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Comprehensive Bibliometric Analysis on High Hydrostatic Pressure as New Sustainable Technology for Food Processing: Key Concepts and Research Trends

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Abstract: The industrial application of high hydrostatic pressure (HHP) can be traced back to the late 19th century in the fields of mechanical and chemical engineering. Its growth as a food preservation technique has developed and massified in certain countries in the last 30 years. However, there is no global overview of the research conducted on this topic. The aim of this study was to recognize global trends in the scientific population on the subject of HHP over time at the main levels of analysis: sources, authors, and publications. This article provides a summary of research related to the use of HHP through a bibliometric analysis using information obtained from the Web of Science (WoS) database between the years 1975–2023, using the terms "pascalization","high-pressure processing", and "high hydrostatic pressure" as input keywords. The results are shown in tables, graphs, and relationship diagrams. The countries most influential and productive in high hydrostatic pressure are the People's R China, the USA, and Spain, with 1578, 1340, and 1003 articles, respectively. Conversely, the authors with the highest metrics are Saraiva, J. (Universidade Aveiro-Portugal), Hendrickx, M. (Katholieke Universiteit Leuven-Belgium), and Wang, T. (China Agricultural University-China). The most productive journals are *Innovative Food Science & Emerging Technologies*, *Food Chemistry*, and *LWT-Food Science and Technology*, all belonging to Elsevier, with 457, 281, and 264 documents, respectively. In relation to the connection between the documents under study and the United Nations Sustainable Development Goals (SDGs), most documents in the period 1975–2023 are linked to SDG 03 (good health and well-being), followed by SDG 02 (zero hunger), and SDG 07 (affordable and clean energy). Finally, the information presented in this work may give valuable key insights for those interested in the development of this interesting topic in non-thermal food preservation. Additionally, it serves as a strategic resource for stakeholders, such as food industry leaders, policymakers, and research funding bodies, by providing a clear understanding of the current state of knowledge and innovation trends. This enables informed decision-making regarding research priorities, investment opportunities, and the development of regulatory frameworks to support the adoption and advancement of non-thermal preservation technologies, ultimately contributing to safer and more sustainable food systems.

Keywords: non-thermal food processes; bibliometric analysis; VosViewer; high hydrostatic pressure; HHP

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1. Introduction

Before recognizing pressure as a strategy for food processing, pressure was initially investigated in the domains of hydrometallurgy, geochemistry, and physics [1]. In the field of engineering, for instance, through the application of pressure, new materials have been developed through the induction of structural transformations and the creation of new high-pressure phases and compounds. In this sense, several techniques for generating high pressure have been developed to create materials, such as hydrogen-rich superconductors, high-energy-density materials, inorganic electrodes, and noble gas compounds, that are normally unavailable at ambient pressure [2].

In food sciences, the study of high pressures has led to the development of a non-thermal food processing technology, usually known as high hydrostatic processing (HHP), by which an alternative energy source is used as the main lethal agent. By employing the application of high pressure, with or without the combination of heat, HHP is capable of inactivating both pathogens and spoilage microorganisms, aiding in extending the shelf life of the processed products while preserving the organoleptic and nutritional properties of food [3].

HHP is an emerging food processing technology that was invented in Japan. Interest in HHP arose around 1990 when the first commercial HHP-processed product was produced [4]. It started with the processing of fruit-based products like jams, and subsequently, additional products have been marketed, including rice, cold meats, soy sauce, and beverages [5].

The fundamentals behind HHP are based on the isostatic principle responsible for the effects on the physical properties of food, and Le Chatelier's principle by which the chemical and microbiological effects of HHP on food are explained [4]. High pressure, usually around 400 to 800 MegaPascal (MPa), is homogeneously transmitted through the food regardless of the dimension or shape of the product and due to the Le Chatelier's principle, where there are minimal effects to the chemical properties of food, while the elimination of microorganisms and enzymes is achieved [4,6,7].

Regarding bacterial inactivation, it has been described that high pressure causes morphological, structural, physiological, and genetic changes in bacteria [8]. The overall effects obtained through the application of HHP are dependent on several variables, such as the pressure employed, temperature and holding time, the food's properties, and the target microorganism [6].

