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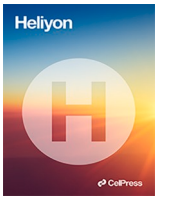

Research article

A bibliometric analysis of ohmic heating on food processing in the last two decades

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ABSTRACT

Novel food processing technologies have been devised to cater to the specific requirements of consumer products and tackle the challenges associated with conventional food processing technologies. Ohmic heating is a contemporary thermal-process technology with advantages for time efficiency, improved sensory and functional quality, and enhanced energy efficiency. This bibliometric investigation aimed to analyze the level of scholarly research on ohmic heating within the field of food research over the past twenty years (2003–2023). The findings indicate an upward annual growth rate of 11.09 % in the subject of food-related ohmic heating research. A total of 769 publications have been published, involving 1841 authors. Brazil is recognized as the nation with the most research contributions while Sastry, S.K., is the most productive author, and Teixeira, J.A. is the most collaborative author. Review studies examining the impact of ohmic processes on the nutritional composition of fruits, vegetables, and grains have garnered the highest number of citations. Innovative Food Science and Emerging Technologies and the Journal of Food Engineering have emerged as the most influential journals in this field. Keywords such as "ohmic heating," "electroconductive heating," and "joule heating" are commonly used in academic publications on the application of ohmic heating in the food industry. Recent trends in this field focus on aspects such as extraction procedures, pasteurization, physicochemical components, and energy usage. Ohmic heating has a bright future. Rapidly growing research shows strong interest, especially recently, because of attractive advantages such as energy efficiency and sustainability. International collaborations will expand its applications in the food industry. Challenges include high capital costs, maintenance, and unclear regulations. Future research should focus on cost-effective materials, thermal stability, food safety, and broader applications. With a clear path, the food industry can adopt ohmic heating technology as affordable and ecofriendly technology more efficiently.

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1. Introduction

Various difficulties that arise in traditional food process technologies have prompted new food process technologies. The primary challenges in enhancing conventional heating technology within the context of heat-applied food process technology are the extensive use of heat sources, prolonged heating duration, and the deterioration of product quality [1]. In contrast to traditional heat technologies that employ conduction, convection, or radiation processes for pathogen and enzyme inactivation and food preservation, contemporary heat technologies use electromagnetic fields or electrical conductivity to induce heat through dipole molecular rotation and ionic migration, thereby substituting electric fields or electrical conductivity. This substitution reduces the heating time compared with that in conventional heating systems [2]. In addition to its time efficiency, this heating technology has other advantages including energy savings, improved sensory qualities, and enhanced functional features when compared with traditional heating methods. Consequently, this emerging technology holds considerable promise for future applications [3]. Several recent advancements in heat technologies include microwave heating, radiofrequency heating, infrared heating, induction heating, and ohmic heating [1,4–6].

Ohmic heating, also known as Joule heating, electro-heating passing, or electroconductive heating, is a recent thermal processing technique in which an electric current is sent through food, generating heat owing to the electrical resistance of the food [7–9]. Unlike microwave and radiofrequency heating, the penetration depth of ohmic heating is unlimited. However, in ohmic heating, the electrode must be in contact with food containing sufficient volumetric heat to modulate energy. In contrast to regular thermal processing, ohmic heating uniformly heats all parts of food, producing a high-quality product with minimal nutrient loss [8,10]. Ohmic heating helps maintain nutrients by preventing the overheating of some areas of the product [8]. This technique can also heat larger food particles (up to 2.54 cm) at a uniform heating rate, which conventional heating cannot achieve [10,11]. Ohmic heating is promising for food processing, including heating liquid foods containing large particles such as soups, stews, and fruit slices in syrups and sauces, as well as heat-sensitive liquids [8,11–14]. Ohmic heating presents the food industry with the opportunity to manufacture products of superior quality, enhanced value, and improved nutritional preservation [7,15]. Ohmic heating also exhibits good performance in preserving the nutrient and phytochemical contents and sensory properties of food products [16–20]. In addition, the production of furan, a carcinogenic component formed during heating, occurs at a lower rate in ohmic heating than in conventional heating [21]. Nevertheless, ohmic applications in the food industry have some disadvantages, including the potential degradation of heat-sensitive nutrients such as vitamins and polyphenols, higher costs for equipment, and the need for meticulous process control to ensure uniform heat distribution. Ohmic heating can become particularly challenging at a large-scale industrial level, where particle size and food composition variations can impact heat distribution [22,23].

Bibliometric research is widely recognized as a statistical approach employed by scholars to assess the outcomes and impacts of authors, institutions, and journals within a specific field of knowledge and scholarly publications [24–28] and thereby to acquire comprehensive and reliable data for a specific subject. This method encompasses utilizing a range of pertinent information, including details on researchers, institutions, countries of origin, journals, and relevant keywords [29–31]. In recent years, bibliometric analysis has gained popularity across various academic disciplines [25,26,30,32–36]. This approach allows for an examination of views, issues, and the progression of scientific research while providing valuable insights to inform future research [37–39].

Although numerous bibliometric studies have been undertaken, only one specifically addresses the topic of ohmic heating. Silva et al. [40] performed a bibliometric investigation of the potential applications of ohmic heating in the food industry. However, the author employed the Web of Science as the analytical database, which is constrained by only including publications from 2010 to 2022. Hence, the primary objective of the current research was to conduct a bibliometric examination of ohmic heating technology within the food industry using the Scopus database, concentrating on literature published between 2003 and 2023. Scopus is a web-based, multidisciplinary, comprehensive indexing and abstraction database developed by Elsevier Co. Scopus provides bibliometric data from peer-reviewed articles published in various disciplines and facilitates connections to documents in its database. The database allows analysis and visualization of scientific research productivity in previous years [41,42]. Scopus has been widely used as

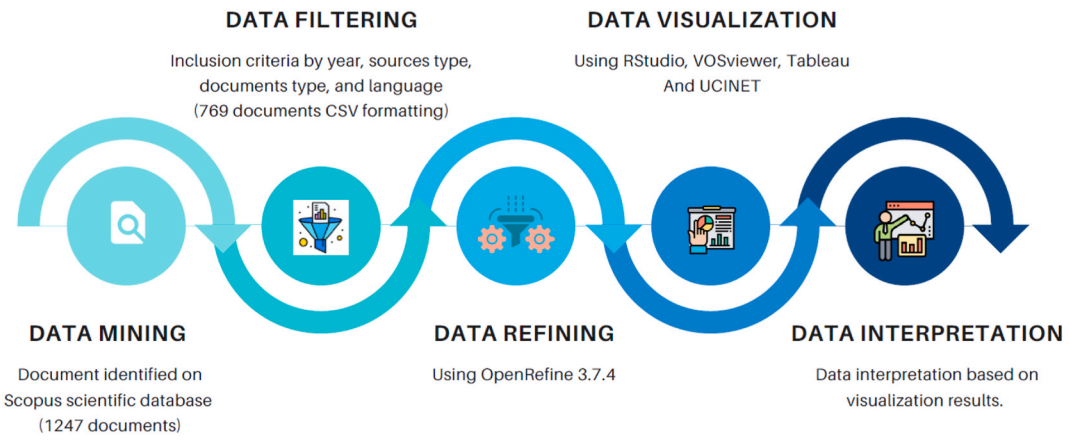


Fig. 1. Outline search strategy for bibliometric analysis.

the main data source in bibliometric analysis by previous researchers [32,43,44].

This study aims to quantitatively evaluate existing literature, identify key contributors, and discern patterns and gaps in scientific publications on food ohmic heating over the past 20 years. We examined global publication trends, contributions by country, affiliation, and international collaborations, the most prolific and collaborative authors, the most cited documents, and research focuses and trends through keyword analysis. This comprehensive mapping is expected to benefit the research community by evaluating the scientific landscape, informing decision-making, identifying potential collaborations, and enhancing the quality and impact of research in food ohmic heating.

2. Methodology and data analysis

This bibliometric review outline strategy was conducted methodically, involving several distinct steps, as shown in Fig. 1. Data used in this study were obtained from the Scopus database (https://www.scopus.com). To ensure consistency and mitigate the potential impact of data alterations, data gathering was conducted on a single day, September 22, 2023. The search terms employed comprised a combination of the title, abstract, and keywords, specifically focusing on the phrase "ohmic heating," in conjunction with the broader category of "food." In total, 1247 documents were acquired. The scope of the search was further restricted to include only materials in the last two decades that were published between 2002 and 2024 **(**specifically from January 2003 to September 2023**)**, written in English, sourced from journals or conference proceedings, and classified as either articles or conference papers. The database search techniques employed included the following criteria: ((TITLE-ABS-KEY("ohmic heating") AND ALL(food)) AND PUBYEAR >2002 AND PUBYEAR <2024 AND (LIMIT-TO LANGUAGE, "English")) AND (LIMIT-TO(SCRTYPE, "J") OR (LIMIT-TO(SCRTYPE, "p")) AND (LIMIT-TO(DOCTYPE, "ar") OR (LIMIT-TO(DOCTYPE, "cp")). In total, 769 documents were acquired within the given restrictions. Obtained data were downloaded in the CSV format and subsequently assessed for database integrity using Microsoft Excel. The assessment encompassed the verification of author information, categorization of the journal, examination of the article title and abstract, and identification of duplicate documents within the database. Data were cleaned using OpenRefine 3.7.4, an open-source software tool (https://openrefine.org), which mitigates data bias by consolidating words with varying spellings that convey the same meaning. For instance, this involves merging terms such as "Ohmic heating" and "ohmic heating," as well as "sublethal injury" and "sublethal injury." Additionally, this addresses the issue of plural and singular forms, such as "biopolymer" and "biopolymers" [30]. Data obtained from OpenRefine were subsequently used for bibliometric analysis.

The data obtained from OpenRefine were additionally analyzed using VOSviewer (version 1.6.18.0), the RStudio bibliometric package (version 4.3.1), Tableau (version 2023.2), and UCINET 6 for Windows [45]. VOSviewer software was used to generate a visual representation of the interconnected network involving nations, authors, and affiliations that made significant contributions to food ohmic research. Data analysis was conducted using RStudio to visually represent primary information trends in articles, journals, and term analysis. Tableau was employed as a data visualization tool to examine annual journal production and citations and study the contributions of individual countries to food-related ohmic heating research while UCINET was used to visualize interactions of those authors with the highest collaborations. The UCINET visualization is a representation of the secondary dataset depicted as an undirected and weighted graph G (V, E), where V and E represent the nodes and edges, respectively, connecting the nodes in the network. Author nodes (actors) represent individuals while edges symbolize the relationships between them. If two authors collaborate on an article, then a relationship exists between them in the graph and shows symmetry. The weight of an edge represents the frequency of collaboration between two authors in writing an article [46].

