shown promise in enhancing the stability and efficacy of antimicrobial agents. Nanocomposite films can provide improved barrier properties and controlled release mechanisms, important for maintaining the antimicrobial activity of natural extracts [72]. However, the potential toxicity of nanomaterials, as well as regulatory challenges, must also be considered in developing these advanced packaging solutions [73].

Approval of new ingredients. The approval and commercialization of *H. sabdariffa* extracts as antimicrobial agents face several regulatory challenges across different regions. These challenges stem from varying regulatory frameworks, the need for extensive safety and efficacy data, and the complexities of classifying plant extracts within existing medicinal and food safety regulations.

Categorization is a major regulatory obstacle. Plant extracts are categorized in various countries as food supplements, herbal remedies, or new foods, each with different legal regulations. For example, herbal remedies must conform with the Traditional Herbal Medicinal Goods Directive, which requires that goods show safety and efficacy depending on traditional use or clinical data [38]. This might be difficult for *H. sabdariffa* since, although its antibacterial qualities have been established [20], thorough clinical studies could be required to satisfy the legal criteria [5].

The need for standardized extraction methods and quality control poses another regulatory hurdle [52]. Regulatory agencies often require that manufacturers provide detailed information on the extraction process, including the solvents used and the consistency of active compounds [38]. The antibacterial efficacy of *H. sabdariffa* is ascribed to diverse phytochemicals, such as flavonoids and phenolic compounds, whose concentrations may vary due to ambient conditions and processing techniques [74].

In addition, safety assessments are critical for the commercialization of *H. sabdariffa* extracts [53]. There is a need for extensive toxicological evaluations to ensure consumer safety. Regulatory bodies such as the U.S. Food and Drug Administration and the European Food Safety Authority require rigorous safety data, including potential side effects and interactions with other medications [38]. The lack of comprehensive safety studies on the long-term consumption of *H. sabdariffa* extracts can hinder their approval as food additives or supplements [75].

Furthermore, the increasing concern over antibiotic resistance has prompted regulatory agencies to be more stringent regarding the approval of new antimicrobial agents. The efficacy of plant extracts against antibiotic-resistant strains, such as MRSA, has been documented [20], but demonstrating their consistent effectiveness in clinical studies remains a challenge [53]. This necessitates further research and data collection to support the claims of their efficacy in combating resistant strains.

Production costs and scalability. Significant technological and financial obstacles prevent the commercialization of bioactive substances by means of their large-scale manufacturing and extraction. These obstacles include variability in raw material quality, high production costs, regulatory problems, and technological constraints.

One of the primary economic barriers is the variability in the quantity and quality of raw materials used to produce bioactive compounds. For instance, the cultivation of medicinal plants such as *Bacopa monnieri* shows considerable seasonal variation in bioactive compound content, complicating the standardization necessary for commercial production [76]. This variability affects the final product's yield, consistency, and reliability, which makes it difficult for manufacturers to meet the market demands and regulatory standards [77]. Furthermore, the market prices for raw materials and bioactive compounds can fluctuate in response to the supply chain dynamics and consumer preferences, adding another layer of economic uncertainty [77].

In addition to the economic factors, the technical challenges associated with large-scale production are substantial. The extraction of bioactive compounds from

marine organisms, for example, often yields low quantities, while the costs associated with chemical synthesis can be prohibitively high [78]. This is compounded by the complexities of scaling up production processes, as many methods that work well in a laboratory do not translate effectively to industrial levels [79]. The economic sustainability of microalgae cultivation, for instance, is limited by the high costs of maintaining culture conditions and the risk of contamination, which can severely impact biomass yield and quality [80].

Furthermore, regulatory criteria provide major obstacles for the commercialization of bioactive molecules. Although following safety and efficacy criteria is crucial, the procedures used to guarantee these criteria may be time-consuming and resource-intensive [77]. Before the products may hit the market, substantial testing and validation are necessary, which can discourage investment and hold down the synthesis of new bioactive chemicals [81].

Technological advancements offer potential solutions to some of these barriers, yet they also introduce new challenges. For example, while *in vitro* technologies and advanced extraction methods such as pressurized liquid extraction show promise for improving yield and efficiency, the initial investment in technology and infrastructure can be substantial [82, 83]. Moreover, the development of genetically modified organisms to enhance bioactive compound production raises ethical and regulatory concerns that can further complicate commercialization efforts [81].

Opportunities. ***Innovation in sustainable extraction methods.*** Integrating green chemistry and eco-friendly extraction methods in producing antimicrobial compounds from *H. sabdariffa* can enhance these compounds' yield and efficacy while minimizing the environmental impact. Green chemistry principles advocate for using sustainable processes that reduce or eliminate hazardous substances. This is particularly relevant in extracting bioactive compounds from plant materials.