This non-thermal technology is commonly used for the processing and preservation of high-quality products, mainly meat products, fruit and vegetables, aquatic products, and beverages, to preserve their nutritive and fresh qualities [7]. Food processing by HHP at low temperatures exerts minimal impact on nutritional properties, especially on small molecules such as vitamins, aromatic compounds, pigments, and various functional compounds that might be affected when processed through thermal technologies [9,10]. Moreover, HHP is a suitable technology for the extraction of bioactive compounds, including polyphenols, isothiocyanates, fatty acids, carotenoids, and essential oils, among others [10].

In terms of sustainability, the production of high-quality products with a prolonged shelf life allows the utilization of products during the harvest period while considerably reducing food waste [7]. Compared to conventional systems, such as chilling and freezing, HHP has a low-energy consumption, is considered an environmentally friendly technology, reduces the need for chemicals and preservatives, and can increase the bioavailability of foods [10].

HHP is considered a promising and sustainable emerging food processing technology that can be applied to a variety of food products and can also be combined with different treatments to improve the desired processing results, such as the enhanced effectiveness of microbial inactivation [11].

Through the evaluation of the current scientific production regarding HHP, the identification of HHP-related tendencies, key contributors, and revealing trends, the aim of this bibliometric analysis was to identify global trends in the scientific population on the subject of HHP over time at the main levels of analysis: sources, authors, and publications. By highlighting important information available in the existing literature, this bibliometric analysis sheds light on the state of the art in the field of high-pressure processing research and serves as a guide for the scientific community to orient future studies on the subject.

2. Materials and Methods

Data of HHP publications used for this article were gathered and downloaded between 15 February 2024 and 22 February 2024 from the Web of Science Core Collection (WoS) from Clarivate Analytics (www.webofscience.com). The analysis was conducted using the following keywords: "pascalization", "high-pressure processing", and "high hydrostatic pressure" in the field of search "topic" (which includes title, abstract, author keywords, and keywords plus), restricting the examination between years 1975 to 2023 and covering around 50 years of scientific research. The overall number of records for the search considered all the disciplines included in the ISI Web of Science, yielding a total of 8541 records. Immediately after the results were obtained, the selected records were exported in a plain text file (.txt) format to consider the full record and cited references for further analysis.

The data sample obtained is composed of 7189 articles (including original papers, early access, proceeding papers, and retracted publications), 1121 review papers, and 153 meeting abstracts among the main types of documents. The number of sources is 1377 and 19,541 authors.

The data gathered from the WoS were classified and presented based on several bibliometric indicators, such as the total number of publications (TP), total number of citations (TC), Hirsch h-index (H), citation per year (C/Y), and citation per paper (C/P). Moreover, the free bibliometric research packages VOSviewer 1.6.19 [12] and R-Package Bibliometrix 4.1.4 [13] were used to analyze graphical links such as co-authorship, co-occurrence, and co-citation, among other bibliometric visualizations. Figure 1 contains a schematic view of the bibliometric analysis process.

