Review Article

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Sustainable innovations in garlic extraction: A comprehensive review and bibliometric analysis of green extraction methods

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Abstract: This review provides a comprehensive analysis of the advancements, challenges, and future directions in green extraction processes for garlic, focusing on the period from 1994 to 2024. Over the past three decades, there has been a significant increase in research on sustainable and environmentally friendly extraction methods, including enzyme-assisted extraction, supercritical fluid extraction, and pressurized liquid extraction, among others. These methods have been shown to enhance the yield and quality of key bioactive compounds, such as allicin and other organosulfur compounds, which are critical to garlic's health benefits. This review highlights the effectiveness of these green extraction techniques in improving the bioavailability, stability, and therapeutic potential of garlic extracts. However, it also addresses the challenges associated with these methods, including scalability, cost-effectiveness, and regulatory acceptance. The need for further optimization and standardization to ensure consistent quality and industrial scalability is emphasized. This article concludes by discussing the future opportunities for green garlic extraction, suggesting that continued innovation and integration with emerging technologies will be key to overcoming current limitations. By doing so, the industry can achieve more sustainable and efficient production methods, meeting the growing demand for natural and eco-friendly products while contributing to the broader goals of environmental sustainability.

Keywords: garlic, green extraction, bibliometric analysis, health

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List of Abbreviations

AC	allicin content
AFS	atomic fluorescence spectrometry
APDC	ammonium pyrrolidine dithiocarbamate
ARGs	antibiotic resistance genes
CCD	central composite design
DES	deep eutectic solvent
DLLME	dispersive liquid–liquid microextraction
dSPE	dispersive solid-phase extraction
EAE	enzyme-assisted extraction
EE	entrapment efficiency
FOS	fructooligosaccharide
GAE	gallic acid equivalents
GMS	glyceryl monostearate
HILIC-MS	hydrophilic interaction liquid chromatography-mass spectrometry
IL	ionic liquid
LC-MS/MS	liquid chromatography tandem mass spectrometry
MAE	microwave-assisted extraction
MRM	multiple reaction monitoring
MWCNT	multiwalled carbon nanotubes
NLC	nanostructured lipid carrier
PLE	pressurized liquid extraction

POD	peroxidase
PPO	polyphenol oxidase
RSD	relative standard deviation
RSM	response surface methodology
SAC	*S*-allyl-L-cysteine
SFE	supercritical fluid extraction
SWE	subcritical water extraction
TFC	total flavonoid content
TPC	total phenolic content
US	ultrasound
VA-LLME	vortex assisted liquid–liquid microextraction

1 Introduction

Garlic (*Allium sativum* L.) has been used for centuries as a natural remedy for various health problems, such as diarrhea, allergies, and elevated blood pressure [1]. Garlic is used in Ayurvedic medicine to treat digestive disorders, respiratory issues, and skin maladies [2]. In European folk medicine, garlic was used to treat various infectious diseases, including tuberculosis, and was believed to protect from the plague [3]. Garlic is responsible for these health benefits due to allicin, sulfur compounds, and flavonoids [4]. Nevertheless, traditional extraction methods for these compounds are limited due to the toxicity and combustibility of the solvents used, and obtaining purified extracts can be a time-consuming, multistep procedure [5].

Green processes for garlic extraction provide various advantages. The methods are environmentally friendly due to their reduced use of hazardous solvents, energy consumption, and waste production. Green extraction processes, through sustainable practices, adhere to environmental conservation principles and promote a healthier planet [6,7]. This renders them a desirable option for industries aiming to minimize their environmental impact. Green extraction methods preserve the quality and functionality of bioactive compounds in garlic extracts. Mild extraction conditions, including reduced temperatures and shorter extraction durations, aid in preserving the effectiveness and bioavailability of extracted compounds. Optimizing the extraction process of garlic yields higher quantities of desired compounds and preserves the beneficial properties of the extracts, including antioxidant, antimicrobial, and anti-inflammatory effects [8]. Green extraction processes are suitable for the food, pharmaceutical, and cosmetic industries due to their ability to produce high-quality extracts.

Green processes for garlic extraction offer advantages in terms of environmental sustainability, product quality, and economic benefits. Industries can enhance their contribution toward environmental sustainability, ensure superior quality of garlic extracts, and attain cost-effectiveness in their extraction procedures by implementing these techniques. Green extraction techniques have been devised to surmount these limitations, and their application areas are continually expanding. The advantages of green extraction techniques include zero waste production, speedier extraction times, and reduced solvent consumption [9]. Supercritical fluid extraction (SFE), subcritical water extraction (SWE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), and pressurized liquid extraction (PLE) are green extraction techniques [10]. In addition to shortened extraction times and reduced solvent consumption, these techniques offer advantages over conventional extraction methods [11].

Given the growing interest in natural remedies and functional foods, there is a pressing need to comprehensively understand the landscape of garlic extraction processes and their implications for health and wellness. This study aims to provide bibliometric insights into garlic extraction processes, synthesizing existing literature to identify trends, advancements, and challenges in the field [12,13]. By systematically analyzing research publications, citation patterns, author collaborations, and geographical distribution, this study seeks to elucidate the global research network surrounding garlic extraction for health and wellness applications. Through this bibliometric analysis, we aim to shed light on the current state of knowledge regarding garlic extraction processes, highlighting key areas for further research and innovation [14]. By leveraging bibliometric techniques, we strive to offer valuable insights for researchers, practitioners, and stakeholders interested in harnessing the full potential of garlic for enhanced health and wellness.

Therefore, the objective of this review article is to summarize the health and wellness benefits of garlic extraction green extraction. The objective of this review is to discuss garlic production, bioactive components in garlic, and potential applications in the food industry. Furthermore, the second objective is to summarize future directions and challenges in the green extraction techniques for valorizing garlic and its bioactive compounds.

2 Methodology

The methodology for this comprehensive review and bibliometric analysis was carefully structured to capture the most relevant literature on garlic extraction using green extraction methods. The Scopus database was selected as the primary source of data due to its extensive coverage of high-quality scientific literature across various disciplines, ensuring the reliability and credibility of the included studies. To ensure that the review encompassed the latest developments and trends, the search was limited to the publications from the years 2017 to 2024. A strategic search query was developed using a combination of specific keywords related to green extraction techniques, including "SFE," "UAE," "MAE," "enzyme-assisted extraction (EAE)," "PLE," and "Emerging Green Extraction Methods." These keywords were combined with the term "garlic" to focus the search on relevant publications.

The selection criteria were further refined to include only peer-reviewed articles published in Scopus-indexed journals. This criterion ensured the inclusion of high-quality and rigorously evaluated studies. However, this approach could potentially exclude relevant findings from other databases, such as Web of Science, PubMed, or Google Scholar, which may also host valuable studies on garlic extraction using green methods. While prioritizing Scopus-indexed journals ensured consistency and reliability, it might have inadvertently limited the scope of the review by excluding gray literature, conference proceedings, or studies published in non-Scopus-indexed journals. Future reviews could benefit from expanding the search to multiple databases to capture a broader spectrum of research findings.

For the bibliometric analysis, the data retrieved from Scopus were processed and analyzed using VOS viewer, a powerful tool for creating visualizations of bibliometric networks. VOS viewer was employed to generate co-authorship networks, keyword co-occurrence maps, and citation analysis, allowing for a detailed exploration of the research landscape. This approach facilitated the identification of key trends, influential researchers, and emerging areas in the field of green garlic extraction. This methodology provides a robust and systematic framework for reviewing and analyzing the literature, offering valuable insights into the advancements and future directions of green extraction methods in garlic processing.

3 Green extraction techniques for garlic

3.1 SFE

SFE has gained significant attention as an efficient and environmentally friendly method for extracting bioactive compounds from garlic. This review summarizes the findings from various studies conducted between 2010 and 2024, which employed SFE under different conditions to achieve varied outcomes. Table 1 shows the overview of SFE conditions, outcomes, and yields/active compounds in garlic extraction studies (2010–2024)The studies reviewed offer valuable insights into the extraction conditions,

Table 1: Summary of SFE conditions, outcomes, and yields/active compounds in garlic extraction studies (2010–2024)

Refs.	Extraction condition	Outcome	Yield/active compounds
Bastos et al. [15]	70°C, 1:1 cosolvent ratio	Higher yields on dry basis at 70°C, improved film properties	88.35% yield, tensile strength 19.07 MPa
Vidović et al. [16]	400 bar, 60°C	3.43% yield, allyl methyl trisulfide as dominant compound	3.43% yield, sulfur compounds including allyl methyl trisulfide
Liu et al. [17]	50°C, 30% methanol	15 phenolic compounds successfully extracted	Phenolic compounds: 15 identified
Chhouk et al. [18]	200°C, 0.5 mL·min^{-1} CO_2 flow	High phenolic content (56.26 mg GAE·g^{-1}) and antioxidant activity	Phenolic acids: garlic acid, 4-hydrobenzoic acid, caffeic acid, *p*-coumaric acid, trans-ferulic acid
Tong and Hai [65]	25 MPa, 40°C	Allicin yield increased by 54% with random packing	0.37% allicin yield
Ye et al. [19]	15 MPa, 40°C	Allicin showed inhibitory effect on HepG2 cells	Allicin concentration-dependent inhibition
Guo [20]	15 MPa, 40°C, 1 h	Garlic oil inhibited *Staphylococcus aureus, Escherichia coli, Bacillus subtilis*	15 MPa pressure optimized for maximum yield
Del Valle et al. [66]	55°C, 30 MPa	19 g·kg^{-1} oleoresin, 75 mg·kg^{-1} allicin selectivity	Allicin yield at 55 kg CO_2/kg substrate
Liang et al. [63]	Supercritical CO_2 extraction	Allicin purity increased to 68.04%	Allicin, diallyl disulfide, diallyl trisulfide
Li et al. [67]	50°C, 30% methanol	Significant yields of garlic essential oil	Essential oil components: 3-vinyl-4H-1,2-dithiin, diallyl trisulfide

outcomes, and the specific bioactive compounds yielded, demonstrating the versatility and effectiveness of SFE in garlic extraction.

The extraction conditions in green processes (Table 1), particularly SFE, are critical determinants of both the yield and the recovery of bioactive compounds. Each parameter such as temperature, pressure, cosolvent type, and ratio plays a pivotal role in optimizing the efficiency, specificity, and quality of the extracted components. Recent studies on garlic extraction using SFE demonstrate how tailored adjustments to these conditions can maximize yield, enhance bioactivity, and expand the functionality of the resulting extracts.

The study by Bastos et al. [15] exemplifies the optimization of SFE to achieve high yields and improve the functional properties of garlic-derived products. Operating at 70°C with a 1:1 cosolvent ratio, the researchers achieved an outstanding yield of 88.35% on a dry basis. Notably, the extracted garlic oil was incorporated into biodegradable films, significantly enhancing their tensile strength. This demonstrates not only the effectiveness of SFE in maximizing yield but also its ability to produce value-added products, such as environmentally friendly packaging materials. The study underscores the dual benefits of high recovery and improved functional properties, illustrating the potential of SFE in industrial applications beyond traditional nutraceuticals.

Similarly, Vidović et al. [16] investigated the influence of high-pressure (400 bar) and moderate temperature (60°C) conditions on the extraction efficiency and composition of garlic extracts. Despite a relatively modest yield of 3.43%, the supercritical CO_2 process selectively extracted sulfur-containing compounds, particularly allyl methyl trisulfide, a bioactive molecule with significant pharmacological properties. This selective extraction highlights SFE's precision in targeting specific compounds through meticulous control of temperature and pressure, making it a valuable technique for producing specialized pharmaceutical ingredients.

The preservation of temperature-sensitive bioactive compounds was a key focus in the studies by Liu et al. [17] and Chhouk et al. [18]. Liu's research used a lower temperature of 50°C combined with a 30% methanol cosolvent to recover 15 phenolic compounds from garlic successfully. This approach ensured the stability and integrity of these delicate molecules. Similarly, Chhouk utilized carbon dioxide-expanded ethanol (CXE) to extract phenolic acids from garlic husks, achieving a high phenolic content and substantial antioxidant activity. These findings highlight SFE's adaptability in preserving bioactivity, particularly when dealing with compounds prone to degradation under high temperatures.

Further emphasizing SFE's capabilities, Ye et al. [19] and Guo [20] optimized extraction conditions to maximize the yield of allicin, a prominent sulfur compound in garlic with anticancer and antibacterial properties. By fine-tuning pressure and temperature parameters, these studies not only achieved significant allicin yields but also preserved its bioactivity. For example, extracted allicin demonstrated notable inhibitory effects on bacterial strains and human cancer cells, underscoring SFE's ability to produce high-quality, therapeutic-grade extracts.

