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Research Trends on Acrylamide Formation and Mitigation in Coffee Processing over Last Ten Years: A Comprehensive Bibliometric Study

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A B S T R A C T

Acrylamide, a potentially carcinogenic compound, forms during high-temperature food processing and has garnered significant attention in the coffee industry due to its implications for public health and food safety. This study analyzes research trends on acrylamide formation and mitigation in coffee processing over the past decade, utilizing bibliometric methods and VOSviewer software. A dataset of publications from 2014 to 2024 was examined to uncover key research themes, leading contributors, and collaborative networks in the field. The analysis reveals a growing body of research focused on understanding the mechanisms of acrylamide formation, developing mitigation strategies, and balancing quality preservation with regulatory compliance. Emerging trends, such as metabolomic approaches and advanced roasting techniques, highlight a shift towards more targeted and sustainable solutions. Additionally, the findings emphasize notable international collaborations, though further interdisciplinary research is needed to address existing gaps and enhance practical applications. This bibliometric study provides valuable insights into the scientific landscape of acrylamide research in coffee processing, offering a foundation for future studies and innovations aimed at ensuring food safety while maintaining coffee quality.

Contribution to Sustainable Development Goals (SDGs)
SDG 3 (Good Health and Well-Being)
SDG 12 (Responsible Consumption and Production)
SDG 17 (Partnerships for the Goals).

1. INTRODUCTION

1.1. Research Background

Coffee is one of the most popular drinks in the world, and its production and processing have a big socioeconomic impact. [1]. However, coffee processing has been linked to the formation of acrylamide, a potentially carcinogenic compound formed via the Maillard reaction during high-temperature treatments, such as roasting [2]. Acrylamide's presence in coffee has raised public health concerns, prompting increased regulatory scrutiny and extensive research on its formation and mitigation strategies.

Acrylamide was classified as a Group 2A probable human carcinogen by the International Agency for Research on Cancer (IARC) in 1994 [3]. Following its identification in food items in

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2002 [4], the investigation of acrylamide has proliferated across various fields, encompassing food chemistry, toxicology, and food processing technology. The intricate mechanisms underlying acrylamide formation in coffee, along with the difficulties in preserving flavor and quality while simultaneously lowering acrylamide levels, have rendered this a significant field of study.

Bibliometric analysis provides a systematic approach to evaluating research trends, identifying key contributors, and mapping collaborations and thematic focuses in scientific literature [5]. VOSviewer, a widely used tool for bibliometric visualization, enables researchers to analyze co-authorship, keyword co-occurrence, and citation networks, offering insights into the evolution and structure of research domains [6].

1.2. Literature Review

Acrylamide is a notable chemical hazard in coffee processing, primarily generated during the roasting stages where elevated temperatures promote the Maillard reaction, a complex series of interactions between amino acids and reducing sugars. This process contributes to the distinct flavor and aroma of coffee while also leading to the formation of acrylamide, a compound known for its potential carcinogenicity. The mechanisms of acrylamide formation in coffee have been elucidated over time through various studies employing bibliometric analysis to map the research developments in this field. For example, A comprehensive bibliometric study was conducted to examine various chemical hazards in coffee, highlighting the historical context of acrylamide research and identifying significant trends and research gaps. The data on publications, quotes, and models of paternity have been aggregated and analyzed, highlighting significant milestones in the exploration of acrylamide training mechanisms, thereby establishing a foundation for future investigations [7].

Recent progress has further clarified the factors that influence the synthesis of acrylamide in coffee, in particular during the fermentation and roasting processes. By researching the function of microorganisms in coffee fermentation, they added to this body of knowledge by claiming that microbial activity can change the concentration of precursors essential to the synthesis of acrylamide. Their findings imply that particular microbial species might enhance or lessen the buildup of acrylamide precursors, pointing to a possible method of regulating acrylamide levels through processing-related selective microbial management. These revelations are crucial for comprehending how the processing parameters might be adjusted to reduce the production of this hazardous substance while preserving the coffee's quality [8].

A noteworthy viewpoint is provided by Ref. [9], which broadens the conversation on acrylamide beyond coffee to include a larger range of foods. Their investigation, which draws comparisons to the coffee business, focuses on the methods for regulating acrylamide levels through different food products. They point out possible tactics that might be used to successfully reduce the production of acrylamide, like adjusting the roasting time and temperature as well as choosing different raw coffee beans. Through their bibliometric exploration of research in acrylamide in general, Ref. [9] provide a comparative framework that improves our understanding of the complexities relating to acrylamide control measures in the processing of coffee specifically.

By summarizing the contributions of these fundamental studies, it becomes evident that there is a dynamic interaction between the chemical processes of the formation of acrylamide and the variables relating to coffee processing practices. The application of bibliometric tools not only helps to map the evolution of research on acrylamide but also highlights the critical gaps in knowledge that require further investigations.