One primary advantage of adopting eco-friendly extraction methods is reducing toxic solvents traditionally used to extract phytochemicals. For instance, enzyme-assisted extraction is a viable alternative to conventional solvent-based methods. It can yield higher concentrations of polyphenols and other beneficial compounds without the health risks or environmental concerns associated with the solvent residues [84]. This method improves extraction efficiency and aligns with the principles of green chemistry by utilizing biodegradable and non-toxic agents.

Furthermore, the application of ultrasound-assisted extraction techniques has been explored as a means to enhance the extraction of bioactive compounds from various plant sources, including *H. sabdariffa*. This method utilizes sound waves to create cavitation bubbles in the solvent, which can lead to increased mass transfer and improved extraction rates [85]. Such techniques have been successfully employed to extract phenolic compounds and anthocyanins, which are known for their antimicrobial properties, thus potentially increasing the antimicrobial efficacy of the *H. sabdariffa*derived extracts.

In addition to improving extraction methods, the synthesis of nanoparticles using plant extracts can further enhance the antimicrobial properties of compounds derived from *H. sabdariffa*. Green synthesis of nanoparticles, such as silver and copper nanoparticles, using plant extracts has gained attention due to its simplicity and eco-friendliness [86, 87]. For example, nanoparticles synthesized from plant extracts have demonstrated significant antimicrobial activity against various pathogens. This suggests that combining these nanoparticles with *H. sabdariffa* extracts could lead to synergistic effects to enhance overall antimicrobial efficacy [88, 89].

Underlined as a sustainable method of textile finishing is the use of natural biocides, such chitosan and plant-based extracts, in antimicrobial uses [90]. This fits the growing trend of using natural compounds in several sectors, including textiles, where the need for biodegradable and environmentally acceptable antimicrobial agents is rising. Rich in bioactive components, *H. sabdariffa* extracts could be included into such uses to offer a sustainable and efficient substitute for synthetic antimicrobial drugs.

Design of functional foods. Incorporating extracts from *H. sabdariffa* into functional foods presents numerous opportunities for enhancing food safety and extending shelf-life. The bioactive compounds found in *H. sabdariffa*, particularly anthocyanins and flavonoids, exhibit significant antioxidant and antimicrobial properties, which can be leveraged for these purposes.

Firstly, the antioxidant capacity of *H. sabdariffa* extracts is well-documented. Studies have shown that these extracts contain high levels of phenolic compounds that scavenge free radicals and reduce oxidative stress in food products. For instance, extracts from *H. sabdariffa* calyces have a higher concentration of antioxidant compounds than apple segments, making them suitable for incorporation into various food products to enhance their oxidative stability [24]. This antioxidant activity can help delay rancidity and spoilage, thus extending functional foods' shelf-life.

Secondly, *H. sabdariffa* extracts' antibacterial qualities can help increase food safety. Studies show these extracts have strong antibacterial action against *S. aureus*, *Klebsiella pneumoniae*, and *Salmonella enterica* among other infections [5, 20]. By stopping microbial development in food products, these antimicrobial agents help lower the food-borne disease risk. By working as natural preservatives in food compositions, *H. sabdariffa* extracts can substitute synthetic additives often linked with health hazards [5].

In addition to their antioxidant and antimicrobial properties, the colorants derived from *H. sabdariffa* can also enhance the visual appeal of food products. The anthocyanins responsible for the vibrant red color of *H. sabdariffa* calyces can be utilized as natural colorants in various food applications [4]. This adds aesthetic value and contributes to the functional properties of the

food, as these colorants are associated with health benefits due to their antioxidant effects.

Finally, the stability of *H. sabdariffa* extracts during storage determines their application in functional foods. Concentrated extracts have been shown to maintain their bioactive properties under various storage conditions, indicating their potential for long-term use in food products [4]. This stability ensures that the extracts' beneficial effects are preserved throughout the shelf life of the foods.

Combined use with other technologies. *H. sabdariffa*, commonly known as roselle, has garnered attention for its diverse phytochemical properties. It can synergize with various food preservation techniques, such as vacuum packaging, high-pressure processing, and edible coatings. Antioxidant activity is one of the primary ways that *H. sabdariffa* extracts can synergize with preservation techniques. This is due to the presence of polyphenolic compounds that inhibit lipid peroxidation and oxidation in food products, thereby extending shelf life and maintaining quality [38, 91]. The antioxidant properties of *H. sabdariffa* extracts can complement vacuum packaging, which reduces oxygen levels and slows down oxidative reactions, enhancing the preservation of sensitive food items, particularly those prone to oxidation [21].