Collectively, these studies illustrate the intricate interplay between extraction conditions and the recovery of bioactive compounds. SFE's capacity to manipulate parameters such as temperature, pressure, and cosolvent ratios ensures efficient extraction of diverse compounds, from phenolics to sulfur compounds like allicin. These findings demonstrate the broad applicability of SFE in producing high-value extracts with retained bioactivity, making it an indispensable tool in the fields of pharmaceuticals, nutraceuticals, and sustainable material development. By tailoring extraction conditions to the specific properties of target compounds, SFE emerges as a leading green technology for optimizing yield, functionality, and environmental sustainability.

3.2 UAE

UAE has become a prominent technique in enhancing the extraction efficiency of bioactive compounds from garlic, offering an environmentally friendly and efficient alternative to conventional methods. This review synthesizes findings from various studies conducted between 2022 and 2024, showing the diverse conditions under which UAE has been applied and the outcomes achieved. The reviewed studies highlight the versatility of UAE in optimizing the extraction process, enhancing yield, and preserving the integrity of valuable bioactive compounds.

Multiple studies employing green technologies such as UAE vividly demonstrate the influence of extraction conditions on the yield and recovery of active compounds. Each study highlights how specific adjustments to parameters such as ultrasound intensity, pretreatment methods, and combinations with other technologies can significantly impact the efficiency and quality of garlic extracts.

Bai et al. [21] examined the effects of ultrasound pretreatment on the drying process of garlic slices, finding a substantial 55.96% increase in moisture-effective diffusivity. However, this enhancement came at the cost of lower allicin content and antioxidant activity. Interestingly, when ultrasound was combined with the ozone water treatment, the total phenolic content (TPC) saw a

25.90% increase, indicating that pairing ultrasound with complementary methods could counterbalance potential losses in bioactive compounds. This underscores the need for synergistic approaches to maintain or enhance critical bioactive constituents while improving process efficiency.

In a complementary vein, Xu et al. [22] investigated a combination of nano-CeO_2 and ultrasound treatment to boost the allicin content while reducing the abundance of antibiotic-resistant genes (ARGs). The study demonstrated a 15.9–16.2% increase in the allicin content alongside a significant decrease in ARGs. This innovative pairing of nanotechnology with ultrasound not only optimized yield but also addressed broader concerns related to food safety and antimicrobial resistance. The findings highlight the dual utility of UAE in both enhancing bioactive recovery and mitigating public health risks.

Further exploring the application of UAE, Jia and Li [23] optimized the extraction conditions for melanoidin from black garlic, achieving a 3.465% yield. Melanoidin, known for its antioxidant properties, benefits from the gentle and efficient action of ultrasound. Similarly, Guo et al. [24] utilized ultrasound pretreatment to enhance garlic drying processes, leading to reduced drying time, improved rehydration rates, and increased allicin content. These studies demonstrate the versatility of UAE in achieving both process efficiency and high-quality bioactive recovery, particularly for compounds like melanoidin and allicin.

Expanding the potential of ultrasound, Jiménez-Amezcua et al. [25] and Chang et al. [26] combined UAE with MAE to enable the simultaneous extraction of multiple bioactives. This approach facilitated the detection of organosulfur compounds such as *S*-allyl-L-cysteine (SAC) and cycloalliin with high sensitivity and yielded extracts with significant antioxidant and cytotoxic activities. This combination of technologies illustrates the potential for producing multifunctional garlic extracts with enhanced bioactive profiles, catering to diverse applications in food, nutraceutical, and pharmaceutical industries.

Finally, studies like those by Malakar et al. [27] and Shekhar et al. [28] underline the adaptability of UAE across a range of applications. These studies optimized UAE

Table 2: Summary of UAE conditions, outcomes, and yields/active compounds in garlic extraction studies (2022–2024)

Refs.	Extraction condition	Outcome	Yield/active compounds
Bai et al. [21]	Ultrasound for 20 min	55.96% increase in moisture effective diffusivity, lowest allicin content, and antioxidant activity	Lowest allicin content, 25.90% higher TPC with ozone water treatment
Xu et al. [22]	Nano-CeO_2 application, ultrasonic treatment	Enhanced allicin content by 15.9–16.2%, reduced ARG abundance	Increased allicin content, decreased ARGs abundance
Jia and Li [23]	Ultrasound time: 40 min, temperature: 70°C	Optimized extraction conditions for melanoidin, yield of 3.465%	3.465% melanoidin yield
Guo et al. [24]	US pretreatment, drying temperatures: 50–70°C	US reduced drying time, improved rehydration rate and allicin content	Highest rehydration rate and allicin content
Jiménez-Amezcua et al. [25]	Simultaneous extraction with ultrasonic MAE	High sensitivity for bioactives, SAC, and cycloalliin detected	SAC: traces-2.32 $mg \cdot g^{-1}$, cycloalliin: 1.23–3.01 $mg \cdot g^{-1}$
Chang et al. [26]	Ultrasonic MAE	High antioxidant capacities, increased cytotoxic activity of NK-92 cells	High TPC, flavonoids, and antioxidant capacities
Malakar et al. [27]	Ultrasonic temperature: 20°C, time: 28.54 min, osmotic concentration: 55.58%	Optimized drying performance with significant mass transfer and quality attributes	15.229 $mg \cdot g^{-1}$ allicin, 7.512 RR
Shekhar et al. [28]	Ultrasound amplitude: 53%, treatment time: 13 min, ethanol concentration: 50%	32.2% extraction yield, 9.9 mg $GAE \cdot g^{-1}$ TPC, 6.8 mg $QE \cdot g^{-1}$ total flavonoid content (TFC), 58% antioxidant activity	32.1738% yield, 9.8661 mg $GAE \cdot g^{-1}$ TPC, 6.8398 mg $QE \cdot g^{-1}$ TFC
Kar and Sutar [68]	US followed by MW, ultrasound power density: 58.43 WL−1, initial bath temperature: 60°C	US + MW resulted in 90.37% peroxidase, 92.38% polyphenol oxidase (PPO) inactivation	2.62 log reduction in *Aspergillus niger*, 92.38% PPO inactivation
Liu et al. [69]	Ultrasonic emulsification, ultrasound time: 10 min	Ultrasonic emulsification produced stable nanoemulsion with strong anti-methicillin-resistant staphylococcus aureus (MRSA) activity	0.125% minimum inhibitory concentration against MRSA, stable nanoemulsion
Shi et al. [70]	Ultrasound-assisted three-phase partitioning, ultrasonic time: 50 min, temperature: 34°C	Simultaneous extraction of allicin and polysaccharides	3.564 $mg \cdot g^{-1}$ allicin, 43.86 $mg \cdot g^{-1}$ polysaccharides
Loghmanifar et al. [71]	Ultrasound time: 10 min, temperature: 30°C, frequency: 37 Hz, power: 40 W	Accelerated process, enhanced antioxidant properties	Enhanced antioxidant properties, 37 Hz frequency optimal

conditions for goals as varied as improving drying performance, stabilizing nanoemulsions, and producing potent antibacterial agents. The results consistently highlighted significant yields of allicin and other bioactives, emphasizing UAE's capability to be fine-tuned for targeted extraction objectives. Collectively, these findings underscore the crucial role of precise extraction conditions in maximizing yield and bioactive recovery, paving the way for more efficient and sustainable garlic extraction processes (Table 2).

3.3 MAE

The reviewed studies highlight how specific extraction conditions significantly influence the yield and recovery of active compounds during MAE. These parameters include microwave power, temperature, solvent composition, extraction time, and pressure, each playing a crucial role in determining the efficiency and quality of the extraction process.

3.3.1 Power and temperature

Yazgan et al. [29] used microwave-assisted acetone extraction to effectively concentrate bioactive compounds, such as diallyl disulfide (46.83%) and allyl trisulfide (20.81%). Precise control over microwave power and solvent properties ensured the efficient release and preservation of these thermolabile compounds. In the study by Oke et al. [30], microwave power between 520 and 1,040 W and an extraction time of 2–10 min achieved an optimal phenolic yield of 28.62% and a TPC of 76.8 mg GAE·g^{-1}. These findings suggest that moderate power and shorter exposure times are critical to minimizing thermal degradation while maximizing compound recovery.

Chahbani et al. [31] examined microwave drying of garlic leaves and found that using a lower power setting (100 W) preserved phenolic compounds, particularly quercetin 3-*O*-rhamnoside, while higher power levels led to degradation. This underscores that higher microwave power, though faster, risks degrading sensitive bioactives, necessitating optimization based on the stability of target compounds.

3.3.2 Solvent composition

The choice of solvent in MAE is a pivotal factor that influences both the yield and the functional quality of the extracted bioactive compounds. The solvent's properties, including polarity, boiling point, and reactivity, must be carefully aligned with the target compounds' characteristics to ensure efficient recovery while preserving their stability.

Jiménez-Amezcua et al. [25] utilized water as a solvent to optimize the extraction of organosulfur compounds from aged garlic. By adhering to the principles of green chemistry, this water-based extraction approach avoided the use of potentially hazardous organic solvents, making it environmentally friendly and sustainable. Under the optimized conditions, the extraction process achieved significant yields of SAC and cycloalliin, compounds known for their potent antioxidant and health-promoting properties. The use of water not only supported the integrity of these sensitive bioactives but also demonstrated its suitability for multifunctional garlic extracts aimed at food and nutraceutical applications.

In contrast, Şen et al. [32] explored the use of dual solvent systems comprising organic and inorganic acids to extract pectin from garlic and onion waste. This approach leveraged the complementary properties of the two acid types, resulting in enhanced yields of pectin ranging from 24.62% to 28.43%. The study revealed that the organic acids contributed to maintaining the structural integrity of pectin, while the inorganic acids improved solubility and extraction efficiency. This dual-system approach highlights how the solvent composition can be tailored to the physicochemical properties of the target compound, leading to better functional outcomes, such as improved pectin quality for industrial applications in food and pharmaceuticals.

These findings underscore the critical role of solvent selection in MAE. For bioactives like organosulfur compounds, water provides a mild and effective medium that aligns with green chemistry goals. On the other hand, for polysaccharides like pectin, combining solvents with synergistic properties can optimize the extraction process, enhancing both the yield and the quality. By tailoring solvent systems to the specific requirements of the target bioactives, researchers can maximize recovery efficiency while ensuring the functionality and application potential of the extracts.

Moreover, the solvent's interaction with microwave energy is another crucial aspect. Solvents like water and organic acids efficiently absorb microwave energy, generating heat and enhancing mass transfer, which accelerates the extraction process. This synergy between solvent properties and microwave irradiation further reinforces the importance of deliberate solvent selection in achieving optimal outcomes in MAE processes.

3.3.3 Extraction time

Extraction time is a critical parameter in MAE as it directly impacts both the yield and the integrity of bioactive compounds. Shorter extraction times often help prevent thermal degradation, preserving sensitive compounds, while overly prolonged exposure can lead to breakdown or loss of bioactivity. Oke et al. [30] optimized the MAE process for phenolic compound extraction from garlic by investigating extraction times ranging between 2 and 10 min. Their findings showed that within this range, the extraction achieved a phenolic yield of 28.62% and a TPC of 76.8 mg GAE·g^{-1} dry extract, highlighting that even short exposure to microwave energy can effectively release bioactives without causing significant degradation. This demonstrates that the precise control of the extraction time is crucial to maintaining a balance between maximizing yield and preserving compound stability.

In contrast, Chahbani et al. [31] investigated the impact of microwave drying times on the phenolic content and antioxidant properties of garlic leaves. Their results revealed that prolonged exposure during microwave drying led to the degradation of phenolic compounds, including flavonoids such as quercetin 3-*O*-rhamnoside. Specifically, drying garlic leaves at higher power levels, and extended times caused a decline in the phenolic content and antioxidant activity, underlining the sensitivity of these compounds to thermal and oxidative stress during prolonged treatment.

These studies emphasize that while shorter extraction or drying times ensure the stability of thermolabile compounds like phenolics and flavonoids, extended exposure can compromise the recovery and functionality of bioactives. For example, exposure beyond optimal durations may initiate secondary degradation pathways, such as oxidation, which reduce the overall efficacy of the extracted compounds.

The ability to fine-tune extraction time is, therefore, one of the critical advantages of MAE. It allows researchers and industrial operators to achieve high yields of target compounds while minimizing risks associated with thermal damage. These findings advocate for the inclusion of precise time control in MAE protocols to ensure efficient and high-quality extraction processes tailored to specific bioactive targets.

3.3.4 Pressure and controlled environments

The role of controlled pressure in MAE has proven critical for enhancing solvent penetration and improving the recovery of bioactive compounds, particularly in cases involving sensitive or thermolabile molecules.