Figure 1. demonstrates the process by which roasting results in the formation of acrylamide. The process entails high-temperature heating via the Maillard reaction between the amino acid asparagine and reducing sugars, especially during the roasting of coffee beans. Acrylamide is produced exclusively under high-temperature conditions, specifically during roasting at temperatures ranging from 180°C to 250°C, and is absent in coffee cherries and raw coffee beans.

Light-roast coffee generally has higher levels of acrylamide than dark-roast coffee, as acrylamide can degrade at elevated temperatures or with extended roasting durations. Acrylamide levels in brewed coffee are considerably lower than in roasted coffee beans, as only a small quantity of the compound dissolves in water during brewing. The International Agency for Research on Cancer (IARC) has categorized acrylamide as "possibly carcinogenic" to humans, suggesting that prolonged, high-level exposure to this substance may elevate cancer risk. International health organizations, including the World Health Organization (WHO), indicate that the health benefits of coffee frequently surpass the potential risks linked to acrylamide exposure. The risk for coffee drinkers is relatively low when coffee is consumed in moderation.

1.2.1. Health Implication

Understanding these basic facts about acrylamide in coffee will continue to be crucial for the scientific community and the coffee industry as a whole, even as debates over the health effects and industry practices change. In recent years, industrial practices and new methods for reducing the presence of this potentially hazardous substance have influenced the mitigation tactics employed to lower the amounts of acrylamide in coffee products. Numerous bibliometric analyses demonstrate the advancements in technology in this field.. For example, Ref. [10] underline the importance of innovative food dehydration methods that not only preserve the flavor and quality of the coffee but actively contribute to the reduction of the formation of acrylamide. Their investigation demonstrates how advancements in drying methods, such infrared and microwave-assisted hydrating, can be used to control the thermal profiles of coffee beans and prevent the formation of acrylamide during roasting.

Recent years have witnessed a considerable evolution in the influence of acrylamide research on public health and industrial practices, driven by several bibliometric studies elucidating the health hazards linked to acrylamide intake, particularly through coffee. Acrylamide, a recognized carcinogen mostly generated during the Maillard reaction in high-temperature food preparation, presents significant health hazards. Research, including that by Ref. [11], underscores the significance of breakthrough technologies like Lab-a-Chip devices, which enhance food safety regulations by facilitating rapid testing and monitoring of acrylamide levels in food products. This technological advancement signifies a shift towards more proactive food safety measures and underscores the essential role

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of research in identifying and mitigating dangers associated with acrylamide exposure from coffee consumption.

1.2.2. Acrylamide Mitigation

In addition to physical mitigation strategies, the role of chemical treatments has attracted attention within the literature as an effective means of managing acrylamide levels. explore the influence of various adsorbents in the management of chemical residues during coffee processing, revealing that the incorporation of active carbon and other adsorbent materials can significantly reduce acrylamide concentrations in coffee products. Their results suggest that the judicious application of chemical treatments can improve food security while maintaining the integrity of the product. Ref. [12] investigate the impact of different adsorbents on the management of chemical residues in coffee processing, demonstrating that the inclusion of activated carbon and other adsorbent materials can substantially decrease acrylamide levels in coffee products. Their findings indicate that the prudent use of chemical treatments can enhance food security while preserving product integrity.

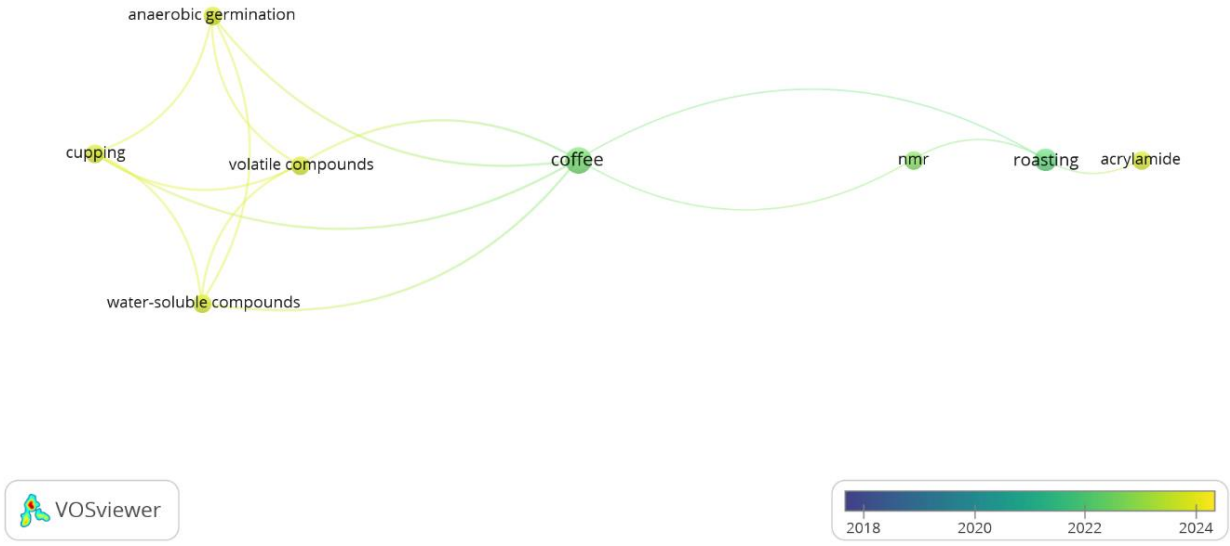

Figure 1. Acrylamide, post-harvest, roasting, and brewing in the coffee

The search enhances quality control processes in coffee production, which can significantly influence acrylamide content. [13]. Their research emphasizes the necessity for systematic methods to oversee and regulate processing factors, such as temperature and duration, which are essential in managing acrylamide development. Integrating quality processes into the production chain and employing targeted interventions enables the reduction of acrylamide levels without sacrificing the sensory qualities of coffee.