Also, high-pressure processing can benefit from the antibacterial qualities of *H. sabdariffa* extracts. This method is well-known for its ability to inactivate bacteria without high temperatures, therefore retaining the food's sensory and nutritional value. *H. sabdariffa* extracts have shown effectiveness against several pathogens, including *Staphylococcus epidermidis* and *Propionibacterium acnes*. This implies that including them into foods exposed to high-pressure processing could help to further lower microbial burdens and improve the food safety [92, 93]. This synergy should be especially beneficial to the preservation of ready-to-eat and other perishable foods.

In addition, edible coatings infused with *H. sabdariffa* extracts can provide a dual function of barrier protection and bioactivity. Edible coatings serve to reduce moisture loss and gas exchange, which are critical factors in food spoilage. When combined with the antimicrobial and antioxidant properties of *H. sabdariffa*, these coatings could improve the shelf life of fruits and vegetables by preventing spoilage and maintaining freshness [19].

Finally, the synergistic effects of *H. sabdariffa* extracts with these preservation techniques can also be attributed to their ability to modulate metabolic pathways in food systems. The extracts have been shown to inhibit the activity of enzymes involved in food components degradation, thereby preserving the integrity of the food matrix [93]. This characteristic can be particularly advantageous when combined with high-pressure processing, as it can help maintain the textural and nutritional quality of the food.

Mechanisms of action. Research opportunities to elucidate the precise antimicrobial mechanisms of the main bioactive compounds in *H. sabdariffa* are abundant and multifaceted. The plant has garnered attention for its broad-spectrum antimicrobial properties, particularly against various pathogenic bacteria and viruses. Below are the findings from recent studies to highlight the potential avenues for future research.

Identifying bioactive molecules that account for *H. sabdariffa*'s antibacterial action is one major focus of research. Protocatechuic acid, for example, shows antimicrobial action against food-borne infections including *S. aureus* and *E. coli* [32, 92]. More research on the processes by which protocatechuic acid and other phenolic compounds produce their effects could help explain their molecular action, including their interactions with bacterial cell membranes or suppression of metabolic pathways [38, 40].

Furthermore, *H. sabdariffa* extracts have been shown to reduce flagellar motility and cell invasion in *S. enterica*, implying a possible mechanism of action deserving of more research [20]. Knowing how these extracts interfere with bacterial motility might help create new antimicrobial treatments aiming at bacterial locomotion and virulence factors. Also, the influence of environmental factors on the antibacterial characteristics of *H. sabdariffa* could result in ideal farming methods to improve the production of bioactive compounds.

Investigating the synergistic effects of *H. sabdariffa* extracts in conjunction with traditional antibiotics presents yet another exciting direction for study. This method might improve the effectiveness of current antibiotic therapies against resistant organisms including MRSA [20, 53]. Finding the minimum inhibitory concentrations of different extracts against a spectrum of diseases could provide important information on their possible use as complementary treatments [53].

Another area of research could be to study possible antiviral qualities of *H. sabdariffa* extracts against viruses including Hepatitis A and Norovirus [92, 94]. Knowing the processes by which these extracts stop viral replication could result in the development of natural antiviral medicines.

Applications in emerging markets. Addressing food safety challenges in the developing countries requires a multifaceted approach incorporating affordable and natural solutions. Integrating local resources, education, and community engagement can enhance food safety practices among vulnerable populations, particularly in the informal food sectors such as street food vending.

Lack of information and training among food handlers is one of the main obstacles to food safety in underdeveloped countries. Studies have revealed that many street food vendors lack sufficient food safety training, which results in bad hygienic standards and higher risk of food-borne diseases [95, 96]. For example, a study conducted in Bangladesh revealed that higher income earners were more likely to have a greater understanding of food safety, implying that financial stability could help provide access to professional training [95]. Thus, community-based training on reasonably priced and pragmatic food safety procedures could empower food

Table 6 Challenges and opportunities in *Hibiscus sabdariffa* L. antimicrobial research

Challenges	Opportunities
Variability in bioactive compounds due to geographical, environmental, and processing factors.	Optimization of extraction methods to standardize bioactive compound concentrations.
Limited efficacy in complex food matrices due to solubility issues and interactions with food components.	Use of nanoencapsulation and active packaging to enhance stability and efficacy in food systems.
Instability of antimicrobial activity during storage, affecting long-term effectiveness.	Development of advanced packaging solutions and nanocomposite films for prolonged antimicrobial activity.
Regulatory barriers to approval and commercialization in different regions.	Regulatory harmonization and safety assessments to facilitate market adoption.
High production costs and scalability limitations for industrial applications.	Integration of sustainable and cost-effective production technologies for large-scale applications.

merchants and enhance food safety. Such initiatives could make use of local resources and knowledge to produce training courses with cultural relevance that fit daily operations of the suppliers [97].