Yazgan et al. [29] demonstrated the effectiveness of pressure control in their study on antimicrobial compound enrichment through MAE. By maintaining precise pressure settings, the researchers ensured optimal solvent penetration into garlic matrices, facilitating the efficient release of bioactive compounds such as diallyl disulfide (46.83%) and allyl trisulfide (20.81%). These sulfur-containing compounds, known for their antimicrobial properties, were preserved in their active form. The pressure regulation likely enhanced the solvent's ability to penetrate cellular walls and extract these compounds effectively while minimizing thermal degradation, showing the importance of pressure in maintaining the bioactivity of target compounds.

Similarly, Jiménez-Amezcua et al. [25] underscored the advantages of pressure-controlled MAE in isolating organosulfur compounds like SAC and cycloalliin. The study employed a water-based solvent system under carefully monitored pressure conditions, achieving high extraction efficiency and minimal loss of bioactivity. The pressurized environment facilitated the extraction of these sensitive compounds by maintaining an equilibrium between temperature and solvent properties. This balance ensured that the thermal stress commonly associated with microwave-assisted processes was mitigated, preserving the integrity of the extracted organosulfur compounds. The yields of SAC (traces to 2.32 mg·g^{-1}) and cycloalliin (1.23–3.01 mg·g^{-1}) highlight the effectiveness of pressure-controlled MAE in achieving both quantity and quality of extraction.

Pressure regulation in MAE offers multiple benefits, including enhanced solvent diffusion, improved mass transfer rates, and reduced extraction times. By combining pressure control with tailored microwave settings and solvent systems, these studies have demonstrated that it is possible to optimize the recovery of bioactive compounds while maintaining their structural and functional integrity. This approach is particularly important for bioactives prone to degradation under high temperatures or prolonged exposure. Moreover, the use of controlled-pressure environments aligns well with green chemistry principles, as it reduces the need for excessive solvent volumes and energy input.

In conclusion, controlled-pressure settings during MAE play a pivotal role in enhancing the extraction of bioactive compounds, especially those with thermolabile or sensitive properties. The studies by Yazgan et al. [29] and Jiménez-Amezcua et al. [25] illustrate how pressure optimization can drive solvent penetration and improve compound recovery, making MAE a highly efficient and versatile technique for the sustainable extraction of valuable bioactives in food, nutraceutical, and pharmaceutical applications (Table 3).

3.4 EAE

EAE has become a crucial method in the extraction of valuable compounds from garlic, leveraging the specificity of enzymes to enhance the yield and quality of bioactive compounds. This review synthesizes findings from various studies conducted between 2009 and 2023, focusing on the conditions under which EAE has been applied, the outcomes achieved, and the yields of key compounds extracted from garlic.

In the 2023 study by Famakinwa et al. [33], the researchers explored the use of EAE for macromolecules, particularly those with potential applications in fortification and nutritional supplementation. The study highlighted the improvements in extraction methods brought about by the use of enzymes, which allow for the efficient recovery of macromolecules from natural resources. These macromolecules, including carbohydrates, proteins, and nucleic acids, are essential for developing fortified products that address nutritional deficiencies. The research underscores the growing interest in sustainable extraction techniques, driven by public awareness of environmental preservation and the need for sustainable development.

The study by Sentkowska and Pyrzynska [34] focused on the stability of selenium compounds in aqueous extracts, examining the impact of solvent pH and storage temperature on the stability of these compounds. Selenium, an essential trace element, exists in various inorganic and organic forms, each with different stability profiles. The research found that the stability of selenium compounds such as selenomethionine and selenocystine was highly dependent on the solvent's pH and storage conditions. This study is significant because it provides insights into the challenges of maintaining the stability of bioactive compounds during and after extraction, which is critical for the efficacy of selenium-enriched dietary supplements.

A study on the enhancement of fructan extraction from garlic was conducted earlier using hemicellulase treatment followed by solvent extraction. Fructans, a type of prebiotic fiber, are valuable for their health benefits, including promoting gut health. The study showed that the use of hemicellulase significantly increased the yield of fructans by 35.4%, resulting in a final yield of 21.23 g/100 g of garlic. In addition, the study explored the purification of fructooligosaccharides (FOS) using an activated charcoal column, achieving a 94% purity of 1-kestose. This research highlights the effectiveness of EAE in improving the yield and purity of specific compounds, making it a valuable

Table 3: Summary of MAE conditions, outcomes, and yields/active compounds in garlic extraction studies (2022–2024)

Refs.	Extraction condition	Outcome	Yield/active compounds
Yazgan et al. [29]	Microwave-assisted acetone extraction	Antimicrobial effects against food-borne bacteria	Diallyl disulfide 46.83%, allyl trisulfide 20.81%
Şen et al. [32]	MAE with organic and inorganic acids	High pectin yields, controlled physicochemical properties	Pectin yields: 24.62–28.43%
Jiménez-Amezcua et al. [25]	Simultaneous MAE using water as solvent	High sensitivity and accuracy for bioactives, SAC and cycloalliin detected	SAC traces-2.32 $mg{\cdot}g^{-1}$, cycloalliin 1.23–3.01 $mg{\cdot}g^{-1}$
Chahbani et al. [31]	Microwave drying, 100–450 W	Phenolics profile changed, best drying at 100 W	Total phenolics increased, quercetin 3-*O*-rhamnoside
Oke et al. [30]	MAE, 520–1,040 W, 2–10 min	Optimal yield 28.62%, TPC 76.8 mg $GAE{\cdot}g^{-1}$ dry extract	28.62% yield, TPC 76.8 mg $GAE{\cdot}g^{-1}$ dry extract
Yingngam et al. [72]	Solvent-free microwave extraction, 640 W, 20 min	High diallyl trisulfide yield, higher than hydrodistillation	High proportion of diallyl trisulfide
Chen et al. [73]	Microwave digestion, 78°C, 30 min	Determination of selenium in selenium-enriched garlic	Selenite and selenate detected, recovery 88.2–113%
Noda et al. [74]	Microwave irradiation, 180–200°C, 2–5 min	Highest phenolic content, EC_{50} value decreased	Phenolic content 40.0 mg-catechin equiv./g-dry treated GH
Ilić et al. [75]	Microwave in methanol, 55°C	High antioxidant activity, slight antiproliferative effect	DPPH radical neutralization 90%, EC_{50} 0.37 $mg{\cdot}mL^{-1}$
Mishra et al. [76]	MAE, time and solvent optimization	Improved extractive values and antioxidant potential	Total extractive value 36.95–49.95%
Shao et al. [77]	Microwave power 100 W, extraction time 75 s, 90% acetone	Optimal garlic oil yield 3.85%	Garlic oil yield 3.85%
Dethier et al. [78]	Microwave irradiation, 37°C, 6 h	Yield of 486 mg vinyldithiins from 100 g garlic	Vinyldithiins yield 486 mg from 100 g garlic
Shah et al. [79]	Microwave-assisted solvent extraction	97% recovery of pendimethalin, linearity range 2–20 $\mu g{\cdot}mL^{-1}$	97% recovery, detection limit 0.059 $\mu g{\cdot}mL^{-1}$

technique for producing high-quality prebiotics from garlic.

Sowbhagya et al. [35] investigated the application of various enzymes, including cellulase, pectinase, protease, and viscozyme, as pretreatments before steam distillation or hydrodistillation for garlic oil extraction. The study found that enzyme pretreatment resulted in a twofold increase in oil yield compared to the control samples without enzyme treatment. The major components of the garlic oil, such as di-2-propenyl trisulfide (52%) and methyl 2-propenyl trisulfide (11.8%), were consistent with the flavor profile of garlic oil extracted using conventional methods. This study demonstrates that enzymes can facilitate the extraction of garlic oil without altering its characteristic flavor profile, making EAE an attractive option for industrial applications in flavor and fragrance production.

Finally, the 2013 study by Lee et al. [36] focused on the EAE of cycloalliin, an organosulfur compound with potential health benefits, using the commercial enzyme Ultraflo L. The researchers optimized the extraction conditions to include an enzyme concentration of 2.5% (v/w), an incubation time of 1 h at 40°C, and a pH of 6.0. Under these conditions, the yield of cycloalliin increased by 1.5-fold compared to nonenzymatic extraction methods. Furthermore, after storage at 60°C for 15 days, the cycloalliin content increased by 3.8-fold, and the polyphenol content tripled. This study highlights the potential of EAE not only to improve the yield of specific bioactive compounds but also to enhance their stability and efficacy over time.

In conclusion, the reviewed studies collectively demonstrate that EAE is a powerful and versatile method for extracting bioactive compounds from garlic. The ability to optimize conditions for specific enzymes allows for significant improvements in yield, purity, and stability of the extracted compounds. EAE is particularly valuable for applications in the food, pharmaceutical, and nutraceutical industries, where the quality and efficacy of bioactive compounds are of paramount importance (Table 4).

3.5 PLE

PLE is an advanced extraction technique that uses elevated temperatures and pressures to enhance the extraction of bioactive compounds from natural materials like garlic. The method is considered "green" due to its efficiency and reduced environmental impact compared to conventional extraction methods. This comprehensive review covers studies conducted from 2016 to 2023, focusing on the conditions under which PLE has been applied to garlic, the outcomes achieved, and the yields of key bioactive compounds (Table 5).

The study by Famakinwa et al. [33] explored the use of PLE for extracting macromolecules, such as carbohydrates, lipids, proteins, and nucleic acids, which play critical roles in living organisms. The study emphasized the importance of developing sustainable extraction methods, moving away from conventional techniques that often involve high temperatures and long extraction times. PLE was identified as a promising alternative due to its ability to efficiently extract macromolecules while preserving their functional properties. This study underscores the potential of PLE not only for improving the extraction process but also for producing high-quality extracts that can be used in fortification and nutritional supplements, addressing nutritional deficits and supporting environmental sustainability.

The study by Horita et al. [37] evaluated the antimicrobial, antioxidant, and sensory properties of garlic extracts obtained via PLE when incorporated into Brazilian low-sodium frankfurters. The PLE method was compared with conventional garlic products, including fresh garlic, garlic powder, and

Table 4: Summary of EAE conditions, outcomes, and yields/active compounds in garlic extraction studies (2009–2023)

Refs.	Extraction condition	Outcome	Yield/active compounds
Famakinwa et al. [33]	EAE for macromolecules	Improved extraction methods for macromolecules	Macromolecules for fortification, nutritional benefits
Sentkowska and Pyrzynska [34]	Stability of selenium compounds in aqueous extracts	Effect of solvent pH and storage temperature on selenium stability	Selenium compounds (selenomethionine, selenocystine)
Shalini et al. [47]	Hemicellulase treatment followed by solvent extraction	Increased fructan yield by 35.4%, FOS purification with 94% 1-kestose	Fructan yield 21.23 g/100 g, 94% 1-kestose in FOS
Sowbhagya et al. [35]	Cellulase, pectinase, protease, viscozyme pretreatment before steam distillation/hydrodistillation	Twofold increase in oil yield, consistent flavor profile	Di-2-propenyl trisulfide 52%, methyl 2-propenyl trisulfide 11.8%
Lee et al. [36]	EAE using Ultraflo L, 40°C, pH 6.0	1.5-fold increase in cycloalliin yield, 3.8-fold increase after storage at 60°C	Cycloalliin yield 1.5-fold increase, polyphenol content 3-fold increase

commercial garlic oil. The study found that the PLE extract had the highest allicin content, a key compound responsible for garlic's antimicrobial properties, followed by fresh garlic and garlic powder. The use of PLE extract in the frankfurters improved their antioxidant properties and provided effective antimicrobial action against spoilage bacteria during the product's shelf life. In addition, the sensory evaluation showed that frankfurters containing PLE extract were more acceptable than those with commercial garlic oil. This study highlights the effectiveness of PLE in enhancing the functional properties of garlic extracts, making it a valuable tool for the food industry, particularly in the development of healthier processed meat products.

Peterssen-Fonseca et al. [38] conducted a study focused on optimizing PLE for the extraction of organosulfur compounds, specifically alliin, and *S*-allyl-cysteine, from giant garlic (*Allium ampeloprasum* L.). The study employed chemometric optimization using RSM to determine the ideal extraction conditions. The results indicated that PLE was highly efficient in extracting these bioactive compounds, with yields significantly higher than those obtained using conventional ultra-turrax extraction. The optimized conditions included specific concentrations of ethanol in the extraction solvent and precise temperature settings, resulting in the extraction of $2.70\ mg \cdot g^{-1}$ of alliin and $2.79\ mg \cdot g^{-1}$ of *S*-allyl-cysteine. This research demonstrates the potential of PLE as a green and efficient technique for extracting valuable organosulfur compounds from garlic, which are known for their health benefits, including their role in preventing chronic diseases such as diabetes and cardiovascular conditions.