The investigation of mitigation strategies indicates a developing agreement among scholars that a comprehensive approach is crucial for the effective management of acrylamide in coffee processing. The integration of technological advancements with sustainable practices and chemical interventions highlights ongoing efforts to safeguard consumer health and enhance sector practices in response to regulatory challenges regarding acrylamide. Ongoing bibliometric analyses will likely provide additional insights into the dynamic interplay of these strategies in modeling research on acrylamide within the sector. In addition, [14] dive into the development of functional products in the food sector, emphasizing the integration of mitigation strategies for acrylamide during food processing. Its analysis shows that the industry can react to health concerns raised by consumers by supporting practices that put making safer food products first. These studies use different bibliometric tools to show that there is a growing trend toward setting operational standards that not only deal with health risks but also meet consumer demands for quality and openness.

In the context of Industry 4.0, Ref. [15] examine how automation and environmental initiatives are transforming acrylamide management procedures in the food business, particularly in coffee processing. The implementation of advanced technologies, including data analytics and automated processing systems, offers a means to more effectively reduce acrylamide generation via real-time monitoring and modifications in processing settings. This technological integration promotes food safety and optimizes operating efficiency, contributing to a comprehensive sustainability agenda. The intersection of health awareness and technological progress signifies a pivotal shift in how industry experts tackle acrylamide-related issues.

1.2.3. Research Objective

This study aims to conduct a bibliometric analysis of worldwide research on acrylamide generation and mitigation in coffee processing. The study seeks to uncover prevailing themes, key contributors, research focal points, and emerging trends within the area. This report analyzes scientific publications to offer a thorough picture of the research landscape and identify areas for future exploration, thereby aiding efforts to improve food safety and quality in coffee production. This study's findings help enhance comprehension of the scientific environment and direct future research on acrylamide reduction in coffee processing, an essential measure for assuring food safety while preserving coffee quality.

2. Materials and Methods

Data collection was performed on October 18, 2024, using the following search query: “TITLE-ABS-KEY(acrylamide AND

coffee) AND LIMIT-TO (PUBSTAGE, “final”) AND LIMIT-TO(LANGUAGE, “English”)”, which resulted in the collection of 121 documents (Figure 2). Documents from the Scopus website are saved in the form of a .ris file type (Figure 3.).