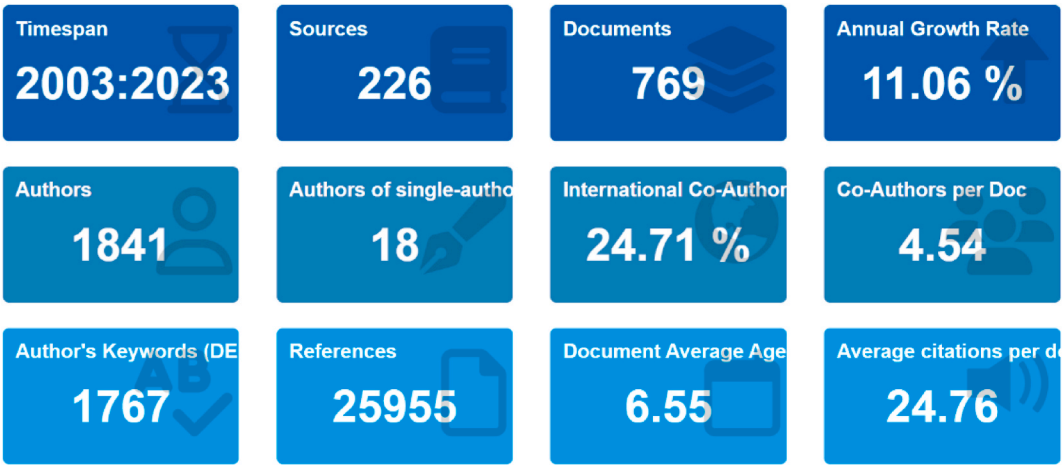


Fig. 2. Main information of bibliometric data of ohmic heating research in the food field from 2003 to 2023.

3. Bibliometric study of ohmic heating in the food field over the last two decades

3.1. Main information data

A total of 769 journal papers on ohmic heating in the food domain were published in the English language during the past 20 years. Articles were published from 226 journals and proceedings sources, encompassing the contributions of 1841 writers. The average annual document productivity was 11.6 %. Based on an analysis of the documents provided, the average number of citations per document was 24.76. Fig. 2 presents the key findings of the bibliometric analysis conducted on the application of ohmic heating in the food industry.

3.2. Analysis trends of publication

The trajectory and pace of advancement in this field are contingent on the quantity of scholarly articles. Over the past 20 years, a total of 769 documents were recorded, comprising 727 journal articles and 42 conference papers published in proceedings. The trend in the number of publications and research citations related to ohmic research in the food sector is presented in Fig. 3. The number of published studies has notably increased over the past two decades. Data indicate a notable upward trajectory, particularly throughout the past five years during which the proportion of publications increased to 45.9 % of the total. In 2021, the maximum number of publications was 91, comprising 85 journal articles and 6 conference papers, although the number of publications declined by 2022 and 2023. However, data for 2023 only covered the first seven months. Therefore, the number of publications may increase during the remaining three months of that year. Fig. 3 illustrates that the proportion of publications originating from journals surpasses that of the documents published in proceedings.

The frequency of citations in scholarly publications has varied over time. The highest citation counts were in 2005, 2015, and 2017, surpassing 1300 citations in comparison to those in other years. Furthermore, the number of publications significantly increased between 2019 and 2022, whereas the number of citations received by these documents substantially decreased from 2020 to 2023.

3.3. Analysis of contribution by country

Sixty countries actively participated in disseminating research related to food ohmic heating. The countries with the most

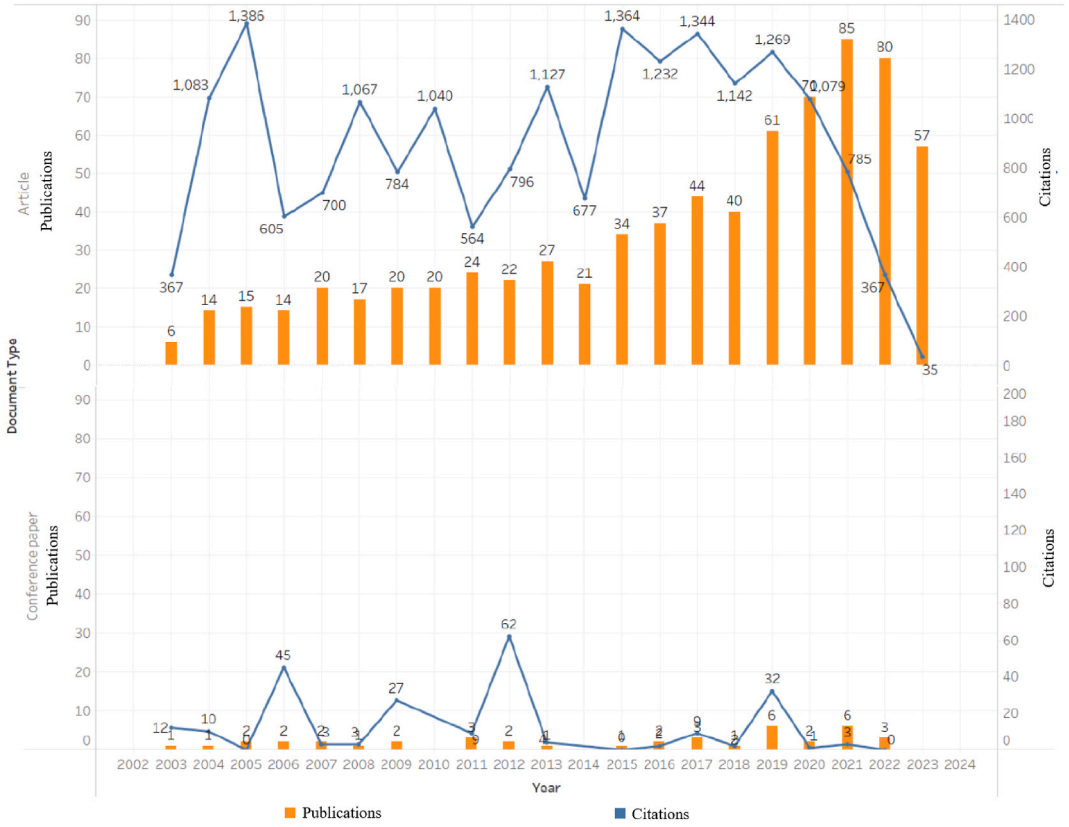
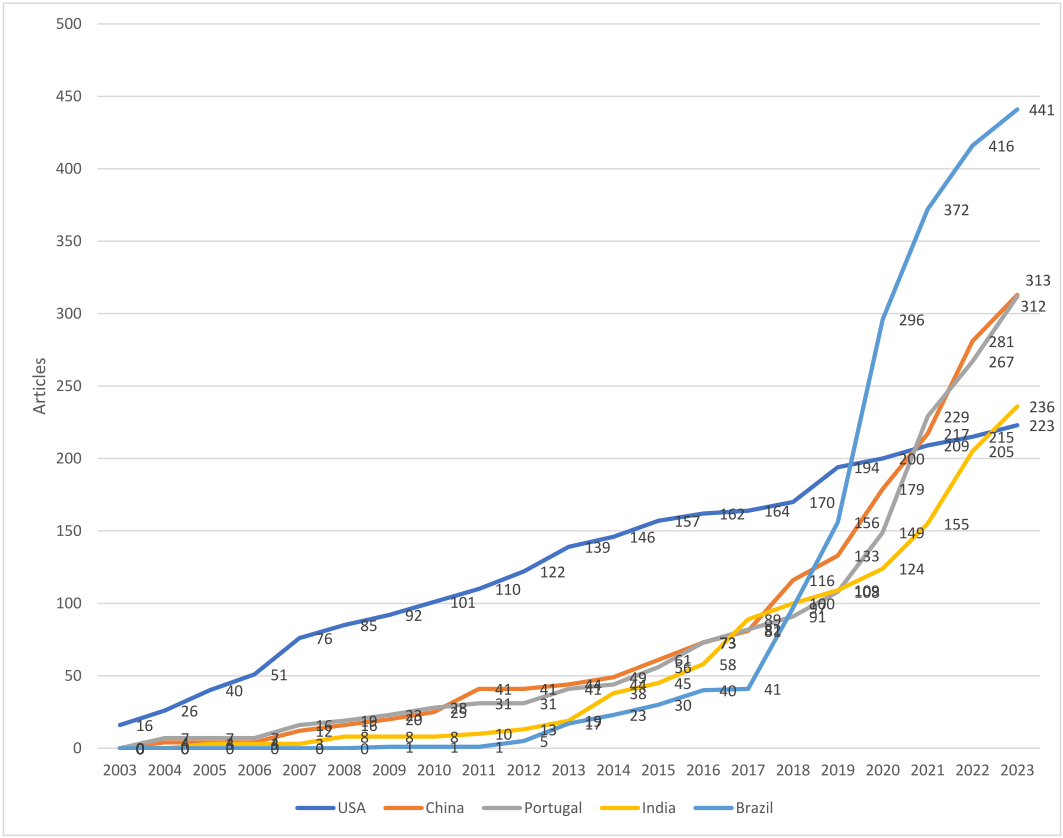


Fig. 3. Trends in the number of publications from 2003 to 2023.



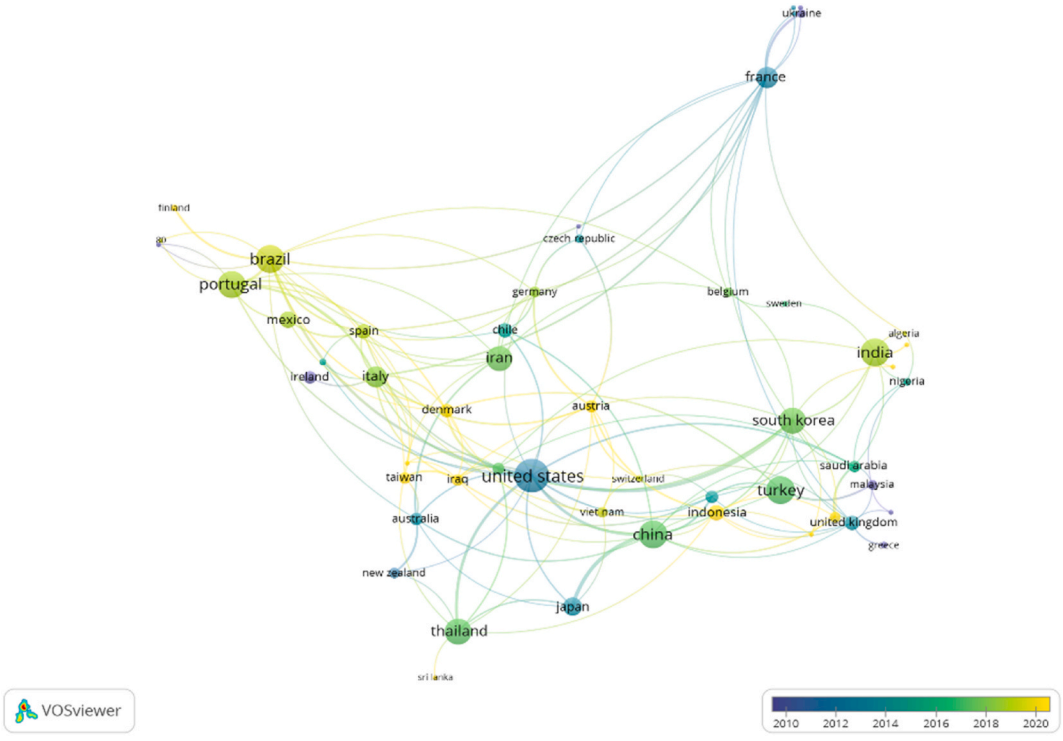


Fig. 4. a) Publication productivity by country, b) coauthorship analysis by country, and c) number of documents with collaborative article authorship by country.