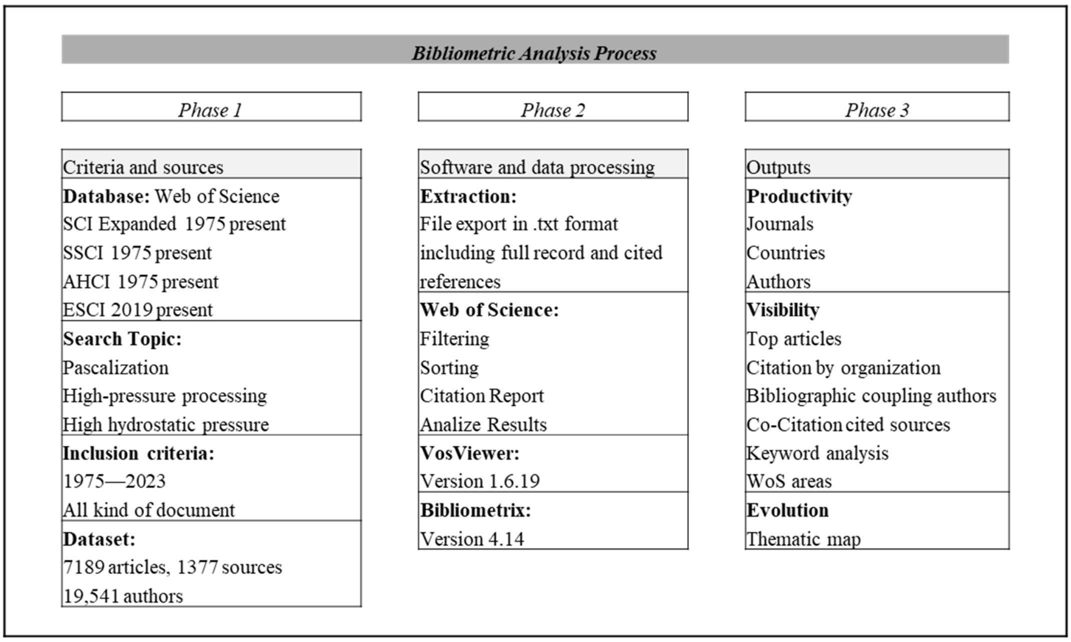

Figure 1. Bibliometric analysis process.

3. Results and Discussion

The results of this bibliometric analysis work are presented in three sections (productivity, visibility, and evolution), which allow the reader to guide and direct his bibliographic search as well as the approach of research topics in the field of high hydrostatic pressures. Section 1 shows data related to productivity at the level of journals, countries, authors, scientific production, and financing agencies. Section 2 is related to visibility issues such as topmost cited articles, bibliometrics relationships, keyword frequency, and the distribution of articles in WoS categories, and it ends with a representation of the relation of articles with U.N. Sustainable Development Goals. Section 3 is focused on the evolution and change of approaches of the research topics addressed over the years. This section includes the following: authors' evolution, thematic map, and thematic evolution, and it ends with each source's evolution.

3.1. Productivity

3.1.1. Most Productive Journals in HHP

For the evaluation of the most productive and influential journals, a ranking was developed taking into account metrics of total publications, total citations, citations per article ratio, impact factor (according to JCR 2023), quartile information, and h-index for the dataset. Table 1 indicates that the source with the greatest number of publications is *Innovative Food Science & Emerging Technologies*. This journal specializes in innovations and key advances in food science and emerging technologies with 457 publications, 18,240 citations, and the highest h-index (69) for the data set; conversely, the journal with the highest impact factor is *Trends in Food Science Technology*, with an impact factor of 15.3 and the highest ratio of citations per publication at 71.52. This journal publishes critical and comprehensive reviews related to the most current technologies in food science and nutrition, focusing on new scientific-technological developments and their potential industrial applications. Concerning the distribution of the 20 most influential journals in quartiles, most of them are located within Q1 (70%).

Table 1. Most Productive Journals in HHP.

R	Journal Name	Publisher	TP	TC	C/P	IF	Q	H
1	*Innovative Food Science & Emerging Technologies*	Elsevier Sci Ltd.	457	18,240	39.91	6.6	1	69
2	*Food Chemistry*	Elsevier Sci Ltd.	281	11,034	39.27	8.8	1	61
3	*LWT-Food Science and Technology*	Elsevier	264	6255	23.69	6.0	1	42
4	*Foods*	Mdpi	216	2164	10.02	5.2	1	22
5	*High Pressure Research*	Taylor & Francis Ltd.	186	1710	9.19	2.0	3	22
6	*Journal of Food Science*	Wiley	180	6881	38.23	3.9	2	44
7	*Food and Bioprocess Technology*	Springer	178	4886	27.45	5.6	1	36
8	*International Journal of Food Microbiology*	Elsevier	168	9754	58.06	5.4	1	52
9	*Food Research International*	Elsevier	166	6834	41.17	8.1	1	43
10	*Journal of Food Protection*	Int Assoc Food Protection	159	6355	39.97	2.0	3	45
11	*Journal of Agricultural and Food Chemistry*	Amer Chemical Soc	132	6028	45.67	6.1	1	44
12	*Trends in Food Science Technology*	Elsevier Science London	132	9440	71.52	15.3	1	57
13	*Food Control*	Elsevier Sci Ltd.	125	3762	30.10	6.0	1	34
14	*Journal of Food Engineering*	Elsevier Sci Ltd.	125	7209	57.67	5.5	1	45
15	*Meat Science*	Elsevier Sci Ltd.	117	5710	48.80	7.1	1	41
16	*International Journal of Food Science and Technology*	Wiley	112	2039	18.21	3.3	2	23
17	*Critical Reviews in Food Science and Nutrition*	Taylor & Francis Inc	110	6284	57.13	10.2	1	46
18	*Applied and Environmental Microbiology*	Amer Soc Microbiology	101	5843	57.85	4.4	2	45
19	*Journal of Food Processing and Preservation*	Wiley	98	940	9.59	2.5	3	15
20	*Food Hydrocolloids*	Elsevier Sci Ltd.	97	3466	35.73	10.7	1	37

R = Ranking; TP = Total Publications; TC = Total Cites; C/P = Cites per publication; IF = Impact factor; Q = Quartile; H = h-index.