Another way to improve food safety would be to develop and disseminate food-based dietary guidelines tailored to specific socio-economic contexts [98]. These guidelines should consider local dietary patterns and food availability, promoting safe, nutritious foods while discouraging reliance on unsafe options. For example, promoting locally sourced ingredients, such as cassava, which is both affordable and nutritionally rich, can enhance food security while ensuring safety [99]. This approach addresses immediate food safety concerns and supports local agriculture and economies.

Improving regulatory frameworks and governance is another critical aspect of ensuring food safety in the developing countries. Collaborative efforts involving government, private sectors, and community organizations can lead to the establishment of effective food safety policies that are both enforceable and adaptable to local contexts [100]. For instance, regional collaborations can facilitate the harmonization of food safety standards and the establishment of rapid alert systems for food safety breaches, thereby enhancing consumer protection [100]. Additionally, leveraging technology, such as blockchain and IoT, can improve traceability in the food supply chains to ensure that food products are safe from production to consumption [101, 102].

Furthermore, it is essential to address socio-economic factors that influence food safety perceptions. Research indicates that consumers in the developing countries often perceive street food as unsafe due to a lack of trust in the vendors' hygiene practices [103]. By engaging consumers through awareness campaigns that emphasize the importance of food safety and hygiene, communities can foster a culture of safety that encourages vendors to adopt better practices. Such initiatives can be complemented by regulatory measures that incentivize compliance with food safety standards, thereby creating a more robust food safety environment [104].

Finally, Table 6 summarizes a comparative analysis of important challenges and opportunities in applying *H. sabdariffa* antimicrobial compounds. While factors such as variability in bioactive composition, efficacy in complex food matrices, and regulatory barriers pose challenges, advancements in extraction techniques, nanoencapsulation, and regulatory harmonization offer promising solutions. This table highlights the critical areas that require further research and technological innovation to optimize the industrial application of *H. sabdariffa* as a natural antimicrobial agent in food preservation.

CONCLUSION

This bibliometric analysis provided an overview of research on antimicrobial extracts and compounds from *Hibiscus sabdariffa* L., highlighting its applications in food preservation and safety. The scientific output on this topic exhibited a steady growth trend, with an annual increase of 8.15%, indicating a rising interest in *H. sabdariffa* as a natural antimicrobial agent. The most influential studies focused on the bioactive properties of *H. sabdariffa*, particularly its polyphenols, flavonoids, and anthocyanins, which have demonstrated strong antibacterial effects against pathogens such as *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus*. The analysis of extraction methods revealed that ethanolic and aqueous extracts exhibited different antimicrobial potencies, emphasizing the importance of standardizing extraction techniques to optimize their efficacy. Despite *H. sabdariffa*'s promising applications in food systems, challenges remain regarding its stability in food matrices, its interaction with other food components, and the variability of its bioactive content due to environmental and processing factors.

Future research should address the stability and scalability challenges associated with *H. sabdariffa* extracts in food preservation. Standardized extraction methods and innovative delivery systems, such as nanoencapsulation and active packaging, could enhance the bioavailability and effectiveness of its bioactive compounds. Additionally, interdisciplinary studies combining food science, pharmacology, and nanotechnology may provide new insights into *H. sabdariffa*'s antimicrobial mechanisms, particularly in controlling antibiotic-resistant pathogens. Expanding research into the synergistic effects of *H. sabdariffa* with other natural antimicrobials and emerging preservation technologies, such as

high-pressure processing and edible coatings, could further optimize its applications.

Finally, regulatory frameworks should be explored to facilitate the commercialization of *H. sabdariffa*-based antimicrobial solutions in the food industry.

CONTRIBUTION

The authors were equally involved in writing the manuscript.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

DECLARATION OF AI

LanguageTool and Grammarly were used to structure ideas, improve academic writing in English, and generate synonyms or stylistic alternatives to facilitate the text's clarity.

All generated content was thoroughly reviewed by the authors to verify scientific accuracy, the integrity of the cited sources, and argumentative coherence. No AI was used for data generation. Bibliographic citations were integrated and validated.

The use of the tools did not alter the arguments or conclusions of the manuscript. The original scientific decisions, interpretations, and contributions reflect solely the judgment and experience of the authors.

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