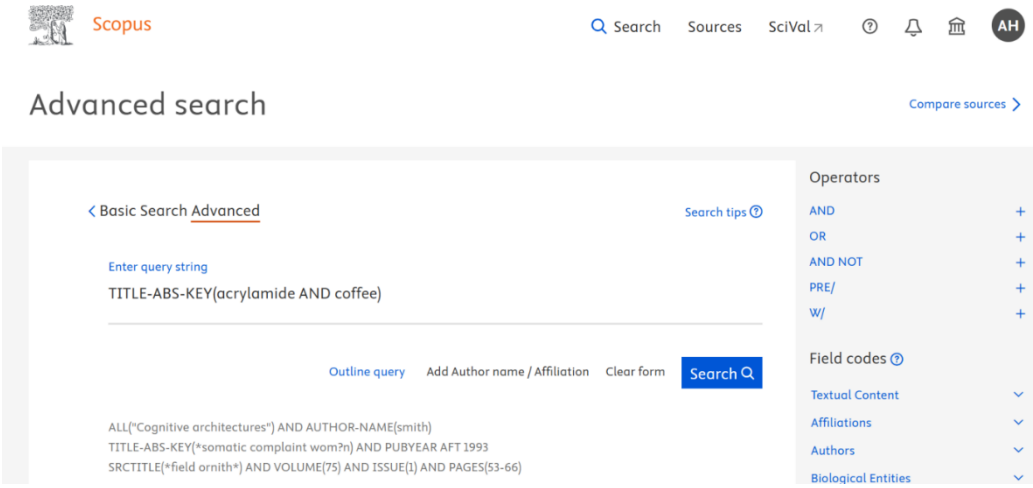

Figure 2. Scopus Keyword-Based Search

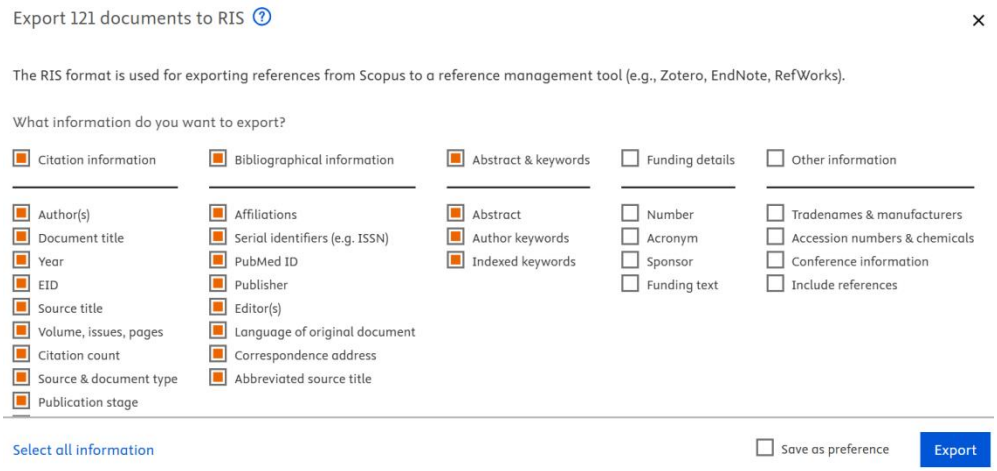

Figure 3. Scopus Document Export

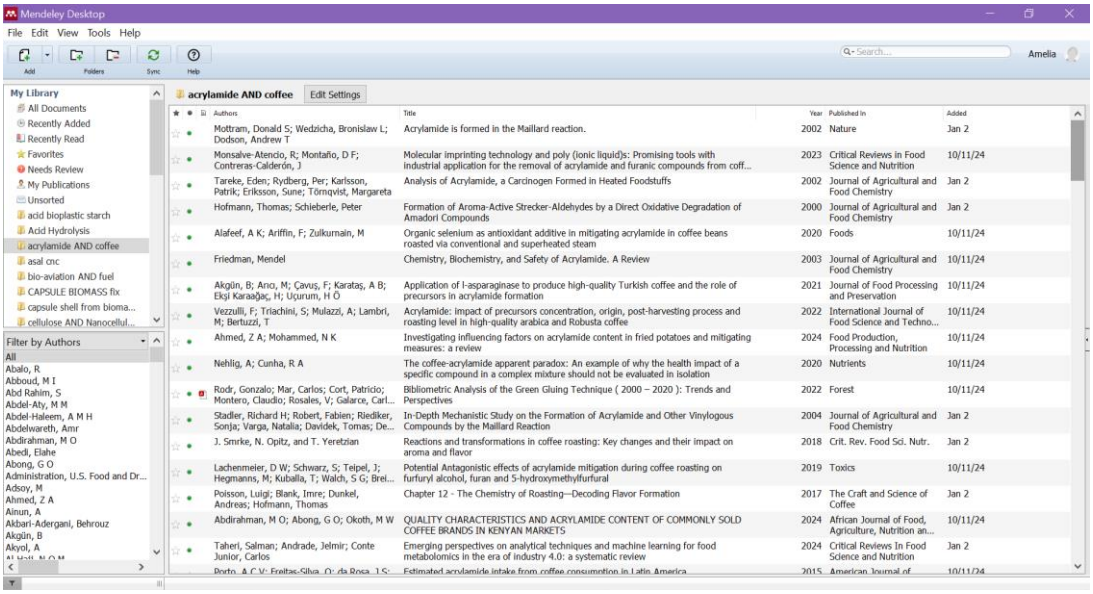

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Figure 4. Mendeley Reference Manager