3.1.2. Most Productive Countries in HHP

In relation to the scientific production by country, Table 2 is presented. This is headed by the People's R China with a number of 1578 articles for the keywords pascalization, high-pressure processing, and high hydrostatic pressure in the period from 1975 to 2023. Next, in the second place of publications, is the USA, which also has the highest h-index (96) and total citations (47,690). Concerning the relation cites per article, the highest metric is 38.71 corresponding to Germany. Finally, it should be noted that the majority of the most productive countries are located in Europe (50%).

Table 2. Most productive and influential countries in HHP.

R	Country	TP	TC	H	C/P
1	People's R China	1578	34,681	77	21.98
2	USA	1340	47,690	96	35.59
3	Spain	1003	34,971	84	34.87
4	Germany	606	23,458	78	38.71
5	France	538	18,635	67	34.64
6	Japan	478	11,213	48	23.46
7	Poland	405	6031	39	14.89
8	Brazil	343	9394	48	27.39
9	Canada	306	10,333	54	33.77
10	Italy	303	9135	52	30.15

R = Ranking; TP = Total Publications; TC = Total Cites; H = h-index; C/P = Cites per publication.

3.1.3. Most Productive Authors

Regarding the most productive and influential authors, Table 3 presents a ranking with different metrics during the period under study. The author with the highest number of publications in high hydrostatic pressures is Saraiva, J., with affiliation at the Aveiro University in Portugal. Meanwhile, regarding the total metric of citations, the highest was Hendricks, M., belonging to the Katholieke University in Leuven, with 5537; this same author also presents the highest h-index (41). Finally, the German author Knor, D. has the highest ratio of citations per article (82.26).

Table 3. Most productive authors in HHP.

R	Author Name	Organization	Country	TP	TC	h	C/P
1	Saraiva, J.	University Aveiro	Portugal	141	3236	33	22.95
2	Hendrickx, M.	Katholieke University Leuven	Belgium	95	5537	41	58.28
3	Wang, Y.	China Agr University	People's R China	85	3049	30	35.87
4	Van Loey, A.	Katholieke University Leuven	Belgium	78	4395	38	56.35
5	Balasubramaniam, V.M.	Ohio State University	USA	70	3141	29	44.87
6	Welti Chanes, J.	Tecnol Monterrey	Mexico	62	1429	21	23.05
7	Barbosa-Canovas, G.	Washington State University	USA	62	3196	32	51.55
8	Knorr, D.	Tech University Berlin	Germany	61	5018	36	82.26
9	Alpas, H.	Middle East Tech University	Turkey	61	2228	27	36.52
10	Ramaswamy, H.	McGill University	Canada	60	1488	23	24.80
11	Michiels, C.	Katholieke University Leuven	Belgium	59	3778	36	64.03
12	Hu, X.	China Agr University	People's R China	58	1921	25	33.12
13	Barba, F.	University Valencia	Spain	56	3697	36	66.02
14	Wang, Y.	China Agr University	People's R China	51	1208	19	23.69
15	Chen, H.	South China Agr University	People's R China	51	1715	26	33.63
16	Cristianini, M.	University Estadual Campinas	Brazil	50	993	19	19.86
17	Guamis, B.	University Autonoma Barcelona	Spain	50	2024	30	40.48
18	Srinivasa Rao, P.	Indian Inst Technol Kharagpur	India	49	1369	21	27.94
19	Swanson, B.	Washington State University	USA	45	2379	28	52.87
20	Heinz, V.	German Inst Food Techno	Germany	44	2452	25	55.73

R = Ranking; TP = Total Publications; TC = Total Cites; H = h-index; C/P = Cites per publication.

3.1.4. Scientific Production in the Years 1975–2023

Figure 2 shows the temporal evolution of the scientific population and their respective citations throughout the period under study. The graph shows an incipient and variable development of publications up to 1990, where the number of publications does not exceed 20 publications per year, then the number of publications increases over time to reach about 500 publications per year in the last 5 years of analysis. Concerning the number of citations per year, a similar development occurs, as with the number of publications.