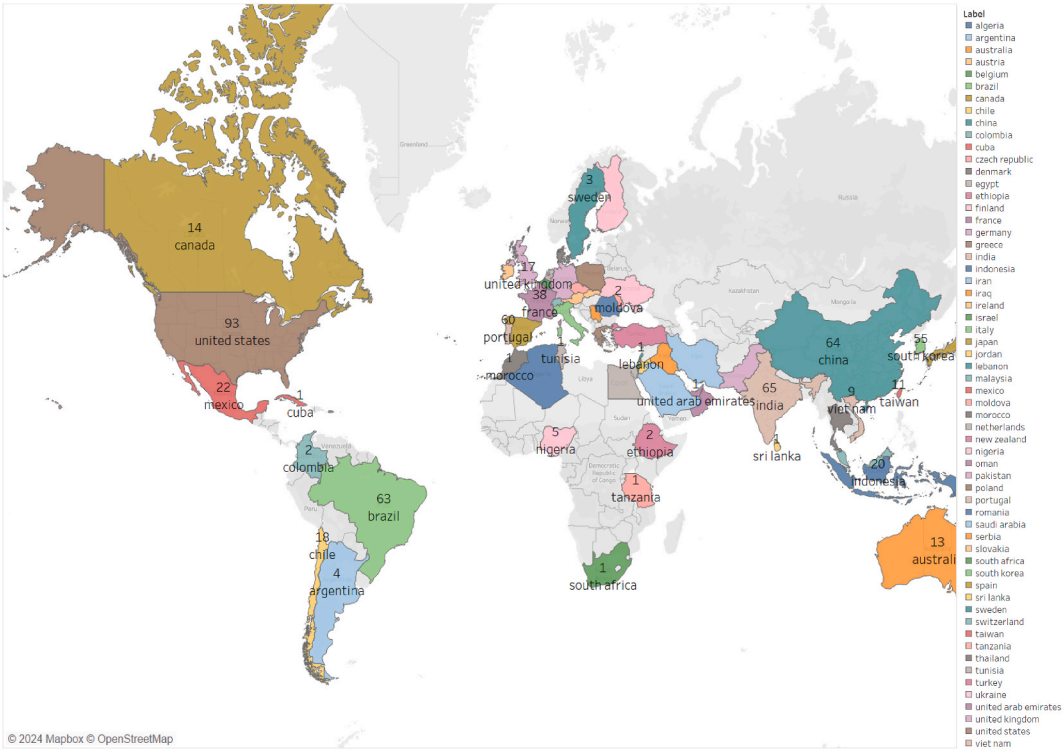


Fig. 4. (*continued*).

significant author productivity were Brazil, China, Portugal, India, and the United States. The publishing production rate among the five countries under consideration is shown in Fig. 4a. In 2003, the United States emerged as the nation with the most extensive publication output, with 16 articles. However, as of mid-2023, the United States has dropped to fifth position, producing 223 documents in total, with an average of 11.15 documents per year. Conversely, Brazil exhibited a notable trend in publishing output, commencing with a solitary publication in 2009 and subsequently experiencing a substantial surge to 41 publications in 2017. This upward trajectory continued, culminating in a total of 441 publications by 2023, with an average annual publication rate of 31.5.

The bibliometric study conducted using VOSviewer (Fig. 4b) reveals that collaborative authorship was observed in 53 of the 60 nations involved. The presence of a larger and more vividly colored circle notation at the location representing the United States signifies a higher degree and longer duration of collaboration compared with that in other countries; the intensity of the network color corresponds to the duration of the collaboration, with darker hues indicating a longer period of collaboration, whereas a lighter yellowish color signifies that writing collaboration commenced within the past year. Indonesia, Austria, Iraq, and Denmark have recently initiated collaborative authorship networks. Fig. 4c illustrates the aggregate count of publications involving coauthorship among various countries. The United States has the highest number of publications, with 93 documents. India had 65 documents while China, Turkey, and Brazil had 64, 64, and 63 documents, respectively.

3.4. Author trends analysis

3.4.1. Author contribution by affiliation

Five affiliates represented the most prominent publishing trend in ohmic heating research within the food industry. The cumulative count of articles and corresponding growth rates for the five affiliates over the examined period is shown in Fig. 5a. The University of Minho in Braga, Portugal, has the largest number of articles, totaling 160 in 2023 and is closely followed by China Agricultural University in China, which has 130 articles, and Kasetsart University in Thailand, which has 99 articles. The productivity data of the top five affiliates over two decades is shown in Fig. 5b. The University of Minho in Braga exhibited a notable upward trend in output from 2015, culminating in a peak level of productivity in 2023. China Agricultural University experienced notable growth in publication output since 2006, positioning this as the second most productive institution in terms of scholarly output, following the University de Minho in Braga.

3.4.2. Author productivity and collaboration

A comprehensive analysis was conducted on 769 scholarly journal publications and papers related to ohmic heating in food. This extensive body of research involved the collaborative contributions of 1841 authors. Over the past two decades, Sastry, S.K., has demonstrated the highest levels of authorship, producing 47 documents. This was followed by Texeira, J.A., with 38 documents while

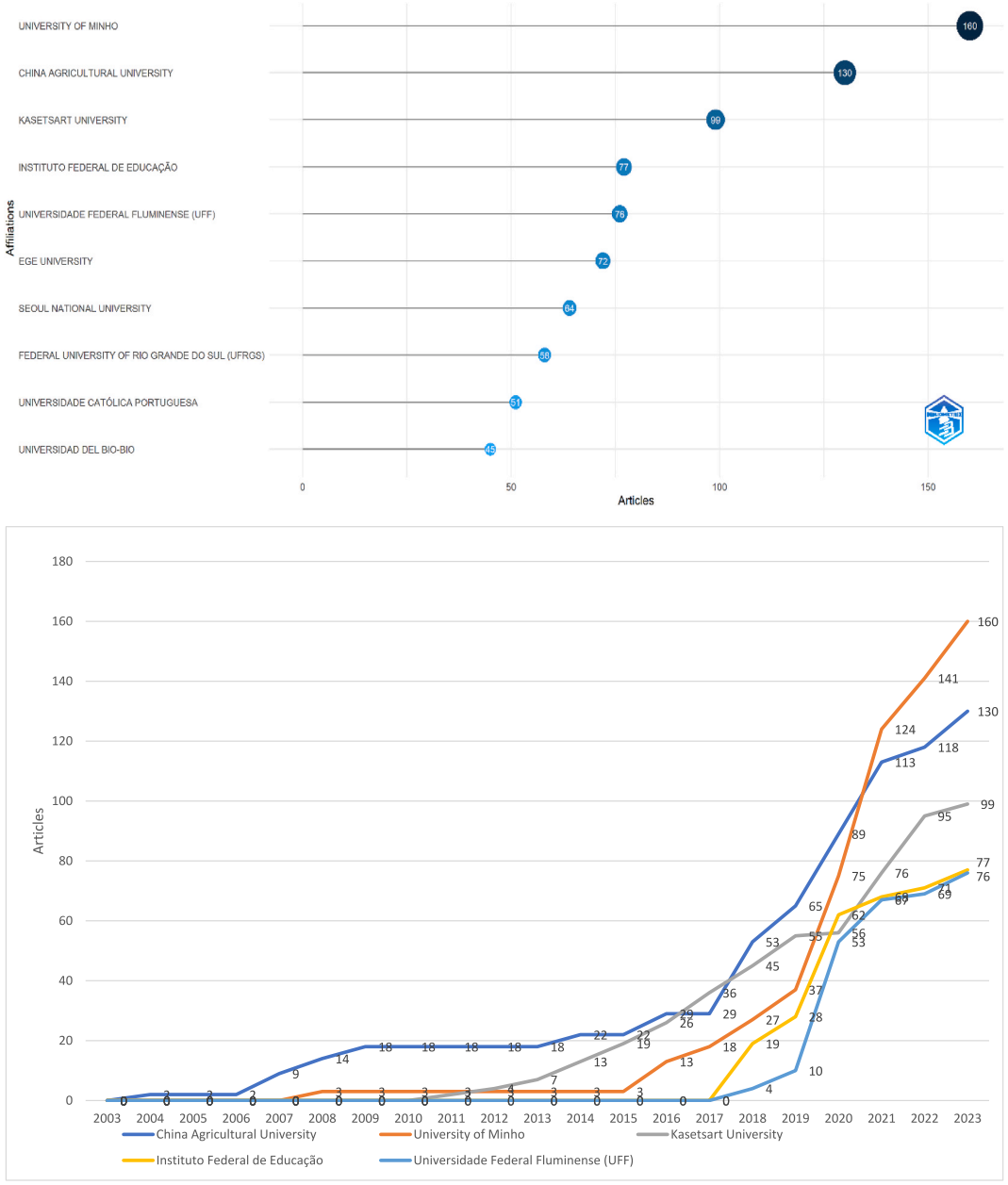


Fig. 5. a) Most relevant affiliation of author, b) author affiliation's production over time.

Pereira, R.N., secured third position with 33 publications. Trends in publication productivity and cumulative number of authors during the period spanning from 2003 to 2023 are shown in Fig. 6. Sastry and Texeira have made significant contributions to ohmic heating through their publications since 2003, and the activities of both authors have been evident for nearly all years evaluated. In 2018, Cruz, Freitas, and Silva commenced scholarly writing. However, in 2020, these three writers exhibited the highest level of productivity, producing a total of 10 papers within a single year.

The top 10 authors who have produced the greatest number of publications over the past two decades are shown in Table 1. The authors Teixeira, J.A., Pereira, R.N., and Vicente, A.A. are linked with Universidade do Minho, Portugal, and have contributed to 99 publications. Cruz, A.G. and Silva, M.C. are Brazilian authors who are associated with the Instituto Federal de Educação Ciência e Tecnologia do Rio de Janeiro while Freitas, M.Q. is associated with the Universidade Federal Fluminense in Brazil. The collective output of these three authors amounted to a cumulative publication count of 68. Sastry, S.K., a researcher affiliated with Ohio State University in the United States, has made a significant scholarly contribution with a total of 47 works in this field.