The study by Krstić et al. [8] compared PLE with SWE for isolating bioactive compounds from the Ranco genotype of garlic. The researchers used RSM to optimize the PLE process, focusing on variables such as ethanol concentration, extraction time, and temperature. The results showed that PLE outperformed SWE in terms of both yield and antioxidant activity of the garlic extracts. The study also measured allicin content, a major organosulfur compound, across all samples. The findings highlighted that PLE provided significant advantages over SWE, particularly in maximizing the TPC and enhancing antioxidant activity. This study reinforces the suitability of PLE as a clean and green method for extracting high-value bioactive compounds from garlic, with applications in the food, pharmaceutical, and nutraceutical industries.

In conclusion, the reviewed studies collectively underscore the effectiveness of PLE as a powerful and environmentally friendly method for extracting bioactive compounds from garlic. The ability to optimize extraction conditions for specific compounds, combined with the significant improvements in yield and bioactivity, positions PLE as a superior technique for both research and industrial applications. Whether for enhancing the antimicrobial and antioxidant properties of food products or for extracting health-promoting organosulfur compounds, PLE proves to be a versatile and effective tool in natural product extraction.

3.6 Other emerging green extraction methods

In recent years, innovative green extraction methods have gained prominence for their efficiency and environmental

Table 5: Summary of PLE studies and their findings

Refs.	Extraction conditions	Key findings	Yield/active compounds
Famakinwa et al. [33]	Sustainable methods with controlled pressure and temperature to extract macromolecules	Preserved functional properties of macromolecules, suitable for nutritional supplements and fortification. Reduced environmental impact	Macromolecules: carbohydrates, lipids, proteins, and nucleic acids
Horita et al. [37]	PLE-derived garlic extracts compared to fresh garlic, powder, and commercial oil for low-sodium frankfurters	Produced extracts with the highest allicin content, improved antimicrobial and antioxidant properties. Enhanced sensory acceptability of frankfurters	High allicin content
Peterssen-Fonseca et al. [38]	Chemometric optimization using ethanol concentrations and temperature settings via response surface methodology (RSM)	Achieved high yields of organosulfur compounds (alliin and *S*-allyl-cysteine). Outperformed conventional ultra-turrax extraction	Alliin: $2.70\ mg \cdot g^{-1}$; *S*-allyl-cysteine: $2.79\ mg \cdot g^{-1}$
Krstić et al. [8]	Comparison of PLE with SWE. RSM optimized ethanol concentration, time, and temperature	PLE provided higher TPC, antioxidant activity, and allicin recovery compared to SWE. Showcased PLE's advantages in bioactive compound recovery	High TPC and allicin recovery

benefits. Among these, ionic liquid (IL)-assisted separation has emerged as a powerful tool for the separation and determination of selenium species in complex food and beverage matrices. For example, successfully utilized ILs as mobile phase modifiers, achieving complete separation of selenium species within 12 min. The method demonstrated impressive detection limits for various selenium compounds, such as Se(IV) and Se(VI), making it a valuable technique for selenium speciation in food samples.

In recent years, innovative green extraction methods have gained significant attention for their ability to enhance efficiency while minimizing environmental impact. Among these, IL-assisted separation has emerged as a groundbreaking approach, particularly for its application in the speciation and quantification of selenium compounds in complex food and beverage matrices. This method leverages the unique properties of ILs, such as their tunable physicochemical characteristics, low volatility, and high solubility for a range of analytes, to optimize separation processes.

For instance, Castro Grijalba et al. [39] demonstrated the potential of ILs as mobile phase modifiers in high-performance liquid chromatography (HPLC) coupled with hydride generation atomic fluorescence spectrometry. This approach facilitated the complete separation of selenium species, including selenite [Se(IV)], selenate [Se(VI)], selenomethionine (SeMet), and Se-methylselenocysteine (SeMeSeCys), within an exceptionally short time frame of 12 min. The study reported remarkable detection limits for these selenium compounds – 0.92 $\mu g \cdot L^{-1}$ for Se(IV), 0.86 $\mu g \cdot L^{-1}$ for Se(VI), 1.41 $\mu g \cdot L^{-1}$ for SeMet, and 1.19 $\mu g \cdot L^{-1}$ for SeMeSeCys – highlighting the method's sensitivity and precision. These capabilities make IL-assisted separation a valuable tool for selenium speciation, particularly in food samples such as garlic and beverages, where selenium's nutritional and health benefits are of interest. This advancement not only enhances analytical accuracy but also underscores the sustainability and versatility of green extraction technologies in addressing complex analytical challenges.

Similarly, a previous study explored the cloud point extraction method for the determination of zinc in medicinal plants, employing nonionic surfactants to enhance extraction efficiency. The method relies on the surfactant-rich phase that forms at a specific temperature or pH to isolate zinc complexes. This approach was rigorously optimized using a multivariate strategy to fine-tune critical parameters, such as pH, temperature, ligand concentrations, and surfactant volumes. The optimized procedure achieved an impressive enhancement factor of 30 when using 2-methyl-8-hydroxyquinoline as the chelating agent and 26 with 1-(2-pyridylazo)-2-naphthol. The method exhibited excellent precision, with relative standard deviations (RSDs) below 5%. This study demonstrated the cloud point extraction method's potential as a robust and efficient technique for preconcentrating trace metals from complex biological matrices, making it an invaluable tool in environmental and biological analyses.

In another innovative study, Castro Grijalba et al. [40] developed an IL-assisted liquid–liquid microextraction technique for selenium speciation in *Allium* and *Brassica* vegetables. This method utilized trihexyl(tetradecyl)phosphonium decanoate as an IL, which formed a hydrophobic complex with selenium. The optimized procedure achieved a remarkable 100-fold preconcentration factor and a high extraction efficiency of 90%. The detection limit for selenium was an impressively low 5.0 $ng \cdot L^{-1}$, underscoring the method's exceptional sensitivity and precision. This technique provided a nonchromatographic alternative for selenium analysis in complex matrices like garlic and broccoli, offering significant advantages over traditional methods, including reduced processing time, lower reagent consumption, and enhanced analytical performance.

Makky et al. [41] adopted a distinct approach by focusing on the development of caffeine-loaded nanostructured lipid carriers (NLCs) as a green technology for pharmaceutical applications, specifically targeting topical alopecia treatment. Their study emphasized the superior efficiency of NLCs in delivering bioactive compounds. The optimized NLC formulation showed high entrapment efficiency (72.55%), a small particle size (358 nm), and rapid drug release (92.9% within 2 h). This novel application of green extraction technology illustrates the potential of lipid-based nanocarriers in enhancing the bioavailability, stability, and therapeutic efficacy of bioactive compounds, making them a promising tool in pharmaceutical innovation.

Finally, Ali et al. [42] employed vortex-assisted liquid–liquid microextraction (VA-LLME) for selenium determination in diverse matrices, including water, soil, and food samples. This green extraction technique combined ammonium pyrrolidine dithiocarbamate as a chelating agent with an IL to achieve high sensitivity and preconcentration capabilities. The optimized method demonstrated an enhancement factor of 98.7 and a detection limit of 0.07 $\mu g \cdot L^{-1}$ for selenium, making it highly effective for trace-level analyses. Selenium concentrations in all tested samples were within the World Health Organization's permissible limits, showcasing the method's practical applicability in ensuring food and water safety. This study highlights VA-LLME as a versatile and efficient approach for analyzing trace elements across a wide range of complex sample matrices.

These studies collectively underscore the versatility and effectiveness of emerging green extraction methods. By leveraging advanced techniques such as ILs, cloud point extraction, and NLCs, researchers have made significant strides in enhancing the extraction, separation, and determination of bioactive compounds in complex matrices. These methods not only offer superior performance but also align with the growing demand for environmentally sustainable processes in food and pharmaceutical industries (Table 6).

3.7 Standardizing green extraction processes globally

Standardizing green extraction processes globally is crucial to advancing sustainable practices in the extraction of bioactive compounds. Techniques offer significant environmental and economic benefits by minimizing solvent use, energy consumption, and waste generation [43–45]. However, the global standardization of these methods faces challenges, including inconsistent protocols, diverse regulatory requirements, and varying industrial applications. The lack of uniform guidelines for operational parameters like temperature, pressure, and solvent systems can affect the reproducibility and scalability of these methods, limiting their widespread adoption. For instance, in SFE processes for garlic, factors such as CO_2 flow rates and cosolvent ratios are critical to achieving optimal yields, underscoring the need for standardized methodologies.

Regulatory acceptance plays a pivotal role in promoting the adoption of green extraction techniques. Regions like the European Union (EU) have actively supported sustainable methods through stringent food and pharmaceutical regulations, fostering the use of solvent-free and nontoxic processes. For example, the acceptance of IL-based separation in food analyses, such as selenium speciation in garlic [39], demonstrates how regulatory frameworks can drive innovation. Similarly, the U.S. Food and Drug Administration has approved solvent-free microwave extraction methods, recognizing their ability to produce high-purity extracts without harmful residues. These regulatory endorsements have facilitated the integration of green processes into industries such as nutraceuticals and dietary supplements.

Table 6: Summary of emerging green extraction methods, conditions, outcomes, and yields/active compounds in garlic and related studies (2011–2022)

Refs.	Extraction condition	Outcome	Yield/active compounds
Castro Grijalba et al. [39]	IL-assisted separation for selenium species in food and beverage samples	Complete separation of Se species within 12 min using IL as mobile phase modifiers	Detection limits: Se(IV) 0.92 $\mu g \cdot L^{-1}$, Se(VI) 0.86 $\mu g \cdot L^{-1}$, SeMet 1.41 $\mu g \cdot L^{-1}$, SeMeSeCys 1.19 $\mu g \cdot L^{-1}$
Castro Grijalba et al. [40]	IL-assisted liquid–liquid microextraction for Se speciation in *Allium* vegetables	High extraction efficiency (90%) and preconcentration factor (100-fold) for inorganic Se in *Allium* and *Brassica* vegetables	Detection limit for Se: 5.0 $ng \cdot L^{-1}$, preconcentration factor: 100-fold
Makky et al. [41]	Caffeine-loaded NLCs for topical alopecia treatment	Improved permeation and efficiency of caffeine-loaded NLCs for hair growth	Entrapment efficiency (EE) 72.55%, particle size 358 nm, % drug release 92.9% after 2 h
Ali et al. [42]	Vortex-assisted liquid–liquid microextraction for Se in water, soil, and food samples	High sensitivity and preconcentration for Se in complex matrices	Enhancement factor: 98.7, detection limit: 0.07 $\mu g \cdot L^{-1}$, Se concentrations below WHO permissible limit
Grijalba et al. [48]	IL-multiwalled carbon nanotube micro-solid phase extraction for As species	High extraction efficiency for As species in garlic using IL and multi-walled carbon nanotubes (MWCNTs), preconcentration factor of 70	Detection limit for As: 7.1 $ng \cdot L^{-1}$, RSDs for As(III) 5.4%, As(V) 4.8%
Martinis et al. [46]	Online IL dispersive microextraction for Se speciation in water and garlic	Nonchromatographic separation, high sensitivity for Se speciation in garlic and water	Detection limit for Se: 15 $ng \cdot L^{-1}$, RSD for Se(IV) 5.1%, calibration linearity R^2 = 0.9993
Lawal and Low [50]	QuEChERS-dSPE IL-based dispersive liquid–liquid microextraction (DLLME) for pesticide residue determination in vegetables	Effective multiresidue analysis of pesticides in vegetables with good accuracy and precision	Detection limits: 0.01–0.28 $\mu g \cdot kg^{-1}$, accuracy 87–127%, precision 0–22%, acceptable matrix effects (≤−86%)
Castro Grijalba et al. [64]	IL-modified mobile phase in HPLC for mercury speciation in food	Efficient separation of Hg species with IL-modified mobile phase in HPLC, accurate results in complex samples	Detection limits: 0.05–0.11 $\mu g \cdot L^{-1}$ for Hg species, accurate Hg speciation in seafood, yeast, and garlic
Bağda and Tüzen [80]	Vortex-assisted IL-dispersive microextraction for Se in food	Novel eco-friendly method for Se determination in food samples with high sensitivity	Detection limit for Se(IV) 0.098 $\mu g \cdot L^{-1}$, RSDs 2.89–3.67%, successful application to food samples

However, inconsistent regulations in developing regions hinder the global adoption of green extraction methods. Advanced technologies like caffeine-loaded NLCs [41], which enhance bioavailability and therapeutic potential, face barriers due to differing safety and efficacy requirements across regions. Moving toward global standardization requires collaborative efforts among regulatory bodies, researchers, and industries. This includes developing universally accepted optimization protocols, as seen in chemometric approaches for PLE [38], and harmonizing safety and sustainability guidelines across borders. By fostering international partnerships and aligning regulatory frameworks, the potential of green extraction methods can be fully realized, ensuring their role in sustainable industrial practices worldwide.