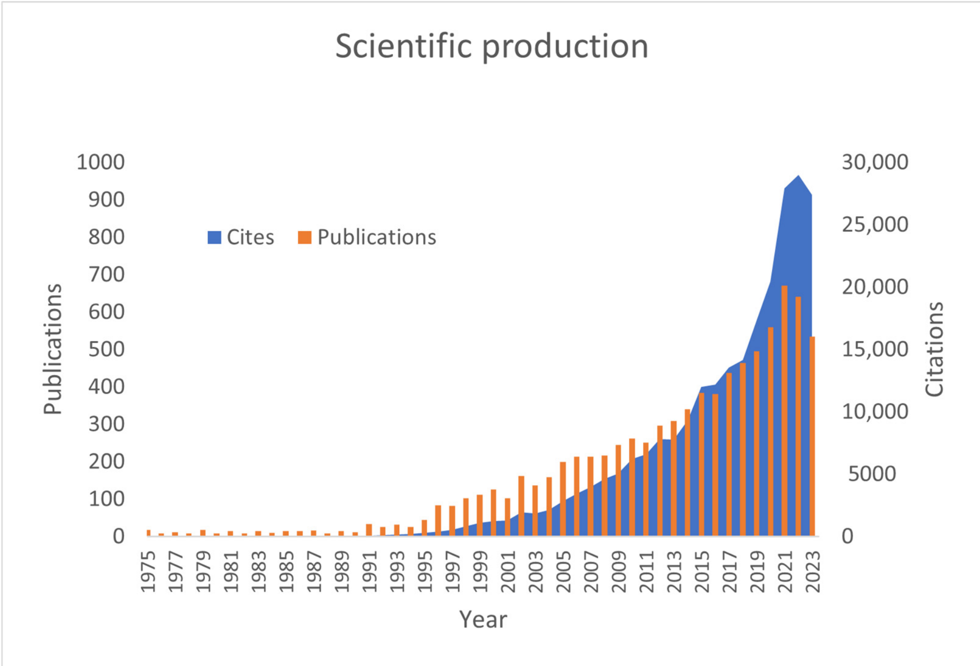

Figure 2. Citations and publications 1975–2023.

3.1.5. Financing Agencies

Table 4 presents the indicators on the productivity of funding agencies reported by researchers in publications on high hydrostatic pressures. In first place is the National Natural Science Foundation of China with 646 publications, 14,611 citations, and an h-index of 57. The second place is occupied by the Spanish Government with 382 publications. It is noteworthy that 50% of the most important funding agencies in the field of high hydrostatic pressures are located in Asia (Japan and China), which could be an indicator that high hydrostatic pressures are an important topic for researchers and industries in these countries.

Table 4. Top 10 Funding Agencies in HHP research.

R	Funding Agency	Country	TP	TC	H
1	National Natural Science Foundation of China	People's R China	646	14,611	57
2	Spanish government	Spain	382	11,190	55
3	European Union EU	-	310	9424	52
4	Fundação para a Ciência e a Tecnologia	Portugal	155	4174	34
5	Conselho Nacional de Desenvolvimento Científico e Tecnológico	Brazil	137	2934	31
6	Ministry of education culture sports science and technology	Japan	136	2984	25
7	Japan Society for the promotion of science	Japan	124	2804	24
8	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	Brazil	116	2494	29
9	Grants in aid for scientific research kakenhi	Japan	114	2712	24
10	National key R+D program of China	People's R China	108	2103	21

R = Ranking; TP = Total Publications; TC = Total Cites; H = h-index; C/P = Cites per publication.

3.2. Visibility

3.2.1. Top 20 Most Cited Articles

Table 5 contains a list of the 20 articles with the highest number of citations in the topic of high hydrostatic pressures in the Web of Science database for the years 1975–2023. The table shows that most of the documents correspond to review papers (65%), 30% to original research papers and finally only one article in the form of a proceeding paper.

Among the top ten most cited papers, bioactive compounds and food preservation through HHP represent the central topics in 60% (6/10) of these articles. The remaining articles (4/10) focus on food safety, the effect of HHP on the nutritional properties of foodstuffs, and the opportunities and challenges surrounding the application of HHP.