Sastry began publishing in 1976 with a conference paper entitled "Artificial Curing for Onions-Progress Report," which was published in the American Society of Agricultural Engineers' paper, Pap ASAE For Winter Meet. In future scholarly works, Sastry's

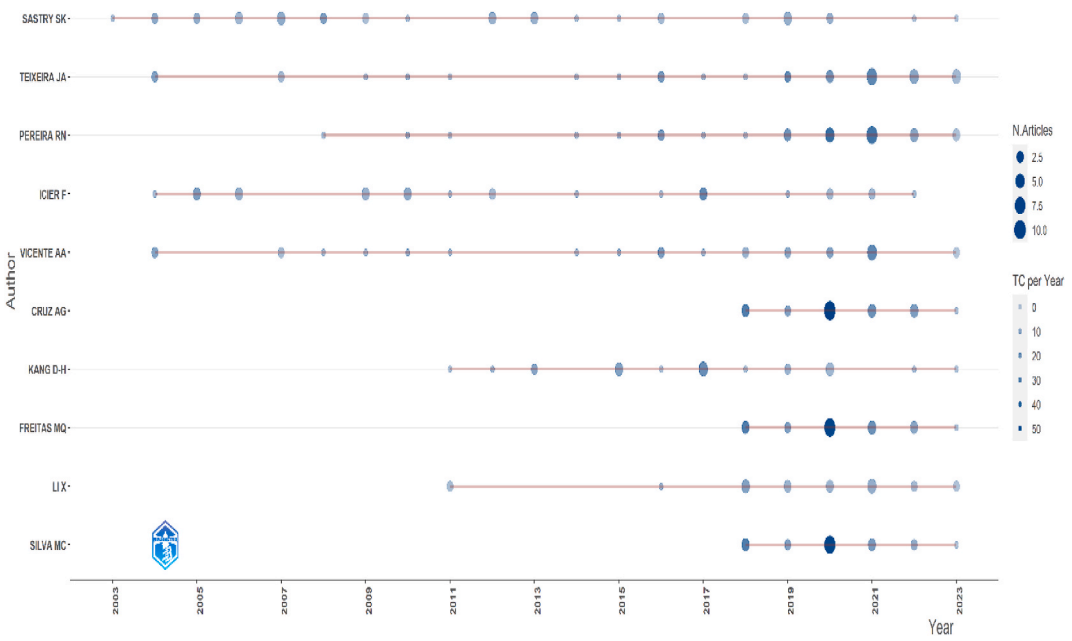


Fig. 6. Author's production over time.

Table 1
Top 10 authors who most contributed to studies on ohmic heating in food.

Rank	Authors	h-index	TC	Documents	International collaboration	Institution	Country	PY Start
1st	Sastry, S.K.	51	8020	47	52.4 %	The Ohio State University	USA	1976
2nd	Teixeira, J. A.	93	37,975	38	53 %	Universidade do Minho	Portugal	1989
3rd	Pereira, R. N.	33	3186	33	27.5 %	Universidade do Minho	Portugal	2007
4th	Vicente, A. A.	81	22,435	28	51.3 %	Universidade do Minho	Portugal	1995
5th	Icier, F.	34	3487	27	7.1 %	Ege University Faculty of Engineering	Turkey	2003
6th	Cruz, A.G.	71	16,292	25	31 %	Instituto Federal de Educaão Ciência e Tecnologia Do Rio de Janeiro	Brazil	2006
7th	Kang, D.H.	50	8329	23	8.2 %	Seoul National University	South Korea	1995
8th	Freitas, M. Q.	54	7552	23	27.9 %	Universidade Federal Fluminense	Brazil	2006
9th	Li, X.	23	1654	22	20 %	Food Quality and Safety Beijing Laboratory	China	2009
10th	Silva, M.C.	44	5080	20	32.5 %	Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro	Brazil	2009

TC = total citation, PYstart = publication year start.

works explored the domain of heat transfer processes, use of heat processes in food preservation, and use of electricity in food preservation technology. Sastry authored the inaugural journal article that incorporated the term "ohmic heating" in its title: "Electrical Conductivities of Selected Solid Foods During Ohmic Heating," which was published in the esteemed magazine Food Engineering in 1991 [47]. Palaniappan, S., coauthored this article and received 232 citations. This essay received the most citations among Sastry's articles. The notable emphasis by Sastry on the use of ohmic heating within the realm of food science is shown in Table 2, with the inclusion of the 10 most frequently referenced articles that primarily focus on this subject. Teixeira as the second most prolific author, commenced his scholarly contributions in 1989 with the publication of an article entitled "*Partial characterization of cell wall from a flocculent strain of Kluyveromyces marxianus*" in Biotechnology Letters [48]. The focus of research by Teixeira was investigating the inhibitory effects on microorganisms, as well as on the study of fermentation and extraction methodologies. The initial mention of ohmic heating by Teixeira occurred in "*The effect of electric field on important food processing enzymes*: *Comparison of inactivation kinetics under conventional and ohmic heating*," which was published in the Journal of Food Science in 2004 [49], However, the most highly referenced article by Teixeira on antimicrobial activity is "*Sodium chloride effect on the aggregation behavior of rhamnolipids and their antifungal activity*," published in Scientific Reports in 2017, with a total of 1353 citations [50]. The study authored by Texeira, entitled "*Erratum: Ohmic heating as a new efficient process for organic synthesis in water*," published in Green Chemistry in 2013 [51] was the first

publication where the term "Ohmic" was included in the title of the work (see Table 2).

Similar to Teixeira, Pereira, R.N., is associated with Universidade do Minho, located in Portugal. Pereira initiated his research publication endeavors in 2007 with the release of an essay titled "*Comparison of chemical properties of food products processed by conventional and ohmic heating*" published in *Chemical Papers* [52]. Pereira exhibited a notable interest in developing technologies, particularly the use of modest electric fields, such as ohmic heating. Pereira has 10 studies that have garnered significant citations, and that pertain to developing technology and phytochemical extraction via ohmic technology. A scholarly essay by Pereira, which garnered the largest number of citations for this author at 408, examines the effects of thermal and nonthermal applications in food processing [3].

Icier, F., was identified as the fourth most significant contributor, with the first entry in the Scopus database in 2003 with a paper entitled "*Effects of microwave and infrared drying on the quality of carrot and garlic*" in European Food Research and Technology [53]. Icier engaged in investigating food-drying techniques, with a focus on applying ohmic heating as a drying method. Five out of the 10 most often cited papers by Icier incorporate the term "ohmic" within the titles of the respective articles.

Vicente, A.A., identified as the sixth most influential contributor to the article on ohmic heating in the context of food processing and is affiliated with the Universidade do Minho, Portugal. A collection of 10 highly cited publications by Vicente demonstrates a notable focus on fermentation, physicochemical qualities of products, and developing technology. The inaugural publication in Scopus was entitled *"Hydrodynamic performance of a three-phase airlift bioreactor with an expanded degassing zone"* in Bioprocess Engineering journal in 1995. The article entitled "*The effect of electric field on important food processing enzymes: Comparison of inactivation kinetics under conventional and ohmic heating*," authored by Castro, I., Macedo, B., and Teixeira, J.A., published in the Journal of Food Science in 2004 was noteworthy as the first article to incorporate the term "ohmic heating" in its title [49].

In recent years, acknowledgment has grown of the necessity for international research collaboration. International collaborations play a crucial role in facilitating the sharing of knowledge among academics and in promoting the integration of various perspectives. Consequently, this enables the effective resolution of difficult interdisciplinary challenges. Collaboration facilitates the acquisition of supplementary resources, including financial support, skilled personnel, and research apparatuses. Academic collaboration encompasses a diverse array of endeavors, such as sharing ideas, data, and insights; establishing connections with scholars from various nations; undertaking field excursions; participating in collaborative grant proposals; and publicizing research outcomes [54]. Regarding international collaboration, Sastry, Teixeira, and Vicente have demonstrated high levels of engagement, with collaboration rates exceeding 50 %, whereas Icier exhibited the lowest collaboration rate of 7.1 %. The author relationship diagram with the most collaboration is shown in Fig. 7 as generated by the UCINET analysis program.

Fig. 7a illustrates that Teixeira collaborated with 99 authors, with the most significant collaboration being with Pereira and Vicente. Fig. 7b shows the collaborations of Vicente with 69 authors, with the most frequent collaborations being with Pereira and Teixeira. Fig. 7c shows that Sastry is the author with the highest number of collaborations with 67 writers, with the most significant cooperation being with Heskitt, B. and Yousef, AE. Table 1 shows that Sastry was first published in 1976, followed by Teixeira in 1989 and Vicente in 1995. This implies that Sastry began publishing before the other two writers, suggesting that Sastry may have been their supervisor. Two articles, "*The influence of field strength, sugar, and solid content on the electrical conductivity of strawberry products*" [55] and "*Ohmic heating of strawberry products: Electrical conductivity measurements and ascorbic acid degradation kinetics*," [56] demonstrate the connection among the three authors. The first article was published in 2003 in the Journal of Food Process Engineering while the second was published in 2004 in Innovative Food Science and Emerging Technologies. The authors include Sastry, S.K., from Ohio State University, USA; Castro, I., Teixeira, J.A., and Vicente, A.A., from Universidade do Minho, Portugal; and Salengke, S., from Hasanuddin University, Indonesia.

After analyzing the publication start dates of each author, Sastry, Teixeira, and Vicente had evidently published earlier, demonstrating their seniority to the other authors. These writers can serve as advocates for international students in the field of ohmic heating, generating a higher international collaboration score compared to their peers.

3.5. Document analysis

Citation is widely used as a qualitative measure to evaluate research success and the entire ecosystem, and citations are commonly seen as indicators of the impact, credibility, or excellence of a scholarly article [57,58]. Table 3 shows the 10 papers of the 769 papers that have garnered the highest number of citations throughout the past two decades on ohmic heating research within the food industry. The article entitled "*Effect of Processing on Phenolic Antioxidants of Fruits, Vegetables, and Grains-A Review*" authored by Nayak, B., Liu, R.H., and Tang, J. and published in Critical Reviews in Food Science and Nutrition, has garnered the highest number of citations (309 in total). This translates into an average of 34.33 citations per year. Of these 10 papers, three were identified as review articles, including "*Effect of processing on phenolic antioxidants of fruits, vegetables, and grains-A Review," "Decontamination technologies for meat products,"* and "*Enhanced extraction from solid foods and biosuspensions by pulsed electrical energy*." Two of these papers were ranked first and second in terms of the number of citations they received. These data indicates that the most referenced ohmic research encompasses the effects of processing on food phenolics and antioxidants [59–61], study of ohmic performance [61–63], microbial inhibition [64], extraction [65–67], and prospective applications of novel technologies in food industry [68].

Nayak et al. [59], discussed how thermal and nonthermal processes affect the phenolic antioxidant content of fruits, vegetables, and seeds. The thermal processes reviewed were blanching, canning, roasting, boiling, ohmic heating, drying, and microwave cooking. Nonthermal processes include the application of high hydrostatic pressure, pulse electric field, irradiation, ultrasound, and dense phase carbon dioxide processes. Some of the findings summarized by Nayak regarding ohmic heating are: ohmic blanching of fresh whole vegetables for 2 min produces the same effect as water blanching for 4 min; the energy delivered by the electric current to the

Table 2
Ten articles with the highest citations from each top 10 authors.