4 Active compounds in garlic

4.1 Overview of bioactive compounds in garlic

Garlic (*Allium sativum* L.) is renowned not only for its culinary applications but also for its broad spectrum of bioactive compounds that confer numerous health benefits. The bioactive profile of garlic is complex, involving various organosulfur compounds, phenolics, and other phytochemicals, which are responsible for its antioxidant, antimicrobial, and therapeutic properties.

4.1.1 Organosulfur compounds

The most well-known bioactive components in garlic are its organosulfur compounds, particularly allicin, which is formed when garlic is crushed or chopped, triggering the enzymatic conversion of alliin by alliinase. Allicin is a volatile compound and is considered the primary contributor to garlic's characteristic aroma and its health benefits, including antimicrobial and cardiovascular protective effects. Other important sulfur-containing compounds in garlic include diallyl disulfide, diallyl trisulfide, and *S*-allylcysteine (SAC), all of which exhibit significant antioxidant and anti-inflammatory activities. Studies, such as those by Peterssen-Fonseca et al. [38], have optimized the extraction of these compounds using advanced techniques like PLE, demonstrating the efficacy of modern methods in enhancing the yield and purity of these bioactives.

4.1.2 Phenolic compounds

Garlic also contains a variety of phenolic compounds, which contribute to its strong antioxidant properties. Phenolics such as flavonoids, including quercetin and its derivatives, have been identified in garlic extracts. These compounds help neutralize free radicals and prevent oxidative stress-related diseases. The work by Chahbani et al. [31] highlighted the impact of extraction methods on the phenolic profile of garlic, particularly through MAE, which preserved and even enhanced the phenolic content in garlic leaves, demonstrating the importance of selecting appropriate extraction techniques to maximize the health benefits of garlic.

4.1.3 Selenium and other trace elements

Selenium is another important bioactive element found in garlic, particularly in selenium-enriched garlic. Selenium is known for its antioxidant properties and its role in enhancing immune function. The stability and extraction of selenium compounds, such as selenomethionine and selenocystine, have been a focus of research, with studies like those by Sentkowska and Pyrzynska [34] and Martinis et al. [46] exploring the optimal conditions for extracting and preserving these compounds in garlic. These studies underscore the need for precise control of extraction conditions, such as pH and temperature, to maintain the integrity of these bioactives.

4.1.4 Polysaccharides and fructans

Polysaccharides, including fructans, are another class of bioactive compounds in garlic that have garnered attention for their prebiotic effects and potential to modulate gut health. Fructans in garlic, particularly FOS, have been studied for their role in promoting beneficial gut microbiota. Shalini et al. [47] demonstrated that EAE methods could significantly increase the yield of fructans from garlic, emphasizing the potential of these compounds in functional foods and nutraceuticals.

4.1.5 Other bioactives

Beyond the well-documented sulfur compounds, phenolics, and trace elements, garlic also contains a variety of other bioactives, such as amino acids (e.g., arginine, cycloalliin), and vitamins, which contribute to its overall health benefits. The work by Lee et al. [36] on EAE of cycloalliin highlights the potential for innovative extraction methods to increase the availability of these lesser-known but important compounds.

In conclusion, garlic's rich composition of bioactive compounds positions it as a powerful natural product with multiple health benefits. The ongoing research into optimizing the extraction and preservation of these compounds, as highlighted by the studies reviewed here, is crucial for fully harnessing garlic's therapeutic potential. Through advanced extraction techniques and a deeper understanding of its bioactive profile, garlic can continue to be a cornerstone of both dietary health and medicinal applications.

4.2 Impact of extraction methods on allicin and organosulfur compounds

The extraction methods employed to obtain bioactive compounds from garlic, particularly allicin and other organosulfur compounds, have a profound impact on the yield, stability, and efficacy of these compounds. Allicin, a key bioactive molecule in garlic, is highly unstable and can quickly degrade into other sulfur-containing compounds, such as diallyl disulfide and diallyl trisulfide, which also possess significant health benefits. The choice of extraction technique is therefore critical in preserving these volatile and reactive compounds, and various innovative methods have been developed to enhance the extraction efficiency while maintaining compound integrity.

SFE is one of the advanced methods that has been shown to effectively extract allicin and other organosulfur compounds from garlic. This method uses supercritical CO_2, often with a co-solvent like ethanol, to efficiently solubilize and extract these bioactives under controlled temperature and pressure conditions. Studies such as those by Bastos et al. [15] and Vidović et al. [16] have demonstrated that SFE can achieve high yields of allicin while minimizing thermal degradation. For instance, Bastos et al. [15] reported that SFE at 70°C with a 1:1 cosolvent ratio resulted in a high yield of allicin and other sulfur compounds, which were shown to significantly improve the properties of fish gelatin-based films. The ability of SFE to maintain the stability of sensitive compounds like allicin makes it a superior choice compared to traditional methods.

EAE utilizes specific enzymes to break down cell walls and release bioactive compounds more effectively. This method has been particularly useful in enhancing the yield of allicin and related organosulfur compounds. The work by Sowbhagya et al. [35] highlighted that pretreating garlic with enzymes such as cellulase, pectinase, and protease before steam distillation or hydrodistillation resulted in a twofold increase in oil yield, with a consistent flavor profile dominated by di-2-propenyl trisulfide. The enzyme treatment not only increased the yield but also preserved the organoleptic properties of garlic oil, which are crucial for both food and medicinal applications.

MAE is another method that has gained attention for its ability to efficiently extract allicin and other organosulfur compounds with reduced processing time and energy consumption. The study by Chahbani et al. [31] demonstrated that MAE, particularly at lower power settings, could effectively extract phenolic compounds and preserve the organosulfur content in garlic leaves. Although primarily focused on phenolics, this method's ability to maintain the integrity of allicin during the extraction process makes it a promising technique for broader applications. In addition, Yazgan et al. [29] utilized microwave-assisted acetone extraction, showing significant antimicrobial effects linked to the high content of diallyl disulfide and allyl trisulfide in the extracts.

PLE is a technique that uses high-pressure solvents at elevated temperatures to enhance the extraction of bioactive compounds. This method has been particularly effective in extracting stable and high-purity organosulfur compounds from garlic. Peterssen-Fonseca et al. [38] utilized PLE to extract alliin and *S*-allyl-cysteine from giant garlic, achieving significantly higher yields compared to conventional methods. The chemometric optimization of PLE conditions, such as ethanol concentration and extraction temperature, allowed for the selective extraction of these compounds, highlighting PLE's potential in producing high-quality garlic extracts.

IL-Assisted Extraction has emerged as a novel approach for the extraction of bioactives from garlic, particularly for selenium species, but it has also shown potential for sulfur compounds. The use of ILs can enhance the solubility and stability of target compounds during extraction, as demonstrated by Castro Grijalba et al. [39], who achieved high extraction efficiency for selenium species in garlic. Although this method has been less commonly applied to allicin, its ability to improve extraction efficiency and maintain compound integrity suggests it could be adapted for organosulfur compounds as well.

VA-LLME is a technique that leverages the rapid mixing and phase separation capabilities of vortex mixing to enhance the extraction of target compounds. Ali et al. [42] applied this method to the extraction of selenium in garlic, demonstrating high sensitivity and efficiency. While primarily focused on trace elements, the method's principles could be adapted for the extraction of volatile organosulfur compounds, offering a rapid and efficient alternative to more traditional techniques.

The extraction method chosen for obtaining allicin and other organosulfur compounds from garlic plays a crucial role in determining the yield, stability, and overall quality of the extracted compounds. Advanced techniques like SFE, EAE, and PLE have shown particular promise in preserving the integrity of these bioactives, offering higher yields and better preservation of their health-promoting properties compared to conventional methods. As research continues to evolve, the optimization and application of these innovative extraction methods will be key to unlocking the full therapeutic potential of garlic's bioactive compounds.

4.3 Effects of green extraction techniques on antioxidants and flavonoids

The pursuit of green extraction techniques has been driven by the need to enhance the yield and purity of bioactive compounds from natural sources, while minimizing the environmental impact and preserving the integrity of these compounds. Among these bioactives, antioxidants and flavonoids are of particular interest due to their potent health benefits, including anti-inflammatory, anticancer, and cardioprotective effects. The various green extraction methods explored in recent studies have demonstrated significant potential in optimizing the extraction of these compounds from garlic and related plant materials.

MAE has emerged as a highly effective method for extracting antioxidants and flavonoids from garlic. The application of microwave energy accelerates the extraction process by rapidly heating the solvent and plant matrix, which enhances the solubilization of target compounds. Chahbani et al. [31] reported that MAE of garlic leaves at a power setting of 100 W resulted in a significant increase in TPC, with a marked presence of flavonoids such as quercetin 3-*O*-rhamnoside. The study highlighted that MAE not only improved the yield but also preserved the antioxidant activity of the extracts, as evidenced by the enhanced DPPH radical scavenging activity. This method proved particularly efficient in balancing energy consumption with extraction efficiency, making it a favorable choice for industrial applications.

Similarly, the study by Oke et al. [30] optimized MAE conditions to achieve an extractable yield of 28.62%, with a TPC of 76.8 mg GAE·g^{-1} dry extract from garlic. The optimization of irradiation power and extraction time was crucial in maximizing the antioxidant properties of the garlic extracts, demonstrating MAE's capability to efficiently concentrate bioactive compounds. The results from these studies underscore the effectiveness of MAE in extracting high yields of antioxidants and flavonoids while maintaining their bioactivity.

IL-Assisted Extraction is a relatively novel approach that has shown promise in enhancing the extraction of flavonoids and other antioxidants from plant materials. The use of ILs as solvents offers several advantages, including high solubility for a wide range of bioactive compounds and the ability to operate at lower temperatures, which helps preserve sensitive compounds. Castro Grijalba et al. [39] demonstrated the efficacy of IL-assisted extraction in separating selenium species from complex matrices like garlic, achieving high sensitivity and extraction efficiency. While this study primarily focused on selenium, the principles of IL-assisted extraction can be applied to flavonoids and antioxidants, suggesting potential for this method in future studies targeting these compounds. In another study, Grijalba et al. [48] applied an IL-assisted micro-solid phase extraction method for the determination of arsenic species in garlic, highlighting the versatility of ILs in extracting a range of bioactives from complex matrices. The ability of ILs to improve the extraction efficiency and stability of bioactive compounds, including flavonoids, presents a promising avenue for further research and application in food and pharmaceutical industries.

VA-LLME has been explored as a green extraction technique for its simplicity, efficiency, and minimal solvent requirement. Ali et al. [42] employed VA-LLME for the extraction of selenium from garlic, achieving high sensitivity and an enhancement factor of 98.7. While the study focused on selenium, the method's efficacy in concentrating bioactives suggests its potential applicability to antioxidants and flavonoids. The rapid phase mixing and separation characteristics of VA-LLME make it an attractive option for extracting sensitive compounds like flavonoids, which can degrade under harsh extraction conditions. The method's ability to achieve high extraction efficiency with minimal solvent use aligns well with the principles of green chemistry, offering a sustainable alternative to conventional extraction techniques.

Deep eutectic solvents (DES) represent another innovative approach to green extraction, offering a biodegradable and nontoxic alternative to traditional organic solvents. Wen et al. [49] investigated the ecotoxicity and biodegradability of DESs, demonstrating their potential as environmentally friendly solvents for bioactive extraction. Although this study focused on the general properties of DESs, their application in extracting antioxidants and flavonoids from garlic could be explored further. DESs are particularly advantageous for extracting flavonoids due to their tunable properties, which can be adjusted to enhance the solubility of specific bioactives. This flexibility, combined with their low toxicity, makes DESs a promising tool for the sustainable extraction of high-value compounds from garlic.

Across these green extraction techniques, a common theme is the preservation or enhancement of the antioxidant activity of the extracted compounds. Whether through the rapid heating of MAE, the solvent properties of ILs, or the efficiency of VA-LLME, these methods have been shown to maintain or even improve the bioactivity of the extracted antioxidants and flavonoids. This is particularly important for applications in food and nutraceutical industries, where the functional properties of these compounds are critical to their efficacy. In conclusion, green extraction techniques such as MAE, IL-assisted extraction, and VA-LLME have demonstrated significant potential in optimizing the extraction of antioxidants and flavonoids from garlic. These methods not only improve the yield and purity of these compounds but also align with the principles of sustainability and green chemistry, making them highly relevant for future applications in various industries. As research continues to refine these techniques, their adoption is likely to expand, offering more efficient and environmentally friendly options for extracting valuable bioactives from natural sources.

4.4 Stability and bioavailability of active compounds in green extracts

The stability and bioavailability of active compounds extracted from natural sources like garlic are critical factors that determine their efficacy in various applications, including food, pharmaceuticals, and nutraceuticals. The use of green extraction methods, which prioritize environmental sustainability and the preservation of bioactive properties, has prompted extensive research into how these techniques influence the stability and bioavailability of the extracted compounds. This section reviews the impact of green extraction techniques on the stability and bioavailability of active compounds, particularly focusing on studies that have utilized these methods on garlic and similar matrices.