In articles discussing bioactive compounds, the emphasis was primarily on extraction techniques. Three articles on food preservation focused on preservation strategies, such as the use of bacteriocins. Those articles related to food safety described mechanisms of microbial pathogen inactivation and the parameters influencing microbial resistance. The effects of HPP on various foodstuffs were also assessed, with a particular focus on proteins. Additionally, the work published by Rastogi et al. (2007) [14] on the opportunities and challenges in high-pressure processing of foods spans topics from the food sectors that might benefit from this technology to the combined effects of HHP with other processing technologies.

Looking at the three most frequently cited articles, the work with the highest frequency of citations, with 1442 citations, refers to a review that studies the different models of spore resistance of microorganisms of the genus Bacillus in hostile environments, where ultra-high hydrostatic pressures are included among other stress agents, written by the authors Nicholson, W.; Munakata, N.; Horneck, G.; Melosh, H.; and Setlow, P. [15], published in the journal *Microbiology and Molecular Biology Reviews* in 2000, with a total of 57.68 citations per year.

The second article in the list, with 1381 citations, explores different techniques for the conventional and unconventional extraction of bioactive compounds with emphasis on issues such as efficiency and mechanisms of action for the extraction of bioactive compounds from medicinal plants. This paper was published in the *Journal of Food Engineering* in the year 2013 by authors Azmir, J.; Zaidul, I.S.M.M.; Rahman, M.M.; Sharif, K.M.; Mohamed, A.; Sahena, F.; Jahurul, M.H.A.; Ghafoor, K.; Norulaini, N.A.N.; and Omar, A.K.M. [16], accounting 115.08 citations per year.

Finally, the third most cited article corresponds to the work of authors Galvez, A.; Abriouel, H.; Lopez, R.; and Omar, N. [17], with 763 citations during the period of 1975–2023. This study aims to provide an insight into the use of bacteriocins as a food biopreservation method in combination with non-thermal treatments such as high hydrostatic pressures and thus providing additional barriers to obtain more effective preservation methods. The work was published in 2007 in the *International Journal of Food Microbiology* and presents a number of citations per year, totaling 42.39. On the other hand, the article ranked sixth in the list is the one that presents the highest metric in terms of the number of citations per year, with a total of 75.75.

The great importance of food quality and safety worldwide is reflected in the most frequently cited topics, including food preservation. For instance, the most cited article on the resistance of Bacillus endospores to extreme terrestrial and extraterrestrial environments highlights the significance of understanding the factors that influence the survival and resistance of bacterial spores, the control of which presents a challenge in the food industry [15].

Moreover, it can be noticed that articles regarding the extraction of bioactive compounds are among the topmost cited papers. The dominance of this topic reflects the interest of the scientific sector not only in taking advantage of plant food components but also in identifying compounds that generate added value to the food we consume, as well as its application in pharmaceuticals and the chemical sector. In this sense, these papers reflect a noticeable concern in identifying proper extraction methods for the obtention of quality compounds [15,18,19]. Since HHP is recognized as a promising and efficient method for food processing and preservation, as well as for the extraction of bioactive compounds, its application has steadily increased over time [3,10].

It is important to mention that, due to significant interest, these topics generate within the scientific community, and a considerable proportion of the most cited articles are reviews, which typically exhibit a higher citation rate compared to original research papers [20].

Table 5. 20 Most cited articles in HHP.