Author	Authorship	Articles	Sources	Cited by
Sastry, S. K	Palaniappan, S., Sastry, S.K.	Electrical conductivities of selected solid foods during ohmic heating	Journal of Food Process Engineering	232
	Sarang, S., Sastry, S.K., Knipe, L.	Electrical conductivity of fruits and meats during ohmic heating	Journal of Food Engineering	211
	Castro, I., Teixeira, J.A., Salengke, S., Sastry, S. K., Vicente, A.A.	Ohmic heating of strawberry products: Electrical conductivity measurements and ascorbic acid degradation kinetics	Innovative Food Science and Emerging Technologies	185
	Palaniappan, S., Sastry, S.K.	Electrical conductivity of selected juices: Influences of temperature, solid content, applied voltage and particle size	Journal of Food Process Engineering	174
	Sastry, S.K., Barach, J.T.	Ohmic and inductive heating	Journal of Food Science	168
	Sastry, S.K., Datta, A.K., Worobo, R.W.	Ultraviolet light	Journal of Food Science	152
	Lima, M., Sastry, S.K.	Effects of ohmic heating frequency on hot air drying rate and juice yield	Journal of Food Engineering	148
	Sensoy, I., Zhang, Q.H., Sastry, S.K.	Inactivation kinetics of *Salmonella* Dublin by pulsed electric field	Journal of Food Process Engineering	133
	Samaranayake, C.P., Sastry, S.K.	Electrode and pH effects on electrochemical reactions during ohmic heating	Journal of Electroanalytical Chemistry	126
	Palaniappan, S., Sastry, S.K, Richter, E.R.	Effects of electricity on microorganism: a review	Journal of Food Processing and Preservation	124
Teixeira, J.A	Rodrigues, A.I., Gudiña, E.J., Teixeira, J.A., Rodrigues, L.R.	Sodium chloride effect on the aggregation behavior of rhamnolipids and their antifungal activity	Scientific Reports	1353
	Rodrigues, L., Banat, I.M., Teixeira, J., Oliveira, R.	Biosurfactants: Potential applications in medicine	Journal of Antimicrobial Chemotherapy	706
	Mussatto, S.I., Machado, E.M.S., Martins, S., Teixeira, J.A.	Production, composition, and application of coffee and its industrial residues	Food and Bioprocess Technology	687
	Martins, S., Mussatto, S.I., Martínez-Avila, G., Montañez-Saenz, J., Aguilar, C.N., Teixeira, J. A.	Bioactive phenolic compounds: production and extraction by solid-state fermentation. A review	Biotechnology Advances	523
	Ballesteros, L.F., Teixeira, J.A., Mussatto, S.I.	Chemical, functional, and structural properties of spent coffee grounds and coffee silverskin	Food and Bioprocess Technology	518
	Mussatto, S.I., Dragone, G., Guimarães, P.M.R., Silva, J.P.A., Carneiro, L.M., Roberto, I.C., Vicente, A., Domingues, L., Teixeira, J.A.	Technological trends, global market, and challenges of bio-ethanol production	Biotechnology Advances	514
	Ruiz, H.A., Rodríguez-Jasso, R.M., Fernandes, B.D., Vicente, A.A., Teixeira, J.A.	Hydrothermal processing, as an alternative for upgrading agriculture residues and marine biomass according to the biorefinery concept: A review	Renewable and Sustainable Energy Reviews	491
	Torres, D.P., Gonçalves, M., Teixeira, J.A., Rodrigues, L.R.	Galacto-oligosaccharides: Production, properties, applications, and significance as prebiotics	Comprehensive Reviews in Food Science and Food Safety	473
	Cerqueira, M.A., Souza, B.W.S., Teixeira, J.A., Vicente, A.A.	Effect of glycerol and corn oil on physicochemical properties of polysaccharide films - A comparative study	Food Hydrocolloids	380
	Pires, E.J., Teixeira, J.A., Brányik, T., Vicente, A.A.	Yeast: The soul of beer's aroma - A review of flavor-active esters and higher alcohols produced by the brewing yeast	Applied Microbiology and Biotechnology	373
Pereira, R. N	Pereira, R.N., Vicente, A.A.	Environmental impact of novel thermal and nonthermal technologies in food processing	Food Research International	408
	Ramos, Ó.L., Reinas, I., Silva, S.I., Fernandes, J. C., Cerqueira, M.A., Pereira, R.N., Vicente, A. A., Poças, M.F., Pintado, M.E., Malcata, F.X.	Effect of whey protein purity and glycerol content upon physical properties of edible films manufactured therefrom	Food Hydrocolloids	353
	Fasolin, L.H., Pereira, R.N., Pinheiro, A.C., Martins, J.T., Andrade, C.C.P., Ramos, O.L., Vicente, A.A.	Emergent food proteins–Toward sustainability, health and innovation	Food Research International	126
	Pereira, R.N., Souza, B.W.S., Cerqueira, M.A., Teixeira, J.A., Vicente, A.A.	Effects of electric fields on protein unfolding and aggregation: Influence on edible films formation	Biomacromolecules	125
	Rocha, C.M.R., Genisheva, Z., Ferreira-Santos, P., Rodrigues, R., Vicente, A.A., Teixeira, J.A., Pereira, R.N.	Electric field-based technologies for valorization of bioresources	Bioresource Technology	100
	Pereira, R.N., Rodrigues, R.M., Genisheva, Z., Oliveira, H., de Freitas, V., Teixeira, J.A., Vicente, A.A.	Effects of ohmic heating on extraction of food-grade phytochemicals from colored potato	LWT	90
	Ramos, O.L., Pereira, R.N., Martins, A., Rodrigues, R., Fuciños, C., Teixeira, J.A., Pastrana, L., Malcata, F.X., Vicente, A.A.	Design of whey protein nanostructures for incorporation and release of nutraceutical compounds in food	Critical Reviews in Food Science and Nutrition	86
	Coelho, M., Pereira, R., Rodrigues, A.S., Teixeira, J.A., Pintado, M.E.	Extraction of tomato by-products' bioactive compounds using ohmic technology	Food and Bioproducts Processing	81

(*continued on next page*)

Table 2 (*continued*)

Author	Authorship	Articles	Sources	Cited by
	Rodrigues, R.M., Martins, A.J., Ramos, O.L., Malcata, F.X., Teixeira, J.A., Vicente, A.A., Pereira, R.N.	Influence of moderate electric fields on gelation of whey protein isolate	Food Hydrocolloids	80
	Ramos, O.L., Pereira, R.N., Rodrigues, R., Teixeira, J.A., Vicente, A.A., Xavier Malcata, F.	Physical effects upon whey protein aggregation for nano-coating production	Food Research International	70
Icier, F.	Erbay, Z., Icier, F.	A review of thin layer drying of foods: Theory, modeling, and experimental results	Critical Reviews in Food Science and Nutrition	399
	Erbay, Z., Icier, F.	Optimization of hot air drying of olive leaves using response surface methodology	Journal of Food Engineering	196
	Icier, F., Ilicali, C.	Temperature dependent electrical conductivities of fruit purees during ohmic heating	Food Research International	155
	Icier, F., Yildiz, H., Baysal, T.	Peroxidase inactivation and color changes during ohmic blanching of pea puree	Journal of Food Engineering	136
	Baysal, T., Icier, F., Ersus, S., Yildiz, H.	Effects of microwave and infrared drying on the quality of carrot and garlic	European Food Research and Technology	122
	Icier, F., Yildiz, H., Baysal, T.	Polyphenoloxidase deactivation kinetics during ohmic heating of grape juice	Journal of Food Engineering	114
	Hepbasli, A., Erbay, Z., Icier, F., Colak, N., Hancioglu, E.	A review of gas engine driven heat pumps (GEHPs) for residential and industrial applications	Renewable and Sustainable Energy Reviews	97
	Icier, F., Ilicali, C.	The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating	European Food Research and Technology	97
	Yildiz-Turp, G., Sengun, I.Y., Kendirci, P., Icier, F.	Effect of ohmic treatment on quality characteristic of meat: A review	Meat Science	88
	Erbay, Z., Icier, F.	Optimization of drying of olive leaves in a pilot-scale heat pump dryer	Drying Technology	88
Vicente, A.A.	Mussatto, S.I., Dragone, G., Guimarães, P.M.R., Silva, J.P.A., Carneiro, L.M., Roberto, I.C., Vicente, A., Domingues, L., Teixeira, J.A.	Technological trends, global market, and challenges of bioethanol production	Biotechnology Advances	514
	Ruiz, H.A., Rodríguez-Jasso, R.M., Fernandes, B.D., Vicente, A.A., Teixeira, J.A.	Hydrothermal processing, as an alternative for upgrading agriculture residues and marine biomass according to the biorefinery concept: A review	Renewable and Sustainable Energy Reviews	491
	Silva, H.D., Cerqueira, M.A., Vicente, A.A.	Nanoemulsions for food applications: development and characterization	Food and Bioprocess Technology	469
	Pereira, R.N., Vicente, A.A.	Environmental impact of novel thermal and nonthermal technologies in food processing	Food Research International	408
	Martins, J.T., Cerqueira, M.A., Vicente, A.A.	Influence of α-tocopherol on physicochemical properties of chitosan-based films	Food Hydrocolloids	383
	Cerqueira, M.A., Souza, B.W.S., Teixeira, J.A., Vicente, A.A.	Effect of glycerol and corn oil on physicochemical properties of polysaccharide films - A comparative study	Food Hydrocolloids	380
	Pires, E.J., Teixeira, J.A., Brányik, T., Vicente, A.A.	Yeast: The soul of beer's aroma - A review of flavor-active esters and higher alcohols produced by the brewing yeast	Applied Microbiology and Biotechnology	373
	Ramos, Ó.L., Reinas, I., Silva, S.I., Fernandes, J. C., Cerqueira, M.A., Pereira, R.N., Vicente, A. A., Poças, M.F., Pintado, M.E., Malcata, F.X.	Effect of whey protein purity and glycerol content upon physical properties of edible films manufactured therefrom	Food Hydrocolloids	353
	Ribeiro, C., Vicente, A.A., Teixeira, J.A., Miranda, C.	Optimization of edible coating composition to retard strawberry fruit senescence	Postharvest Biology and Technology	335
	Casariego, A., Souza, B.W.S., Cerqueira, M.A., Teixeira, J.A., Cruz, L., Díaz, R., Vicente, A.A.	Chitosan/clay films' properties as affected by biopolymer and clay micro/nanoparticles' concentrations	Food Hydrocolloids	333

sample can heat uniformly and quickly without being affected by the shape and size of the sample [69]. In an artichoke by-product, the application of ohmic blanching with 25–40 V/cm inactivated peroxidase faster and maintained a higher total phenolic content than water blanching at 85 °C [70]. These authors also reported that ohmic blanching with 40 V/cm at 85 °C with a peroxidase inactivation time of 310 ± 2 s was equivalent to 100 °C water blanching with a time of 300 ± 2 s. Mass transfer increases during osmotic dehydration after ohmic blanching, and the diffusion rate is more effective due to faster cell damage from the combination of thermal and electrical heat [71]. Vikram et al. compared the thermal degradation kinetics of orange juice with those of several new process technologies compared with conventional processing. The process technologies evaluated were ohmic, infrared, and microwave heating systems, and of the four heating methods used, ohmic heating caused the lowest vitamin damage, whereas microwave heating produced the highest [60].