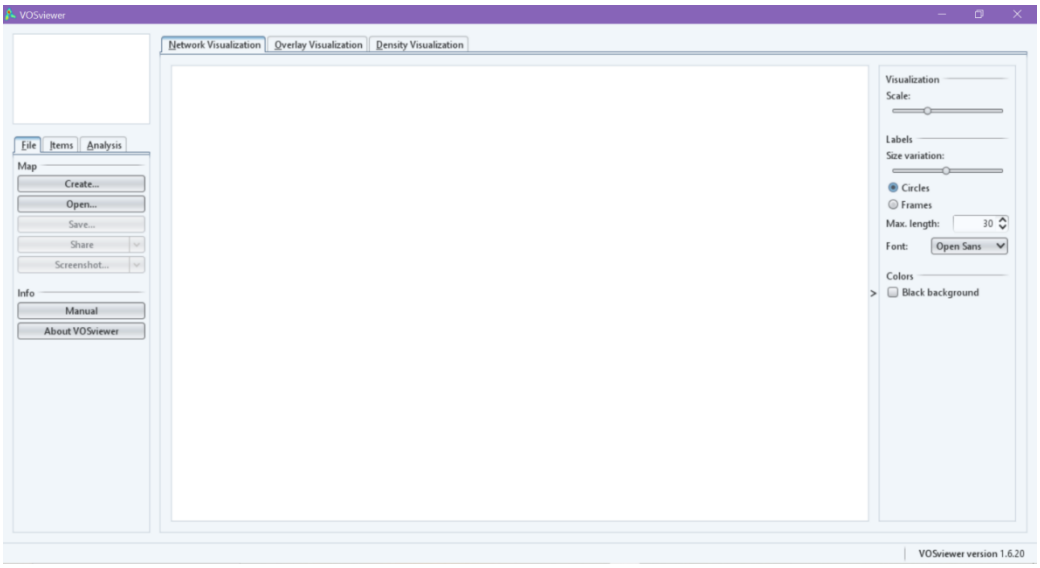

Figure 5. VOSviewer Software Version 1.6.20 for Windows

The collected data was then limited to publication years between 2015 and 2024 (or the last 10 years) and sorted using Mendeley as a reference manager to eliminate duplicates and mismatches in title, abstract, and keywords, resulting in 88 documents (Figure 4). Content analysis was conducted on several aspects, including document type, keywords, publication year, journal, and citations. After that, VOSviewer software (version 1.6.20 for Windows) was used to evaluate it (Figure 5).

3. Results and Discussion

3.1. Document Type

The type of published papers was first analyzed, as it is an indication of researchers interested in the development of acrylamide in coffee. Figure 6. shows the distribution of document types. In the last 10 years, experimental studies have become the most common studies conducted by researchers, followed by review articles and conference reports. Various experiments conducted in the laboratory are aimed at identifying acrylamide compounds in coffee that are potentially harmful to health, so there is a need to reduce acrylamide levels. Several review articles and conference proceedings have been published as part of ongoing research aimed at improving the latest knowledge regarding acrylamide in coffee.

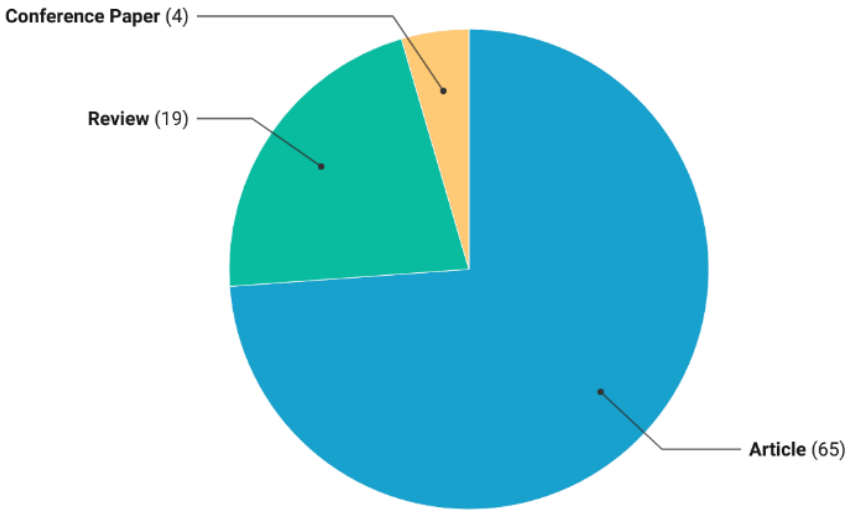

Figure 6. Diagram showing the counts of each document type.

The analysis of document types, as shown in Figure 6., provides valuable insights into the focus of research on acrylamide in coffee over the past decade. Experimental investigations constitute the most commonly published publications, succeeded by review articles and conference reports. This trend indicates an increasing interest among researchers in performing empirical studies on the formation and occurrence of acrylamide chemicals in coffee.

Experimental studies dominate the research landscape, indicating a strong emphasis on laboratory-based experiments aimed at identifying acrylamide and assessing its potential health risks. Researchers are focusing on understanding the formation of acrylamide during coffee processing, as well as exploring methods to mitigate or reduce its levels [16], [17]. This focus is crucial given the health concerns associated with acrylamide, a compound classified as a potential carcinogen by various health organizations [4].

The existence of review papers and conference reports, however less numerous than experimental investigations, underscores the ongoing endeavor to consolidate and share recent discoveries. Review articles are essential for synthesizing current information, pinpointing research deficiencies, and suggesting new avenues for future investigations. [4]. Conference reports, on the other hand, serve as a platform for sharing preliminary results, promoting discussions, and fostering collaboration among researchers in the field [18].

The prevalence of experimental studies in recent publications indicates that the research community is actively tackling the difficulties associated with acrylamide in coffee. Simultaneously, review articles and conference reports enhance the continuous endeavor to augment and refresh the corpus of knowledge, guaranteeing that academics, policymakers, and the coffee sector possess access to the most contemporary and pertinent information.

3.2. Keywords

The visual map is created based on the results of a bibliographic analysis of keywords. Keywords from published papers help describe the research and provide an index that facilitates the analysis of research trends in a specialized field [19]. A co-occurrence keyword analysis was conducted to find phrases that appear together in one or more texts, yielding 54 keywords associated with acrylamide in coffee. Keyword selection is performed to eliminate term redundancy and biased correlations within the generated visual map. The bibliographic keyword analysis results were utilized to construct a visual map comprising four clusters organized around the ten keywords exhibiting the highest connectivity and overall link strength. Table 1 indicates that the phrases "acrylamide" and "coffee" are frequently referenced in experimental literature.