Stability is a key concern when dealing with bioactive compounds, as many of these molecules, including allicin and other organosulfur compounds in garlic, are prone to degradation under certain conditions. Various factors such as pH, temperature, and the presence of light can significantly affect the stability of these compounds during and after extraction. For instance, Sentkowska and Pyrzynska [34] investigated the stability of selenium compounds in aqueous extracts, focusing on both inorganic and organic selenium species. Their study revealed that the solvent pH and storage temperature were critical factors influencing the stability of selenium compounds. While the study primarily dealt with selenium, the principles can be extended to other bioactives, indicating that careful control of extraction conditions is essential to maintain the stability of sensitive compounds.

Similarly, Lee et al. [36] explored the EAE of cycloalliin from garlic, a compound known for its health benefits. They found that the stability of cycloalliin increased significantly when stored at elevated temperatures after extraction, with a 3.8-fold increase observed at 60°C over 15 days. This suggests that certain storage conditions can actually enhance the stability of some bioactives, although this is highly dependent on the nature of the compound and the extraction method used.

The choice of extraction method also plays a pivotal role in determining the stability of bioactives. Makky et al. [41] developed caffeine-loaded NLCs for topical applications, using green extraction techniques to enhance the bioavailability and stability of the active compounds. The study demonstrated that the use of optimized lipid carriers not only improved the stability of caffeine in the formulation but also ensured sustained release, which is crucial for maintaining bioactivity over time.

Bioavailability refers to the extent and rate at which the active compounds are absorbed and become available at the site of physiological activity. In the context of green extracts, bioavailability is influenced by several factors, including the solubility of the bioactives, the nature of the extraction medium, and the presence of enhancing agents such as surfactants or lipid carriers. Ali et al. [42] employed a VA-LLME method for selenium extraction in various matrices, including food and soil samples. This method significantly enhanced the bioavailability of selenium by improving its extraction efficiency and concentrating the bioactive forms. The study's findings are particularly relevant for selenium, which is known to have low bioavailability in its inorganic form but can be significantly improved through green extraction methods that enhance its solubility and stability.

Grijalba et al. [48] explored the use of ILs in combination with MWCNTs for the extraction of arsenic species in garlic. This innovative approach not only improved the extraction efficiency but also enhanced the bioavailability of arsenic species by concentrating them in a form that is more readily absorbed by biological systems. The study highlights the potential of using advanced materials and green solvents to enhance the bioavailability of bioactives in complex matrices.

Moreover, the use of DESs, as investigated by Wen et al. [49], offers another promising avenue for improving the bioavailability of bioactives. DESs, known for their low toxicity and biodegradability, were shown to interact favorably with cellular membranes, thereby enhancing the uptake and bioavailability of the extracted compounds. This is particularly important for compounds that are typically difficult to solubilize and absorb, such as flavonoids and polyphenols.

The stability and bioavailability of bioactive compounds are also affected by postextraction processing and storage conditions. Horita et al. [37] examined the impact of different garlic extracts, including those obtained via PLE, on the antioxidant and antimicrobial properties in low-sodium frankfurters. Their findings indicated that PLE-extracted garlic had superior bioactive retention and stability during the product's shelf life compared to conventional garlic extracts. This suggests that PLE not only enhances the extraction yield but also preserves the bioactivity of the compounds during storage, contributing to better overall efficacy in food products.

Lawal and Low [50] also demonstrated that the use of IL-based DLLME in the determination of pesticide residues resulted in high accuracy and precision, with acceptable matrix effects. This method ensured that bioactive compounds in the samples remained stable and bioavailable for analysis, highlighting the importance of choosing appropriate extraction and processing methods to maintain the integrity of bioactives.

5 Traditional extraction of garlic

Traditionally, garlic is extracted by pulverizing or slicing the cloves to release bioactive compounds, particularly allicin [51]. The crushed garlic is often soaked in water or oil to extract the compounds. Oil extraction is widely utilized in traditional medicine and cooking, as it is believed to preserve garlic's active compounds [52]. Garlic is sometimes fermented in some cultures to enhance its medicinal properties. The pulverized garlic cloves are soaked in saline brine and fermented for several weeks to produce fermented garlic [53]. The resultant product is believed to have enhanced antioxidant and anti-inflammatory properties.

Although these traditional extraction techniques have been utilized for centuries, they have some limitations. For instance, using oil to extract garlic compounds can result in high levels of saturated fat and calories in the final product [54]. In addition, traditional extraction techniques can be time-consuming and require a large quantity of garlic to generate a small amount of extract [55]. As a result, ecological and sustainable modern extraction techniques have been devised to obtain garlic extracts with high concentrations of bioactive compounds. These methods include, among others, SFE, UAE, and MAE. These modern techniques are more effective and environmentally favorable and produce extracts with greater purity and potency than conventional methods.

In conventional garlic extraction, organic solvents such as ethanol, methanol, or hexane are typically employed [2]. The garlic is first minced to release bioactive compounds, and then the desired compounds are extracted from the garlic using a solvent. The mixture is then filtered to remove solid particles, and the solvent is evaporated to obtain the crude extract. This conventional approach has some drawbacks [56]. First, using organic solvents can cause pollution and other environmental issues. Second, the extraction procedure can be labor-intensive and time-consuming, requiring multiple stages to obtain a pure extract. Third, the extract's yield and quality can vary based on the solvent and extraction conditions used.

Due to their low cost and relative simplicity, conventional extraction methods are still extensively utilized despite their limitations and the growing interest in developing more sustainable and environmentally favorable extraction techniques, such as green extraction techniques that use nontoxic solvents and reduce pollution and energy. These methods can increase the extracts' yield and quality while reducing the environmental impact.

6 Advantages and disadvantages of garlic extraction using green process

Green garlic extraction methods offer a sustainable and efficient alternative to conventional techniques as shown in Table 7. These methods prioritize eco-friendliness by minimizing or eliminating the use of toxic organic solvents, replacing them with water or bio-based solvents, as demonstrated by Jiménez-Amezcua et al. [25] in water-based MAE. They also align with green chemistry principles, as evidenced by the use of CO_2 in SFE and ethanol in PLE, reducing the environmental impact of extraction processes. In addition, green methods enhance bioactive compound recovery and preserve their functionality. For example, Bai et al. [21] reported that ultrasound pretreatment, combined with ozone water treatment, improved phenolic content by 25.90%, while Krstić et al. [8] showed that PLE outperformed conventional methods in extracting sulfur-rich bioactives like allicin and alliin.

Another notable advantage of green extraction methods is their ability to selectively target specific compounds while preserving their integrity. Techniques like IL-assisted extraction [39] and SFE [16] demonstrated the effective recovery of sulfur compounds and phenolics. Furthermore, these methods significantly reduce processing times, with MAE and UAE yielding results within minutes, as reported by Oke et al. [30]. Their scalability and economic feasibility make them attractive for industrial applications, particularly in food and pharmaceutical sectors, as highlighted by Horita et al. [37], who showed the enhanced sensory and antimicrobial properties of PLE-derived garlic extracts in low-sodium frankfurters.

Despite these advantages, green extraction methods are not without challenges. High initial costs for equipment, such as high-pressure systems required for SFE and PLE, can be a barrier to adoption, especially for small-scale producers. In addition, these techniques require extensive optimization of variables like temperature, pressure, and solvent composition. Studies like Peterssen-Fonseca et al. [38] and Krstić et al. [8] utilized advanced optimization methods, such as RSM, which can be resource-intensive and require specialized expertise. Furthermore, certain solvents may not be compatible with all bioactive compounds, potentially leading to degradation. For instance, Yazgan et al. [29] noted the need for precise control of MAE parameters to preserve thermolabile compounds like allicin. Overall, while green extraction methods offer significant environmental and functional benefits, they require careful optimization and investment to overcome challenges like cost, complexity, and potential bioactive degradation. Addressing these limitations through technological advancements and standardized protocols will be key to ensuring their widespread adoption in the future.

7 Bibliometric analysis of garlic extraction research

7.1 Yearly output of scholarly publications related garlic extraction

This section examines the yearly output of scholarly publications related to garlic extraction, providing insights into the evolving trends and dynamics within the field over the specified time frame. Attention is given to understanding the temporal distribution of scholarly output, essential for identifying emerging patterns, addressing research gaps, and charting future research directions. A comprehensive overview of garlic extraction's scholarly landscape is presented through a meticulous examination of publication trends, shedding light on critical milestones, fluctuations, and areas of sustained interest. The temporal evolution of garlic extraction literature is scrutinized to elucidate the trajectory of research activity and its implications for scientific advancement and innovation in this critical domain.

Figure 1 provides a comprehensive overview of the annual publication output dedicated to garlic extraction research from 2010 to 2023. The data presented in the graph offers valuable insights into the evolving trends and dynamics within the field over the specified time frame. The visualization reveals notable fluctuations in scholarly publications across different years. For instance, in 2010, the year commenced with a modest output of 20 publications, followed by a significant increase in 2011 to 42 publications, indicating a doubling of research activity within one year. Subsequent years witnessed varying levels of publication activity, with fluctuations observed in publication counts. Noteworthy peaks in publication output are evident in 2014, 2017, 2019, 2020, and 2022,

Table 7: The summary of advantages and disadvantages of garlic extraction using green and traditional processes

Extraction process	Advantages	Disadvantages
Green extraction processes	Environmentally friendly	Limited scalability
	Reduced solvent usage	Longer extraction times
	Potential for higher compound yield	Equipment and operational costs
	Enhanced preservation of bioactive compounds	Complex extraction conditions
	Improved safety due to nontoxic solvents	Extraction selectivity may vary
Traditional processes	Established and widely used methods	Solvent toxicity and safety concerns
	Higher scalability for industrial applications	Risk of degradation or loss of bioactive compounds
	Shorter extraction times	Potential for solvent residues in final product
	Standardized extraction protocols	Potential environmental impact
	Extraction selectivity for specific compounds	Higher solvent usage and waste generation

indicating periods of heightened research interest and productivity within the field.

Of particular interest is the remarkable surge in publications observed in 2021, reaching a count of 86 publications, marking a substantial increase compared to previous years. This surge may reflect a culmination of factors such as advancements in research methodologies, increased funding opportunities, and growing recognition of garlic extraction's potential applications in various fields, including health, food, and pharmaceutical industries. Furthermore, the subsequent peak in 2022 with 102 publications suggests sustained momentum and continued interest in garlic extraction research. Overall, the trends depicted in Figure 1 underscore the dynamic nature of garlic extraction research, with fluctuations in publication output reflecting shifts in research priorities, emerging areas of interest, and advancements in scientific knowledge. These insights provide valuable context for understanding the trajectory of research activity within the field and offer valuable guidance for future research directions and strategic planning.

7.2 Geographical distribution of publications on garlic extraction

In this section, the geographical distribution of scholarly publications on garlic extraction is examined, delving into the global landscape of research contributions in this field. An understanding of the geographical distribution of publications is deemed essential for discerning regional research priorities, identifying collaborative networks, and assessing the global impact of garlic extraction research. Through an analysis of publication data from various regions, insights into the geographic distribution of research activity are aimed to be provided, highlighting key contributors and regional disparities in research output. By mapping the geographical distribution of publications, patterns, and trends that contribute to a nuanced understanding of the global research landscape surrounding garlic extraction are sought to be uncovered. This analysis not only sheds light on the geographic spread of research efforts but also informs strategic collaborations and resource allocation to foster greater collaboration and knowledge exchange across borders.

Table 8 outlines the 20 most prolific nations concerning garlic extraction research, ranking them based on the number of articles authored by corresponding authors affiliated with institutions in each country. The dominance of China at the top of the list, with 155 articles, can be attributed to several factors. First, China has a long history of garlic cultivation and utilization, making it a natural leader in garlic-related research. The country's large population and extensive agricultural sector provide ample resources and expertise for researching garlic extraction methods and applications. In addition, China's strategic investments in scientific research and development have bolstered its research output across various fields, including agricultural and food sciences.