Four of the top 10 cited documents discuss ohmic process characteristics in food processing. The effects of temperature and product electrical conductivity on ohmic heating performance have been evaluated for fruit and meat products [61–63]. Castro found that heat treatment produced a marked decrease in the conductivity of strawberry pulps examined. However, variations in the conductive properties of strawberry pulp were observed when conventional or ohmic pretreatment methods were applied. Ascorbic acid

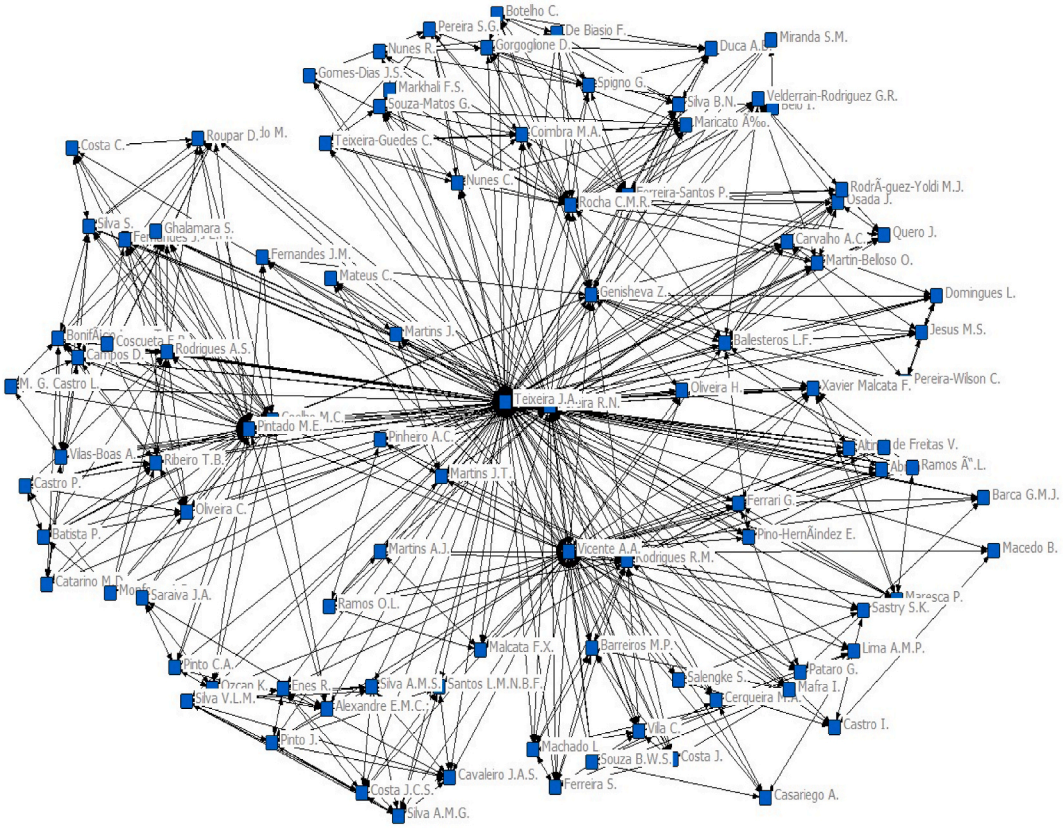


Fig. 7. a) Collaboration network for Teixeira, J.A., b) Collaboration network for Sastry, S.K., c) Collaboration network for Vicente, A.A.

degradation showed a first-order kinetic behavior during conventional and ohmic heat treatments. The obtained kinetic constants were within the range of values reported in the literature for various food systems, and the degradation of ascorbic acid was unaffected by the presence of an electric field [61]. In the electrical conductivity tests of fresh fruit (red apple, golden apple, peach, pear, pineapple, and strawberry) and sliced meat (chicken, pork, and beef) from 25 °C to 140 °C, conductivity linearly increased with increasing temperature. The electrical conductivity of peaches and strawberries was higher than that of apples, pears, or pineapples; furthermore, the conductivity of fruit was lower than that of meat. Fatty meat has a lower conductivity than lean meat [62]. Icier and Ilicali [63] discovered that the electrical conductivity of fruit puree is strongly influenced by temperature and is contingent upon the concentration of ions and the volume of pulp. The temperature dependent increase in the electrical conductivity of the fruit puree exhibited a linear relationship. The rate of temperature change observed in the apricot pulp was higher than that observed in the peach pulp across all the applied stress gradients. Bubbling occurred above 60 °C, particularly when greater voltage gradients were applied. The avoidance of bubble formation can be achieved by measures that include the careful selection of inert electrode coatings, application of high frequency power, and implementation of strategies to prevent the presence of air bubbles in the sample. A mathematical model incorporating the system performance coefficients can be employed to precisely forecast the ohmic heating duration of the fruit pulp.

Ohmic heating has been established as one of the latest methods for essential oil extraction [65]. The combination of ohmic-assisted hydrodistillation (OAHD) with conventional methods can overcome the long extraction time. Gavahian et al. [65] used OAHD for the extraction process of *Thymus vulgaris* L essential oil in 24.75 min, 35.25 min faster than the hydrodistillation technique. Gas chromatography–mass spectrometry analysis showed no significant difference between the essential oils obtained using OAHD or hydrodistillation techniques. OAHD is also recommended as a faster more economical and environmentally friendly method than the hydrodistillation method for essential oil extraction. Lakkakula et al. [67] analyzed the effect of ohmic heating on the extraction of bran oil. With the addition of bran moisture, ohmic heating showed that bran remained stable and that the percentage of fat extracted was increased up to 93 %, whereas, without the use of ohmic heating, only 53 % was produced. Several previous studies have shown the effectiveness of ohmic applications in the extraction of other foodstuffs [72,73]. Vorobiev and Levonka [66] recommended the use of a pulsed electric field (pulsed electric field, pulsed ohmic heating, and high-voltage electrical discharge) as an alternative to processing liquid-solid products to maintain the nutritional and sensory quality, protein quality, and polysaccharides extracted from suspensions (e.g., yeast suspensions in water, *Escherichia coli* cells), compared with conventional processing, either mechanical or thermal, or chemical. Pretreatment combinations of several methods can produce additional synergistic effects that are useful for

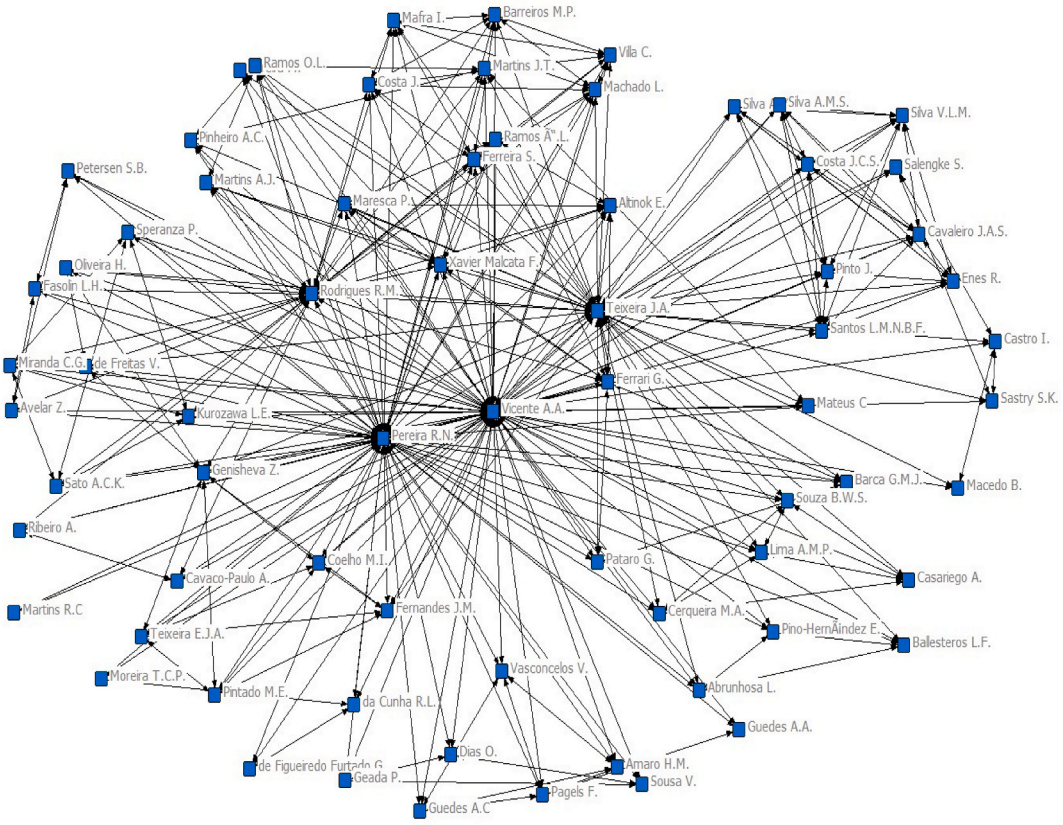


Fig. 7. (*continued*).

product processing. From a practical point of view, the development of such combined technologies is essential for improving dehydration and extraction processes.

The article "*Mapping Trends in Novel and Emerging Food Processing Technologies Around the World*" by Jermann et al. [68] examines various innovative and emerging food processing technologies worldwide. These include high-pressure processing, pulsed electric field, ultraviolet light, microwave heating, radiation and ohmic heating, ozone, pressure and CO_2, ultrasound, cold atmospheric plasma, and electrolyzed water. Jermann found that ohmic heating is a crucial technology for liquid items such as dairy products, sauces, soups, purees, and beverages. According to a European poll, the technology has considerable potential for commercial implementation within the next 5–10 years.

Nayak et al. [59] and Jermann et al. [68] examined the merits and limitations of ohmic heating in the food industry. Both articles highlight the benefits of ohmic heating, including fast and uniform heating, improved energy efficiency, and reduced processing time. Additionally, ohmic heating minimizes nutrient loss because of its short heating time and helps maintain better nutrient content and sensory quality than traditional food processing methods. The disadvantages of ohmic heating pertain to the comparatively expensive initial investment required, which significantly limits the broader implementation of the technology. Additionally, complex process control systems necessitate precise controls to ensure consistent and safe heating. Furthermore, the absence of clear regulations and approvals from regulatory bodies hinders the adoption of this technology in the food industry.