Table 1. 10 Keywords with Highest Total Link Strength

No	Keywords	Cluster	Links	Total Link Strength	Occurrences
1	Acrylamide	2	53	418	74
2	Coffee	2	53	338	43
3	Chemistry	4	51	221	21
4	Human	1	46	179	18
5	Amides	2	48	166	24
6	Food Contamination	4	42	104	10
7	Female	1	28	95	9
8	Adult	1	26	89	7
9	Nonhuman	3	37	85	9
10	Male	1	26	77	6

Keywords are nouns or phrases that can efficiently convey the main idea or general importance of a research study, making it easier to analyze research trends in scientific domains [19], [20]. Three visualizations produced by VOSviewer with these terms are displayed in Figure 7. In this paper, the phrase "acrylamide AND coffee" appears as a keyword. A network depiction of the clusters corresponding to each topic area under investigation is shown in Figure 7(a). An overlay visualization approach showing the years that research on the most sought-after terms was done is shown in Figure 7(b). The density visualization of the frequency of phrase usage in the study using density visualization is shown in Figure 7(c). The color of a phrase can be used to determine how often it is used. The brightness of the color of a phrase is strongly related to its frequency [21].

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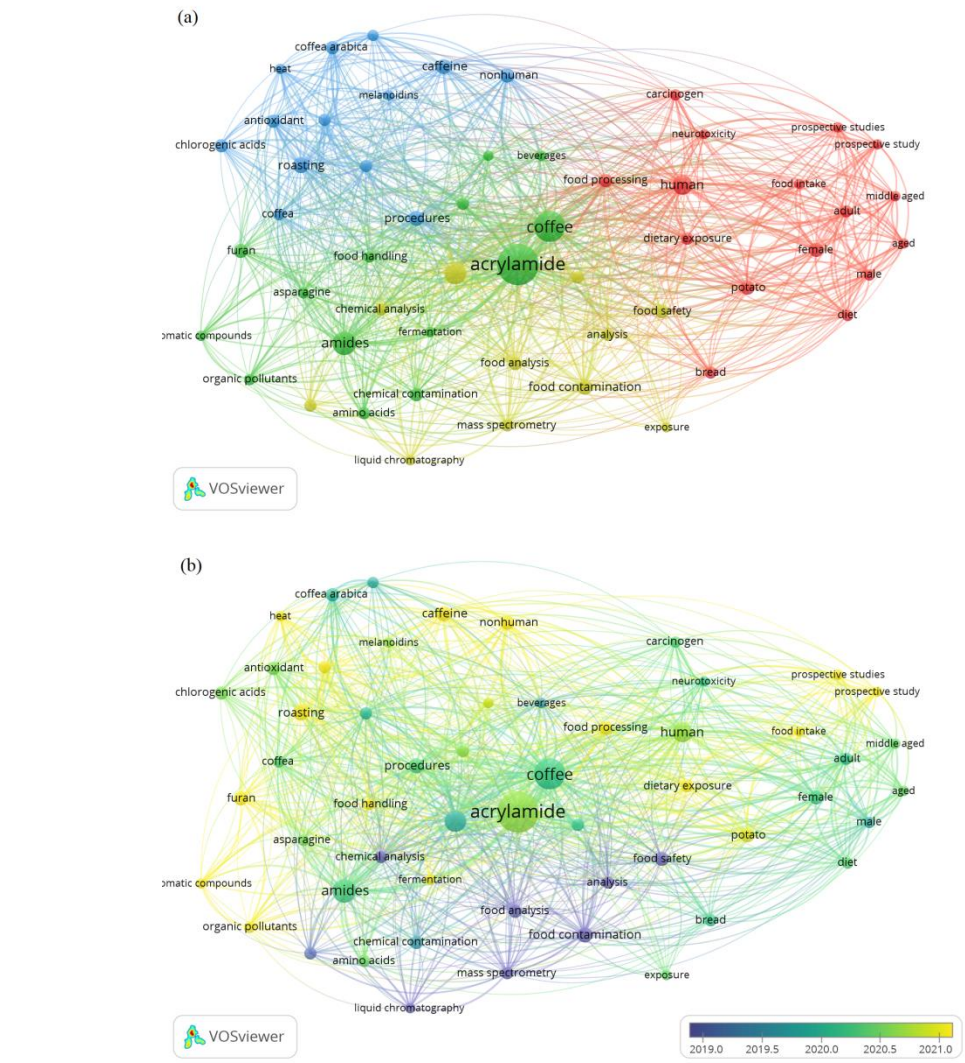

Figure 7. Network Visualization (a), Overlay Visualization (b), and Density Visualization (c) of Acrylamide-Coffee.

3.3 Year of Publication

In 2015, a book chapter titled "Analysis of Acrylamide in Coffee" was the first study found [22]. Figure 8. illustrates the highest level of scientific interest in acrylamide in coffee, with 17 publications published in 2021. Up to October 2024, 12 documents were released, and it is anticipated that this number will increase until the end of December 2024.