India's position as the second most prolific nation, with 64 articles, reflects its burgeoning research landscape and growing interest in garlic extraction. India boasts a rich biodiversity and a tradition of herbal medicine, which has spurred research into the medicinal properties and extraction techniques of garlic. Furthermore, India's

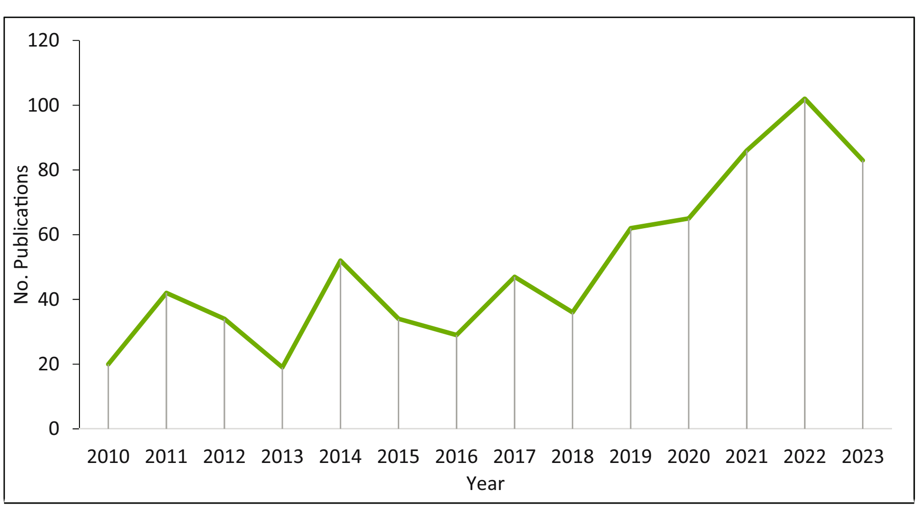

Figure 1: Annual publication output on garlic extraction.

Table 8: The 20 most prolific nations ranked by the affiliations of corresponding authors related garlic extraction

Rank	Country	Numbers of articles
1	China	155
2	India	64
3	South Korea	41
4	United States	39
5	Iran	37
6	Spain	33
7	Pakistan	31
8	Egypt	28
9	Italy	28
10	Indonesia	25
11	Thailand	25
12	Japan	24
13	Brazil	19
14	Germany	19
15	Turkey	19
16	Saudi Arabia	18
17	Malaysia	17
18	Poland	15
19	Iraq	14
20	Mexico	14

robust scientific infrastructure, coupled with government initiatives to promote research and innovation, has facilitated the growth of garlic extraction research within the country.

Similarly, South Korea's strong presence in garlic extraction research, with 41 articles, can be attributed to its advanced research facilities, government support for scientific endeavors, and a focus on technology-driven innovation. The United States, Iran, and other nations in the ranking also demonstrate significant contributions to garlic extraction literature, driven by factors such as research funding, academic collaborations, and national research priorities. Overall, the rankings in Table 8 reflect a combination of historical context, research infrastructure, government support, and scientific expertise, all of which contribute to the varying degrees of research output observed across different nations in the field of garlic extraction.

7.3 Identification of top-cited publications and the 20 most cited journals in the context of garlic extraction

In this section, the focus is on the identification of top-cited publications and the 20 most cited journals within the realm of garlic extraction research. By scrutinizing citation metrics, insights into the seminal works and influential journals shaping the discourse in this field are aimed to be provided. Through an analysis of citation counts and journal impact factors, valuable insights into the scholarly landscape surrounding garlic extraction are offered, elucidating the pivotal contributions and authoritative sources driving advancements in research and innovation. By highlighting the most cited publications and journals, a comprehensive overview of the foundational knowledge and prevailing trends within the domain of garlic extraction is provided, guiding researchers, practitioners, and policymakers in navigating the vast and dynamic body of literature in this critical field.

Table 9 offers a comprehensive overview of the most cited documents related to garlic extraction, providing insights into the authors, titles, publication years, source titles, total citation counts, and references for each publication. These highly cited studies serve as pillars in the field of garlic extraction research, reflecting their substantial impact and influence. One noteworthy contribution is the article by da Cruz Cabral et al. [57], which delves into the application of plant-derived compounds to combat fungal spoilage and mycotoxin production in foods, boasting a total citation count of 315. Similarly, a previous study published in BMC Complementary and Alternative Medicine explored the potent α-amylase inhibitory activity of Indian Ayurvedic medicinal plants and has garnered 262 citations. These seminal works exemplify the diverse applications and therapeutic potentials of garlic compounds, ranging from antimicrobial effects to enzymatic inhibition, thereby enriching our understanding of garlic's health-promoting properties.

Furthermore, significant contributions such as the isolation and structural characterization of cellulose nanocrystals from garlic straw residues [58] and the sunlight-based irradiation strategy for the green synthesis of silver nanoparticles using garlic extract [59] underscore the innovative approaches employed in garlic extraction research. In addition, the review article by Putnik et al. [60] provides a comprehensive overview of organosulfur compounds from *Allium* spp., elucidating their bioavailability, antimicrobial activities, and anti-inflammatory properties. These studies not only showcase the versatility of garlic in various applications but also highlight the importance of sustainable extraction methods and their potential impact on health and wellness.

The highly cited publications in Table 3 cover a wide spectrum of topics, including antibacterial effects, antioxidant properties, extraction techniques, and biomedical applications of garlic compounds. For instance, Karuppiah and Rajaram [61] investigate the antibacterial effects of

Table 9: The documents with the highest citation counts related garlic extraction

Title	Year	Source title	Total citation	Refs.
Application of plant derived compounds to control fungal spoilage and mycotoxin production in foods	2013	International Journal of Food Microbiology	315	da Cruz Cabral et al. [57]
Potent α-amylase inhibitory activity of Indian Ayurvedic medicinal plants	2011	BMC Complementary and Alternative Medicine	262	Zinjarde et al. [81]
Isolation and structural characterization of cellulose nanocrystals extracted from garlic straw residues	2016	Industrial Crops and Products	234	Kallel et al. [58]
Sunlight-based irradiation strategy for rapid green synthesis of highly stable silver nanoparticles using aqueous garlic (*Allium sativum*) extract and their antibacterial potential	2011	Materials Chemistry and Physics	228	Rastogi and Arunachalam [59]
An overview of organosulfur compounds from *Allium* spp.: From processing and preservation to evaluation of their bioavailability, antimicrobial, and anti-inflammatory properties	2019	Food Chemistry	178	Putnik et al. [60]
Antibacterial effect of *Allium sativum* cloves and *Zingiber officinale* rhizomes against multiple-drug resistant clinical pathogens	2012	Asian Pacific Journal of Tropical Biomedicine	157	Karuppiah and Rajaram [61]
Optimization of UAE of bioactive compounds from wild garlic (*Allium ursinum* L.)	2016	Ultrasonics Sonochemistry	137	Tomšik et al. [62]
Traditional uses of medicinal plants of Nandiar Khuwarr catchment (District Battagram), Pakistan	2011	Journal of Medicinal Plants Research	119	Haq et al. [82]

Allium sativum cloves and *Zingiber officinale* rhizomes against drug-resistant clinical pathogens, while a previous study explored the encapsulation of garlic extract using complex coacervation for improved stability and functionality. Moreover, previous studies shed light on the chemopreventive functions and molecular mechanisms of garlic organosulfur compounds, contributing to our knowledge of garlic's potential role in disease prevention and management.

Moreover, the geographical distribution of research contributions, as evidenced by the affiliations of corresponding authors in Table 3, highlights the global significance of garlic extraction research. While countries like China, India, and South Korea lead in terms of research output, collaborations among researchers from diverse regions contribute to the collective knowledge base in garlic extraction. This international collaboration fosters cross-cultural exchanges and facilitates the dissemination of research findings, ultimately enriching the global scientific community's understanding of garlic's therapeutic potential and applications in health and wellness.

In conclusion, Table 9 encapsulates the breadth and depth of research endeavors in garlic extraction, offering a glimpse into the seminal works and influential publications that have shaped the field. By synthesizing knowledge from diverse disciplines and regions, these highly cited publications pave the way for continued exploration and innovation in garlic extraction for health and wellness applications. As researchers continue to unravel the complexities of garlic's bioactive compounds and their mechanisms of action, the findings presented in Table 3 catalyze future research directions aimed at harnessing the full potential of garlic for improving human health and well-being.

7.4 Co-occurrence of garlic extraction

The co-occurrence network in Figure 2 offers a detailed visualization of the relationships between frequently used keywords in garlic extraction research. By setting a minimum threshold of 5 occurrences, the network reveals 236 connections among keywords, emphasizing recurring themes and important research directions. At the heart of this network lies the keyword "Garlic," which serves as the central node, reflecting its pivotal role in the entire field. The size of this node indicates the significant attention garlic has received across multiple studies. Around this node, various thematic clusters can be observed, each representing a specific area of research focus within the broader context of garlic extraction.

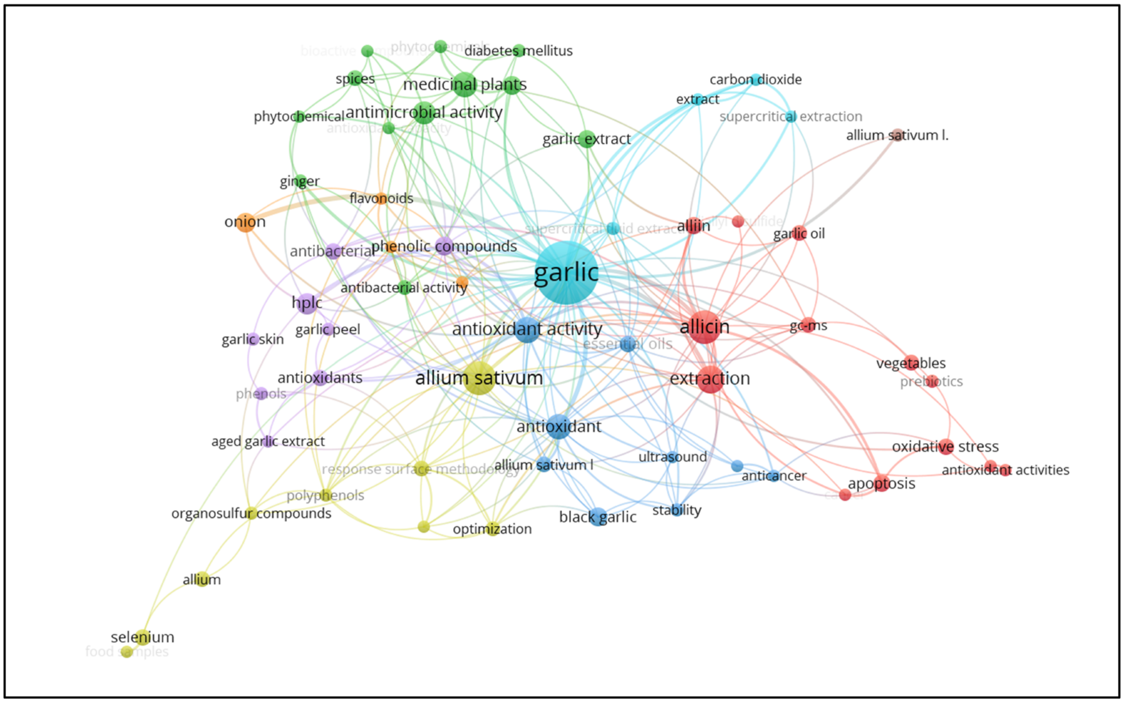

Figure 2: Co-occurrence of authors' keywords: Minimum keywords threshold of 5 and 236 links.

The first notable cluster revolves around garlic's bioactive compounds and their health-related applications. Keywords such as *allicin*, *Allium sativum*, *antioxidant activity*, and *antimicrobial activity* form tightly interconnected groups, indicating that a substantial portion of the literature centers on these aspects. The presence of *allicin*, a sulfur-containing compound known for its medicinal properties, is highly relevant, as many studies explore its role in enhancing the antioxidant and antimicrobial potential of garlic. *Antioxidant activity* appears as a frequently recurring term, reflecting the significant interest in garlic's ability to combat oxidative stress and reduce damage from free radicals. In addition, *antimicrobial activity* suggests an active research domain exploring garlic's potential in fighting bacterial, viral, and fungal infections. The term *oxidative stress*, closely connected to antioxidant-related research, further underscores the widespread interest in understanding how garlic can mitigate oxidative damage, particularly in relation to chronic diseases and aging.

The second major thematic cluster in the network focuses on the extraction methodologies employed to isolate and optimize garlic's bioactive compounds. Keywords such as *extraction*, *supercritical extraction*, *ultrasound*, and *RSM* feature prominently, illustrating the broad range of technologies being tested and refined in garlic extraction processes. *Supercritical extraction*, for instance, is gaining attention for its efficiency in preserving sensitive compounds like allicin, while *UAE* is highlighted for its ability to enhance yield in a time-efficient manner. The frequent appearance of *RSM* points to its utility in optimizing various extraction parameters, helping researchers fine-tune processes to maximize the extraction of valuable components from garlic. In addition, the keyword *garlic oil* appears within this cluster, indicating an interest in oil-based products derived from garlic, which have applications in both the food and pharmaceutical industries. The connection with *stability* suggests that researchers are also investigating how to improve the stability and shelf-life of garlic extracts, which is crucial for commercial viability.