3.6. Source analysis

Over the last 20 years, 226 sources have contributed to the publication of journals and proceedings in the field of ohmic heating. The 10 sources with the highest contributions in relevant publications are shown in Table 4. Some journals, such as Innovative Food Science and Emerging Technologies and the Journal of Food Engineering, have made substantial and influential contributions. The citation score and Scimago Journal Rank (SJR) indicate the quality and influence of these journals in the scientific community. The Journal of Innovative Food Science and Emerging Technologies ranked first with 88 documents, showing significant contributions in this field. The high citation score and Q1 ranking indicate that the journal is highly influential. The Journal of Food Engineering ranked second with 71 documents. Although the number of documents is less than first place, a slightly higher citation score indicates that these documents hold significant importance within the scientific community. LWT, with 52 documents, ranks third with significant contributions since 1973. The high citation and SJR scores show that this journal is also influential. Despite having only 19 documents, Food Chemistry has a high citation score, indicating that these documents are highly esteemed and significantly impact the scientific

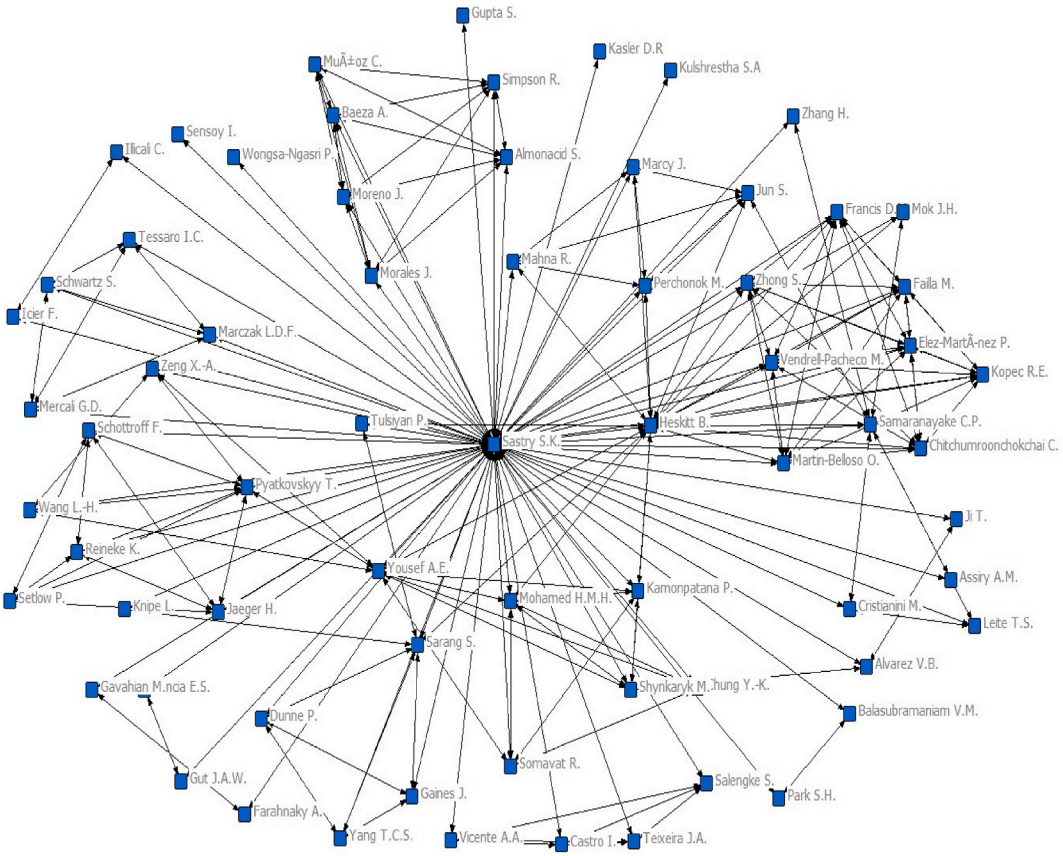


Fig. 7. (*continued*).

Table 3
Top 10 articles cited in "ohmic heating in food".

Rank	Authors	Title	Year	Journal	Total citations	TC per year
1st	Nayak, B., Liu, R.H., and Tang, J.	Effect of Processing on phenolic antioxidants of fruits, vegetables, and grains—A review	2015	Critical Reviews in Food Science and Nutrition	309	34.33
2nd	Aymerich, T., Picouet, P.A., and Monfort, J.M.	Decontamination technologies for meat products	2008	Meat Science	287	15.11
3rd	Vikram, V.B., Ramesh M.N., and Prapulla, S.G.	Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods	2005	Journal of Food Engineering	283	17.69
4th	Lakkakula, N.R., Lima, M., and Walker, T.	Rice bran stabilization and rice bran oil extraction using ohmic heating	2004	Bioresource Technology	212	10.6
5th	Sarang, S., Sastry, S.K., and Knipe L.	Electrical conductivity of fruits and meats during ohmic heating	2008	Journal of Food Engineering	209	13.06
6th	Castro, I., Teixeira, J.A., Salengke, Sastry, S.K., and Vicente, A.A.	Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics	2004	Innovative Food Science & Emerging Technologies	182	9.1
7th	Vorobiev, E. and Lebovka, N.	Enhanced extraction from solid foods and biosuspensions by pulsed electrical energy	2010	Food Engineering Reviews	152	8
8th	Icier, F. and Ilicali, C.	Temperature dependent electrical conductivities of fruit purees during ohmic heating	2005	Food Research International	151	10.79
9th	Jermann, C., Koutchma, T., Margas, E., Leadley, C and Polski, V.R.	Mapping trends in novel and emerging food processing technologies around the world	2015	Innovative Food Science & Emerging Technologies	147	16.33
10th	Gavahian, M., Farahnaky, S., Javidnia, K., and Majzoobi, M.	Comparison of ohmic-assisted hydrodistillation with traditional hydrodistillation for the extraction of essential oils from *Thymus vulgaris* L.	2012	Innovative Food Science & Emerging Technologies	147	12.25

Table 4
Top 10 journals that have published the most studies related to ohmic heating in food research.

Rank	Journal	Documents	Cites score	SJR	Best rank	SCY
1st	Innovative Food Science and Emerging Technologies	88	11.1	1.27	Q1	2000 to present
2nd	Journal of Food Engineering	71	11.8	1.16	Q1	1982–2024
3rd	LWT	52	9.6	1.17	Q1	1973, from 1984 to 1989, from 1991 to Present
4th	Journal of Food Process Engineering	29	5.3	0.55	Q1	1982–2024
5th	Journal of Food Processing and Preservation	27	3.4	0.49	Q2	1977 to present
6th	Food and Bioprocess Technology	23	9.1	0.98	Q1	2008 to present
7th	Food Research International	23	12	1.36	Q1	1992 to present
8th	Journal of Food Science	21	9.3	0.71	Q1	1936 to present
9th	Food Chemistry	19	14.9	1.62	Q1	1976–2024
10th	Foods	17	5.8	0.77	Q1	2012 to present

SJR = Scimago Journal Rank, SCY = Scopus Coverage year.

community.

The productivity of these five publishers has increased over the past two decades. Fig. 8 illustrates the progression of productivity in publishing research on ohmic heating across different journals from 2000 to 2023. Each colored line reflects the increase in the cumulative number of documents published by that journal over time. The productivity of Innovative Food Science and Emerging Technology (red line) significantly increased from around 2008 to 2023. This journal shows steady and significant growth, reflecting that more and more research related to ohmic heating is being published in this journal. The productivity of the Journal of Food Engineering (green line) consistently increased from 2000 to 2023, with rapid growth after 2015. This steady increase indicates that the journal continues to be a significant source for publications in the field of ohmic heating. The LWT journal (yellow line) shows a steady increase from the beginning of the period assessed to 2023, with a significant spike seen after 2015; the LWT journal has been an essential platform for ohmic heating research, especially in the last two decades.

3.7. Keyword analysis

Keywords are the embodiment of the essence of an article. The analysis of keywords can show the direction and main points of research in the field of food ohmic heating [33]. Keyword cooccurrence analysis is used to identify gaps and track the development of scientific research in a field [26,44,74]. VOSviewer is used to understand research trends and identify emerging research areas by visualizing the relationship between keywords based on their frequency of co-occurrence in the literature. VOSviewer was used in this study to identify the main keywords and relationships between them in research related to ohmic heating technology in the food sector. The analysis used all keywords, with a minimum occurrence limited to seven times. Subsequently, 5578 keywords were found, but only 316 met these criteria and were divided into five clusters as shown in Fig. 9a; the main elements of the figure are keyword size, cluster

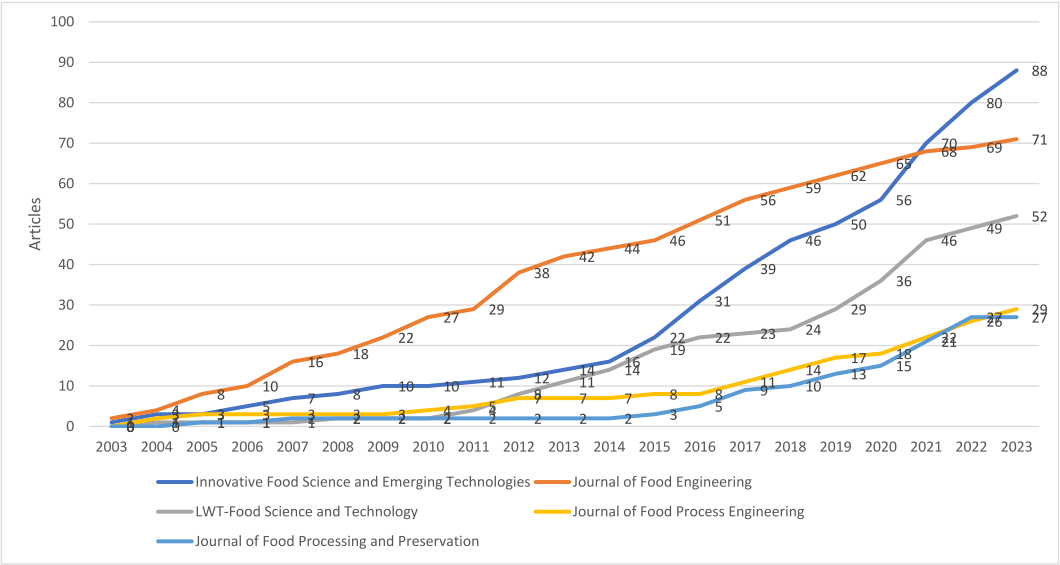


Fig. 8. Source productivity over time.