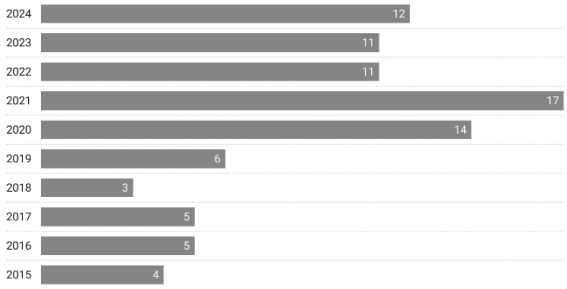

Figure 8. Distribution of the total number of documents released year 2015-2024.

The increase in publications about acrylamide in coffee indicates an increasing scholarly interest in the subject, as demonstrated by the data shown in Figure 3. The initial study, a book chapter entitled Analysis of Acrylamide in Coffee, was published in 2015 [22]. This initiated a series of study efforts focused on comprehending the occurrence, production, and health effects of acrylamide in coffee.

The zenith of scholarly interest in this topic transpired in 2021, with 17 publications, constituting the largest annual output to date. This increase may be ascribed to heightened awareness of acrylamide as a potential health hazard and its designation as a carcinogen by health organizations, likely prompting researchers to concentrate on discovering and reducing its creation during coffee processing [16].

By October 2024, 12 documents have been released, and this figure is expected to increase by year-end. The persistent findings indicate that acrylamide in coffee is a critical study focus, propelled by enduring concerns regarding food safety, public health, and regulatory initiatives focused at diminishing acrylamide concentrations in food items [3].

The consistent rise in articles from 2015 to 2024 underscores the ongoing interest in comprehending acrylamide in coffee. Researchers are diligently enhancing a corpus of information aimed at informing industry practices and public health policy.

3.3. Author Productivity and Affiliation Country

VOSviewer evaluates author collaboration when they report research with a specific focus. 6 authors are collaborating, namely Ishihara, J from Azabu University, Sagamihara, Japan; Iwasaki, M from National Cancer Center Japan, Tokyo, Japan; Kotemori, A. from Azabu University, Sagamihara, Japan; Sawada, N from Epidemiology and Prevention Group, Center for Public Health Sciences, National Cancer Center, Tokyo, Japan; Sobue, T from Osaka University, Suita, Japan; and Tsugane, S from ; have the strongest link strength with a total link strength of 15. It turns out that the 6 authors are all affiliated with the same in Japan. Figure 4 displays the author collaboration links with the highest link strength.

VOSviewer evaluates authors from Spain as the country with the most publications, with 11 documents, which is followed by Poland (9), Italy (9), the United States (8), Germany (7), Chine (5), and Japan (2) ((Figure 9). Even if authors from Japan only publish 2 papers, they have the strongest link strength with a total link strength of 15. This could be a result of Japanese authors working together with authors from other nations to increase their overall link strength value.

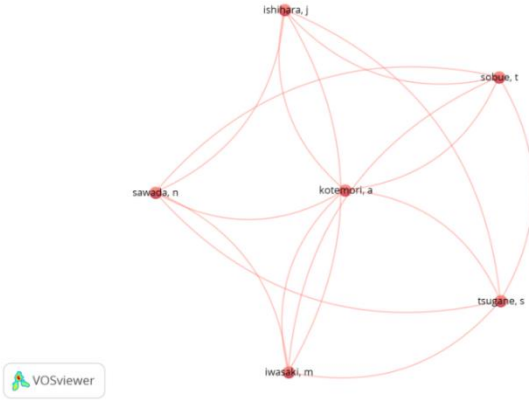

Figure 9. The Author Collaboration Network with the highest Total Link Strength.

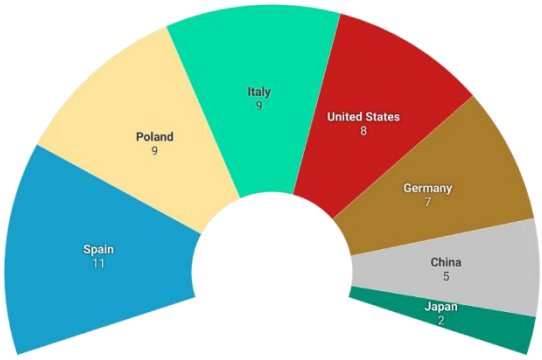

Figure 10. Affiliation Country of Publications.

The VOSviewer analysis indicates that writers from Spain are predominant in the number of publications about the research topic, contributing 11 papers. Authors from Poland (9), Italy (9), the United States (8), Germany (7), China (5), and Japan (2) closely follow them, as illustrated in Figure 10. Although Japanese authors have published only two works, they demonstrate the highest total link strength, quantified at 15. This data is compelling, indicating that Japanese authors are significantly integrated into the research network, perhaps owing to their robust collaborative endeavors with international peers.