Overall, this co-occurrence analysis reveals the multifaceted nature of garlic extraction research. The strong connections between bioactive components, such as allicin, and advanced extraction methods highlight the dual focus on both understanding garlic's health benefits and improving the techniques used to extract these valuable compounds. This combination of thematic richness and technological exploration makes garlic extraction a continually evolving and relevant area of scientific inquiry.

7.5 Future recommendation based on co-occurrence of authors' keywords

The co-occurrence network depicted in Figure 2 highlights established research trends and emerging opportunities in garlic extraction. Based on this visualization, several future research directions can be proposed to address existing gaps and to expand upon the current body of knowledge. These recommendations focus on refining extraction techniques, exploring under-researched bioactive compounds, enhancing understanding of garlic's role in chronic disease prevention, developing functional foods and nutraceuticals, and standardizing garlic extraction processes for consistent quality and efficacy.

A key area that stands out for future research is the further development and optimization of garlic extraction techniques. The co-occurrence of keywords such as *supercritical extraction* and *ultrasound* shows that these methods have already garnered significant attention, but there remains considerable scope for exploring novel and alternative technologies. Methods like *enzymatic extraction*, *MAE*, or *pulsed electric field (PEF) extraction* could offer more sustainable and effective approaches, particularly for sensitive compounds like *allicin*, which are prone to degradation under conventional extraction conditions. Future studies could compare the efficiency, environmental impact, and cost-effectiveness of these methods, paving the way for more eco-friendly and industrially scalable garlic extraction processes. In addition, further research could focus on optimizing these extraction methods to enhance the preservation of bioactive compounds, ensuring the maximum yield of functional ingredients from garlic.

Another recommendation is to expand the investigation into lesser-studied bioactive compounds in garlic. While *allicin* and its associated antioxidant and antimicrobial properties dominate the current research, the network reveals that other bioactive compounds, such as *ajoene*, *saponins*, and *polysulfides*, remain relatively underexplored. These compounds hold considerable potential for diverse health applications, such as anti-inflammatory, antifungal, and anticancer properties, which have yet to be fully elucidated. Future research should focus on isolating these compounds, studying their biological activities, and assessing how different extraction techniques affect their stability and bioavailability. This deeper investigation into garlic's less prominent bioactive compounds could open new avenues for therapeutic applications and create opportunities for novel garlic-based products targeting specific health conditions.

In addition, garlic's role in managing oxidative stress and preventing chronic diseases merits further exploration. The co-occurrence of keywords such as *oxidative stress* and *antioxidant activity* points to an existing interest in garlic's potential to combat oxidative damage, yet the direct links between garlic's bioactive compounds and their impact on specific chronic diseases, such as cardiovascular disease, diabetes, and neurodegenerative disorders, are still not fully understood. Future studies should aim to provide more clinical and mechanistic insights into how garlic's antioxidant properties can be harnessed to prevent or alleviate the progression of these diseases. In particular, *in vivo* and clinical trials could focus on the dosage, bioavailability, and long-term effects of garlic and its extracts on human health. Moreover, exploring synergistic effects between garlic and other medicinal plants, such as *ginger* and *onion*, could lead to novel therapeutic formulations with enhanced efficacy.

Furthermore, there is significant potential to integrate garlic into functional foods and nutraceuticals. The presence of keywords like *vegetables*, *prebiotics*, and *garlic oil* in the network suggests that garlic is increasingly being considered for use in food products that provide additional health benefits beyond basic nutrition. Future research could focus on the development of garlic-enriched foods and beverages that retain bioactive compounds, particularly those with antioxidant and antimicrobial properties. Research on food processing technologies that protect the stability and bioavailability of these compounds is essential. In addition, interdisciplinary collaboration between food scientists and nutritionists could lead to the creation of garlic-based nutraceuticals that are easy to incorporate into daily diets. These products could target specific health outcomes, such as immune boosting, gut health improvement, or cardiovascular support, thus offering consumers accessible ways to benefit from garlic's therapeutic properties.

Finally, standardization and quality control of garlic extracts should be prioritized in future research to ensure consistency and efficacy across garlic-based products. The co-occurrence of terms such as *stability* and *garlic oil* highlights the ongoing challenges related to maintaining the integrity of garlic's bioactive compounds during extraction, processing, and storage. Future studies should focus on establishing standardized protocols for the extraction and processing of garlic to ensure uniform quality in terms of bioactive content and product stability. This could involve the development of advanced analytical methods, such as HPLC or mass spectrometry, to accurately quantify bioactive compounds in garlic extracts and monitor their degradation over time. In addition, developing guidelines for the proper labeling and certification of garlic products would help build consumer confidence and ensure that the therapeutic potential of garlic is consistently delivered in commercial products.

In conclusion, the co-occurrence network of keywords reveals important trends and opportunities for future research in garlic extraction. By optimizing extraction techniques, exploring under-researched bioactive compounds, investigating garlic's role in chronic disease prevention, integrating garlic into functional foods and nutraceuticals, and establishing standardized protocols for quality control, researchers can significantly advance the field and unlock the full potential of garlic's therapeutic and commercial applications.

8 Challenges and limitations in green garlic extraction

Green extraction methods for garlic, while promising, face several challenges and limitations that must be addressed to maximize their effectiveness and scalability. These challenges stem from technical, economic, and regulatory aspects, as well as the inherent complexity of garlic's bioactive compounds.

8.1 Technical challenges

One of the most significant technical hurdles is optimizing extraction parameters for the diverse bioactive compounds in garlic, such as allicin, phenolic compounds, and sulfur-containing organosulfur compounds. Each compound requires specific extraction conditions, and balancing these to achieve comprehensive extraction remains challenging. For instance, SFE demands precise control over temperature, pressure, and solvent composition to maximize yields of targeted compounds like allicin [15,16]. Similarly, EAE relies on enzyme specificity and activity, which can be affected by pH, temperature, and extraction time [35,36]. In addition, maintaining the stability of bioactive compounds during extraction is a critical issue. Compounds like allicin are highly unstable and prone to degradation under certain extraction conditions [19]. Emerging techniques, such as PLE and IL-assisted methods, show promise but require further refinement to ensure compound integrity [8,39].

8.2 Economic and scalability issues

The scalability of green extraction methods poses another limitation. Techniques like SFE and MAE are often cost-intensive due to the need for specialized equipment and energy consumption [25,63]. While these methods are efficient on a laboratory scale, transitioning to industrial-scale operations requires significant investment and process optimization to make them economically viable. Moreover, the variability in raw garlic quality and composition can impact extraction efficiency and consistency, especially when scaling up. Factors like garlic variety, cultivation conditions, and postharvest processing influence the yield and quality of bioactive compounds, complicating the development of standardized extraction protocols [18,33].

8.3 Regulatory and sustainability concerns

From a regulatory perspective, the use of emerging solvents, such as ILs and DESs, raises concerns about safety and environmental impact. While marketed as "green," their toxicity and biodegradability profiles require further investigation to meet regulatory approval for food and pharmaceutical applications [42,49]. Life cycle analysis (LCA) studies on green extraction processes are also limited. Understanding the environmental footprint of these methods, including energy consumption, solvent use, and waste generation, is crucial for ensuring that they align with sustainability goals. The lack of comprehensive LCAs limits the ability to validate these methods as truly green [41,50].

8.4 Integration and application challenges

Integrating green extraction techniques into existing industrial frameworks is another challenge. The compatibility of these methods with downstream processing, such as formulation and packaging, is often overlooked. For instance, while NLCs and other encapsulation techniques enhance bioavailability, their incorporation into green extraction workflows requires additional research and development [41]. Finally, addressing the gap in applications beyond food science is necessary. While the health and wellness benefits of garlic are well-documented, the development of green-extracted compounds for nutraceuticals, cosmetics, and pharmaceuticals remains underexplored [47,64].

9 Future directions and opportunities

The evolving landscape of green extraction technologies offers promising future directions and significant opportunities for enhancing the extraction of bioactive compounds from garlic. As sustainability becomes an increasingly important consideration in both research and industry, the focus on refining and optimizing green extraction methods is likely to intensify. Based on the data provided, several key areas emerge as critical for the future development of these techniques.

First, there is substantial potential in further optimizing existing green extraction methods such as EAE, SFE, and PLE. The primary focus should be on improving extraction efficiency while minimizing environmental impact. For instance, optimizing the use of enzymes in EAE could lead to more effective breakdown of garlic cell walls, thus enhancing the release of valuable organosulfur compounds and other bioactives. Advances in enzyme technology, such as the development of more robust and specific enzymes, could significantly reduce the limitations currently faced in terms of reaction conditions and scalability.

Another promising area is the exploration of novel solvents and techniques that offer improved safety and efficiency. ILs and DESs, for example, have shown potential in enhancing the extraction of specific bioactive compounds while reducing the use of hazardous organic solvents. However, further research is needed to fully understand the environmental and health impacts of these solvents, particularly when used at an industrial scale. The development of more biodegradable and nontoxic alternatives could make these solvents more viable for widespread application in green extraction processes.

The integration of green extraction methods with emerging technologies such as nanotechnology also presents exciting opportunities. Nanostructured materials, such as NLCs, have already demonstrated their potential in improving the bioavailability and stability of extracted compounds. In the future, the combination of green extraction techniques with nanotechnology could lead to the development of more efficient delivery systems for garlic bioactives, particularly in pharmaceutical and nutraceutical applications. This could enhance the therapeutic efficacy of garlic-derived products while maintaining the environmental benefits of green extraction.

Furthermore, the use of computational tools and chemometric methods for the optimization of extraction processes represents another promising direction. The application of techniques such as RSM and multivariate optimization has already been shown to improve the efficiency of extraction processes. As computational power increases and software becomes more accessible, these tools could play a central role in the rapid development and scaling up of green extraction methods, allowing for more precise control over extraction conditions and better prediction of outcomes.

Sustainability considerations will also drive the exploration of circular economy principles in green extraction processes. This includes the potential reuse and recycling of solvents, as well as the valorization of garlic by-products. For example, residues from the extraction process could be repurposed as feedstock for bioenergy production or as raw material for other high-value products, thereby reducing waste and enhancing the overall sustainability of the extraction process. The development of closed-loop systems where solvents and materials are continuously reused could significantly reduce the environmental footprint of garlic extraction operations.

Finally, regulatory frameworks and consumer preferences are likely to influence the future direction of green garlic extraction. As consumers become more aware of the environmental impact of the products they consume, there will be growing demand for natural products extracted using sustainable methods. This shift in consumer behavior, coupled with stricter environmental regulations, will likely drive further innovation in green extraction technologies. Companies that can effectively communicate the environmental benefits of their products, backed by robust scientific data, will be well-positioned to capture market share in the growing natural products sector.

In conclusion, the future of green garlic extraction is filled with opportunities for innovation and improvement. By focusing on optimizing existing methods, exploring novel technologies and solvents, integrating with nanotechnology, and applying advanced computational tools, researchers and industry professionals can overcome current challenges and unlock the full potential of green extraction processes. These advancements will not only contribute to more sustainable production practices but also open up new avenues for the development of high-value garlic-derived products that meet the growing consumer demand for environmentally friendly and health-promoting products.

10 Conclusion

Based on the data provided, it is evident that the research and development in the field of green extraction processes for garlic have seen significant advancements over the years. The increasing number of publications, especially in recent years, highlights a growing interest and recognition of the importance of sustainable and environmentally friendly extraction techniques. These methods, including

EAE, SFE, PLE, and various emerging techniques such as IL-based extractions, have shown promising results in improving the efficiency, yield, and quality of bioactive compounds extracted from garlic.

One of the key findings from the reviewed studies is the enhancement of the yield and quality of organosulfur compounds, such as allicin and its derivatives, which are pivotal to garlic's health benefits. The use of green solvents and techniques has not only minimized the environmental impact but also improved the safety and sustainability of the extraction processes. In addition, the integration of these green methods with modern technologies, such as nanotechnology and chemometrics, has further enhanced the bioavailability, stability, and therapeutic potential of garlic extracts.

However, despite these advancements, challenges remain, particularly in the scalability, cost-effectiveness, and regulatory acceptance of these green methods. There is a need for further optimization and standardization of these processes to ensure consistent and high-quality outputs that can be scaled up for industrial applications. Moreover, understanding the long-term environmental impacts of these new solvents and techniques is crucial for their broader adoption. In conclusion, the future of garlic extraction lies in the continued exploration and refinement of green extraction techniques. By addressing the existing challenges and leveraging new technologies, the industry can achieve more sustainable, efficient, and economically viable methods for producing high-quality garlic extracts. This will not only meet the growing consumer demand for natural and environmentally friendly products but also contribute to the overall sustainability of the food and nutraceutical industries.

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