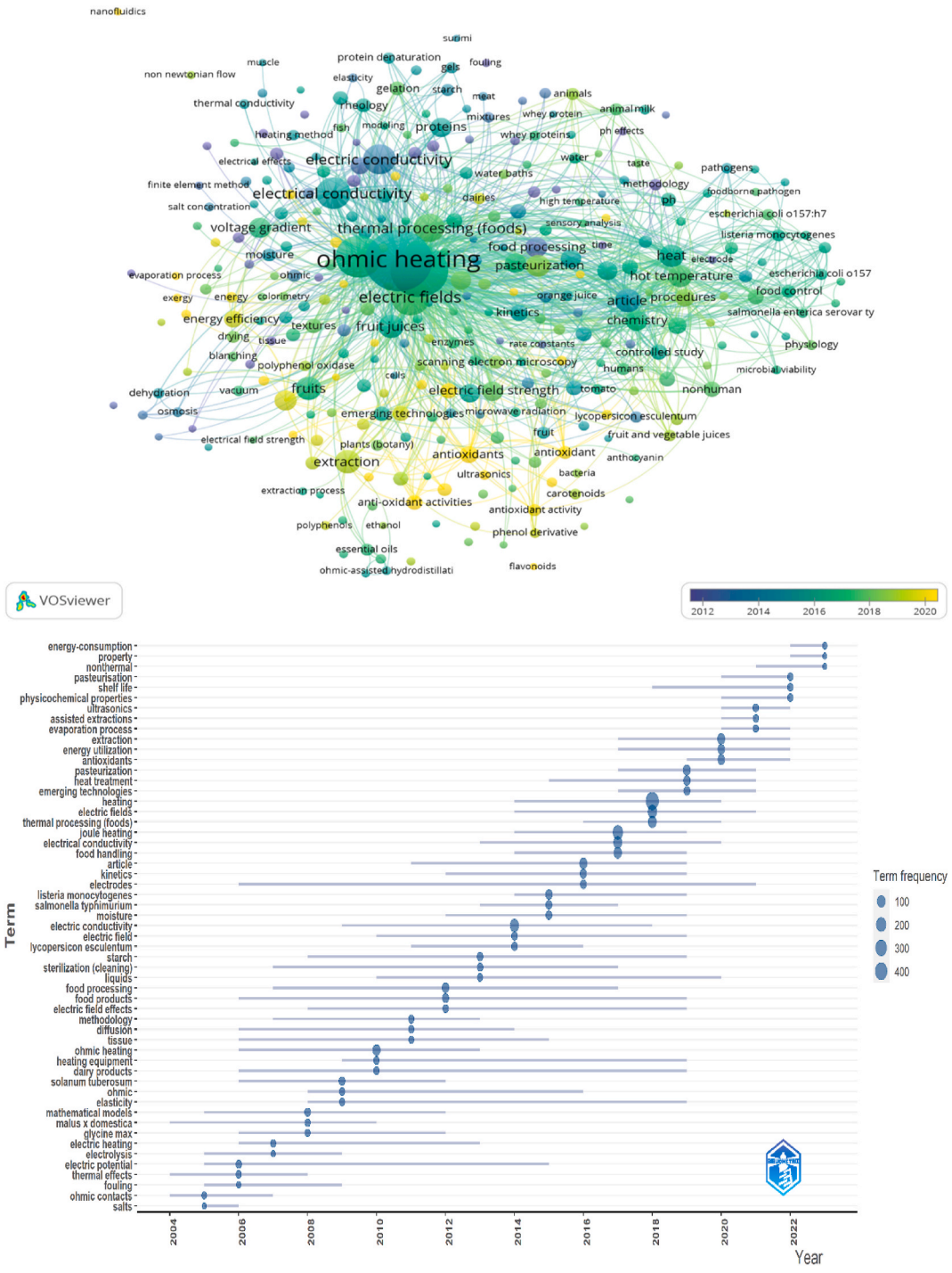


Fig. 9. a) Cooccurrence analysis of keyword, b) trends topics based on keyword plus.

color, and connecting lines. Fig. 9a shows the trend in keyword usage, where the darker the notation color of the keyword, the longer the keyword has been used while a lighter color shows the more recent use of the keyword. Fig. 9a demonstrates that the term "ohmic heating" is consistently and prominently utilized, suggesting that this is the primary area of interest in this research. The most recently used keywords are "antioxidant" and "antioxidant activity."

In Fig. 9a, different colors in the keyword network indicate research clusters. More prominent keywords, such as "ohmic heating" and "food processing," show a higher frequency of occurrence. The connecting lines between keywords indicate how often they appear together in the literature. The red cluster focuses on ohmic heating technology, including terms such as "electrical conductivity" and

"thermal processing." The blue cluster focuses more on practical applications in the food industry, with keywords such as "food preservation" and "nutritional quality."

The analysis also shows an increasing trend of research linking ohmic heating to improved food quality and safety. Interest is growing in applying this technology to food preservation and nutritional value enhancement. These findings indicate that future research may focus on optimizing ohmic heating technology for various food applications. Less explored areas, such as the long-term impact on food quality, require further attention.

The keywords in Table 5 show the main themes and focus areas in ohmic heating research. A high total link strength indicates that the keywords have links to other topics, signaling their importance in the research network. "Ohmic heating" as a keyword ranks first with the highest total link strength, indicating that this is the primary and most frequently discussed topic in related research. This keyword has many connections with other keywords, showing its relevance and centrality in the research network. The keywords" heating," "joule heating," "electric fields," and "heat" rank the highest in total link strength after "ohmic heating," showing similarity with the primary keyword as the central keyword in this research. "Electric conductivity" is a keyword that focuses on a critical factor in the efficiency and effectiveness of ohmic heating. The keyword "food processing" indicates the direct application of ohmic heating in the thermal processing of food, showing relevance in the food industry. The keyword "conventional heating" indicates a comparison with conventional heating methods, which is essential for contextualization and comparison of effectiveness. The keyword "fruit juices" highlights specific applications in fruit juice processing, indicating a research focus on a specific food product.

Fig. 9b shows the trend development of research topics based on keyword plus; RStudio [75] was used to display the term frequency of the keywords during the observation period. Fig. 9b explains how specific topics in ohmic heating research have evolved. By analyzing the frequency and distribution of these terms, we can understand research trends, key focus areas, and the evolution of interest in this field. The x-axis depicts the research period, and the dots represent the frequency of occurrence in each particular year. The size of the dot indicates the frequency where the larger the dot, the higher the frequency of the occurrence of the keyword. The figure shows increased frequency over time, indicating increased interest and research in these areas. Terms such as "ohmic heating," "electric fields," and "thermal processing (foods)" have a relatively high frequency and show a consistent upward trend. In 20 years, "ohmic heating" has shown a significant increase in frequency, indicating that this topic is increasingly important and widely researched. "Electric field," "joule heating," and "electrical conductivity" also consistently increase, indicating their relevance to ohmic heating and the considerable interest in physical mechanisms and conductivity properties in ohmic research. Several terms show frequency peaks in specific periods, for example, "thermal processing," which shows a significant increase starting from around 2012. Terms such as "energy consumption," "nonthermal," and "pasteurization" show an increasing frequency pattern in specific years, signaling a shift in research focus to these areas in certain periods. Research trends show that there is increasing attention to nonconventional heating methods and their applications in food processing, and the focus on energy efficiency and physicochemical characteristics is also becoming increasingly crucial in ohmic heating research.

4. Challenge, perspectives and limitations of the study

The publication of scientific research in food ohmic heating over the past 20 years shows promising prospects for applying more efficient, effective, and environmentally friendly renewable technologies. The keyword analysis shows that recent research trends have paid increasing attention to ohmic applications in fields such as extraction, evaporation, pasteurization processes, potential cost, and process efficiency. Ohmic heating promises a higher extraction efficiency for phytochemicals, essential oils, and fatty oil components from food. A more effective process represents an excellent opportunity for industrial applications. Ohmic heating is particularly promising for applying to liquid and semisolid products, fish, poultry, and meat. Educating consumers on the benefits of ohmic heating, such as improved nutritional quality and reduced chemical additives may increase market acceptance and demand for products processed using this technology.

Ohmic heating can contribute to more sustainable food processing practices by reducing energy consumption and minimizing waste. This concept aligns with the global trend toward more environmentally friendly manufacturing processes. With maximum energy use, minimal waste, and minimal carbon production, ohmic heating food processing can be a promising technology, especially in areas with abundant renewable energy sources such as hydrothermal, solar power, wind or other energy sources that are less polluting and more environmentally friendly.

Table 5
The most used keywords (rank based on total link strength).

Rank	Keywords	Occurrences	Total Link Strength
1st	Ohmic heating	465	3782
2nd	Heating	344	3578
3rd	Joule heating	218	2145
4th	Electric fields	153	1559
5th	Heat	65	1172
6th	Electric conductivity	113	1143
7th	Hot temperature	60	1116
8th	Thermal processing (foods)	98	1056
9th	Conventional heating	74	814
10th	Fruit juices	67	718

However, some challenges remain in the wide adoption and further development of ohmic heating in the food industry such as: (1) Technology integration: Integrating ohmic heating with existing processing lines can be complex and costly. The need for specialized equipment and modifications to existing systems may deter some industries from adopting this technology. (2) Scalability: Although laboratory-scale experiments have shown promising results, scaling up this process to an industrial level presents significant challenges, and uniform heating and process control must be addressed to ensure consistent product quality. Ensuring that the ohmic heating process meets food safety standards and regulatory requirements is critical. Therefore, continued research is required to fully understand the effects of ohmic heating on different types of food products and to establish standardized protocols.

The limitations of this bibliometric analysis relate to the large number of keywords used in all articles and the emergence of some keywords. In addition, we had to eliminate the analysis of the relationship between affiliations in the data presentation because the nonuniform writing of affiliations made it challenging to interpret the picture accurately.

Furthermore, relying on specific databases for data collection can bias article selection and potentially overlook relevant research not indexed in those databases. The dynamic nature of research means that the field is constantly evolving, and new studies may change the current understanding and trends identified in this analysis.

Despite these limitations, the findings of this study can contribute to a valid discussion of the scientific literature on ohmic heating in food. By highlighting current challenges, future perspectives, and existing limitations, this study provides a comprehensive overview that can guide future research and industrial applications in food ohmic heating.

5. Conclusion

This bibliometric analysis identified a significant increase in scientific articles on ohmic heating in the food field over the past 20 years. Authors tend to show a preference for disseminating their research findings through publishing articles in academic journals as opposed to presenting them in conference proceedings. Authors in the United States, China, and Portugal were consistently published throughout the years analyzed. However, Brazil was the most prolific country, especially in the last six years. Sastry, S.K., was identified as the most prolific author, with the highest number of papers, 37. In addition, Teixeira, J.A. has achieved the highest level of international cooperation, with a cooperation score of 53 %. The study "*Effect of Processing on Phenolic Antioxidants of Fruits, Vegetables, and Grains-A Review*," written by Nayak et al., received the most citations, with a total of 309. The primary source of contributions is the journal Innovative Food Science and Emerging Technologies, which has published 88 studies. Keywords such as "ohmic heating," "heating," and "joule heating" have emerged as prominent topics in research articles related to ohmic heating in the food industry. Recent research has broadened the scope of this field to include extraction processes, pasteurization, sterilization, physicochemical component salvage, and energy use efficiency.

Ohmic heating has bright prospects in the future. Rapidly growing research shows considerable interest in this field, especially in recent years. The promising energy efficiency and sustainability potential make this technology even more attractive to explore. Research collaborations between countries will help disseminate this technology and expand future applications in the food industry. However, challenges such as significant capital investments for equipment and maintenance and unclear regulations remain to be overcome. Future research must investigate cost-effective materials for industrial applications, assess the thermal stability of nonuniform products, ensure food safety, and research potential applications in various food products. By finding a clear path forward, food industry stakeholders will find it easier to adopt affordable and environmentally friendly ohmic heating technology.

CRediT authorship contribution statement

Purnama Ningsih S. Maspeke: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Data curation. **Salengke Salengke:** Writing – review & editing, Validation, Supervision, Formal analysis. **Junaedi Muhidong:** Writing – review & editing, Supervision, Formal analysis. **Andi Dirpan:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

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Data availability

Data will be made available on request.

Declaration of competing interest

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

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