The substantial link strength of Japanese writers, despite a comparatively low publication count, undoubtedly signifies their active participation in notable co-authorship and international collaboration. This worldwide collaboration can augment the visibility and influence of their work, despite their publication output being less substantial than that of certain other nations [23], [24]. This discovery highlights the significance of collaboration in scientific research since robust partnerships can enhance the impact and scope of individual researchers and their contributions [25].

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Furthermore, the varied representation of nations in this analysis underscores the international scope of the research on this subject, incorporating contributions from Europe, Asia, and the United States. The significant involvement of Spain, Poland, and Italy indicates that European nations are at the forefront of knowledge advancement in this domain, whilst the participation of the United States and Asian countries such as Japan and China reflects widespread global interest in the topic [26].

In summary, whereas Spain excels in publication quantity, Japan is distinguished by its robust link strength, highlighting the significance of international collaboration in enhancing research visibility and impact [27]. These findings illustrate the interdependent nature of the worldwide research community and the essential importance of collaboration in scientific progress [28].

3.4. Most Documents Published in Journals and Most Cited Documents

Additionally, most of the journals listed in Table 2 are categorized in the first and second quartiles (Q1 and Q2), based on their impact factors. Journals in these quartiles are recognized for their high-quality research output and wide readership [29], [30]. The prevalence of publications in Q1 and Q2 journals signifies that this discipline garners substantial academic interest, and the generated information is presumably enhancing wider dialogues in food safety, chemistry, and public health [31]. The prominence of this research in prestigious publications is crucial for shaping subsequent studies, directing policy, and informing industrial practices [32]. Notably, the high citation count across several of these journals further underscores the relevance and influence of the research, as it demonstrates that these studies are not only widely read but also frequently referenced by other scholars and professionals in the field [33].

The concentration of publications in Q1 and Q2 journals also indicates that this field of study attracts significant scholarly attention, and the knowledge produced is likely to contribute to broader discussions in food safety, chemistry, and public health. The visibility of this research in high-impact journals is essential for influencing further studies, guiding policy, and informing industry practices [34].

Table 2. Journals with the highest number of publications on "acrylamide AND coffee"

Journal Name	Number of Relevant Documents	Highest Quartile*)	Total Cites	Most Cited
Foods	12	Q1	167	[35]
Journal of Food Processing and Preservation	4	Q2	29	[36]
Nutrients	3	Q1	89	[37]
PLoS One	3	Q1	40	[38]
Journal of Chromatography	3	Q2	155	[39]
Food Chemistry	3	Q1	73	[40]

3.5. Future Research Need

Future research must prioritize interdisciplinary strategies to tackle the complexities associated with acrylamide formation and mitigation in coffee processing. The development of innovative roasting technologies that reduce acrylamide formation while maintaining the sensory qualities of coffee, including flavor and aroma, is a critical area of focus. Microwave-assisted roasting, infrared heating, and controlled atmosphere roasting present potential opportunities; however, they necessitate additional investigation and refinement [41], [42]

Another focus area is the application of omics technologies, such as metabolomics and genomics, to clarify the biochemical pathways involved in acrylamide formation. These insights may facilitate the identification of biomarkers or genetic traits in coffee beans associated with decreased acrylamide precursors [43]. Furthermore, investigations into consumer perceptions and educational initiatives concerning acrylamide mitigation strategies may facilitate the alignment of scientific progress with market acceptance [44].

Future research should examine the environmental sustainability of proposed mitigation techniques, ensuring alignment with global initiatives aimed at reducing carbon footprints in food processing. The incorporation of sustainability metrics in assessing acrylamide mitigation technologies may enhance their adoption and ensure long-term viability [45].

4. Conclusion

This study offers a comprehensive bibliometric analysis of research trends on acrylamide formation and mitigation in coffee processing, employing VOSviewer to visualize global research outputs, collaborations, and thematic developments. Over the past decade, the growing scientific interest in acrylamide has been driven by its potential health risks and regulatory implications. Key research domains include uncovering the mechanisms of acrylamide formation, developing effective mitigation strategies, and reconciling food safety with quality preservation in coffee production. The analysis highlights significant contributions from leading researchers and institutions in food science and toxicology, along with notable international collaborations. These efforts underscore the importance of interdisciplinary research that bridges advancements in food chemistry with practical processing technologies. Emerging trends, such as metabolomic approaches and advanced thermal processing methods, signal a shift towards precision-driven and sustainable solutions to reduce acrylamide levels in coffee. This study provides critical insights for future research by identifying areas of strength and gaps in the existing literature. Priority should be given to refining mitigation strategies that maintain the sensory attributes of coffee, exploring alternative roasting techniques, and enhancing public awareness of food safety. Additionally, fostering stronger international partnerships and improving knowledge dissemination will be essential in addressing the multifaceted challenges posed by acrylamide in coffee processing. By synthesizing a decade of research, this bibliometric analysis serves as a valuable resource for both researchers and industry stakeholders, guiding focused and impactful studies. It ultimately aims to ensure the safety and quality of one of the world's most popular beverages while contributing to public health and sustainable development goals.

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