R	TC	Title	Authors	Ref.	Type	Year	C/Y
1	1442	Resistance of *Bacillus* endospores to extreme terrestrial and extraterrestrial environments	Nicholson, W.L.; Munakata, N.; Horneck, G.; Melosh, HJ.; Setlow, P.	[15]	r	2000	57.68
2	1381	Techniques for extraction of bioactive compounds from plant materials: A review	Azmir, J.; Zaidul, I.S.M.; Rahman, M.M.; Sharif, K.M.; Mohamed, A.; Sahena, F.; Jahurul, M.H.A.; Ghafoor, K.; Norulaini, N.A.N.; Omar, A.K.M.	[16]	r	2013	115.08
3	763	Bacteriocin-based strategies for food biopreservation	Galvez, A.; Abriouel, H.; Lopez, R.L.; Ben Omar, N.	[17]	a; pp	2007	42.39
4	713	Techniques for Analysis of Plant Phenolic Compounds	Khoddami, A.; Wilkes, M.A.; Roberts, T.H.	[18]	r	2013	59.42
5	701	Preservative agents in foods—Mode of action and microbial resistance mechanisms	Brul, S.; Coote.; P.	[21]	r	1999	26.96
6	606	Natural Antioxidants in Foods and Medicinal Plants: Extraction, Assessment and Resources	Xu, D.P.; Li, Y.; Meng, X.; Zhou, T.; Zhou, Y.; Zheng, J.; Zhang, J.J.; Li, H.B.;	[19]	r	2017	75.75
7	601	High pressure effects on protein structure and function	Mozhaev, V.V.; Heremans, K.; Frank, J.; Masson, P.; Balny, C.	[22]	a	1996	20.72
8	590	Proteins under pressure—the influence of high hydrostatic-pressure on structure, function and assembly of proteins and protein complexes	Gross, M.; Jaenicke, R.	[23]	r	1994	19.03
9	579	Review: High-pressure, microbial inactivation and food preservation	Cheftel, J.C.	[24]	r	1995	19.3
10	572	Opportunities and challenges in high pressure processing of foods	Rastogi, N.K.; Raghavarao, K.S.M.S.; Balasubramaniam, V.M.; Niranjan, K.; Knorr, D.	[14]	r	2007	31.78
11	518	Effects of high pressure on meat: A review	Cheftel, J.C.; Culioli, J.	[25]	r	1997	18.5
12	511	Application of Natural Antimicrobials for Food Preservation	Tiwari, B.K.; Valdramidis, V.P.; O'Donnell, C.P.; Muthukumarappan, K.; Bourke, P.; Cullen, P.J.	[26]	r	2009	31.94
13	494	Recent advances in the microbiology of high pressure processing	Smelt, J.P.P.M.	[27]	a	1998	18.3
14	488	Extraction of anthocyanins from grape by-products assisted by ultrasonics, high hydrostatic pressure or pulsed electric fields: A comparison	Corrales, M.; Toepfl, S.; Butz, P.; Knorr, D.; Tauscher, B.	[28]	a	2008	28.71
15	485	Biological effects of high hydrostatic pressure on food microorganisms	Hoover, D.G.; Metrick, C.; Papineau, A.M.; Farkas, D.F.; Knorr, D.	[29]	a	1989	13.47
16	473	Pressure stability of proteins	Silva, J.L.; Weber, G.	[30]	r	1993	14.78
17	466	Effect of high-pressure processing on colour, texture and flavour of fruit- and vegetable-based food products: a review	Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M.	[31]	a	2008	27.41
18	450	Impact of high pressure processing on total antioxidant activity, phenolic, ascorbic acid, anthocyanin content and colour of strawberry and blackberry purees	Patras, A.; Brunton, N.P.; Da Pieve, S.; Butler, F.	[32]	a	2009	28.13
19	445	Antioxidants of Natural Plant Origins: From Sources to Food Industry Applications	Lourenco, S.C.; Moldao-Martins, M.; Alves, V.D.	[33]	r	2019	74.17
20	439	Emerging technologies for the pretreatment of lignocellulosic biomass	Hassan, S.S.; Williams, G.A.; Jaiswal, A.K.	[34]	r	2018	62.71

R = Ranking; TP = Total Publications; Ref = Reference; C/Y = Cites per year; a = Research article; r = Review; pp = Proceeding paper.

3.2.2. Bibliometrics Relationships

Figure 3 presents the bibliometric citation ratio by organization. Of the 4637 organizations presented in the dataset, 221 exceed the threshold of 15 documents per organization and are presented in the diagram, which shows six clusters with different colors. Polish Academy of Sciences is the most prominent in cluster 1 with 147 documents and 1423 in total link strength, China Agricultural University, in cluster 2, is the most prominent with 216 documents and a total link strength of 6226. Cluster 3 presents two prominent organizations (Consejo Superior de Investigaciones Científicas-CSIC and Katholieke Universiteit Leuven) with 207 and 177 documents, respectively. On the other hand, Universidade de Aveiro is the most important in cluster 4 with 145 documents. In the orange cluster (5), Washington State University, Ohio State University, and University of Delaware have similar metrics and are the most important. Finally, in the light blue cluster 6, Oregon State University is the most important with 92 documents and a total link strength of 3280.

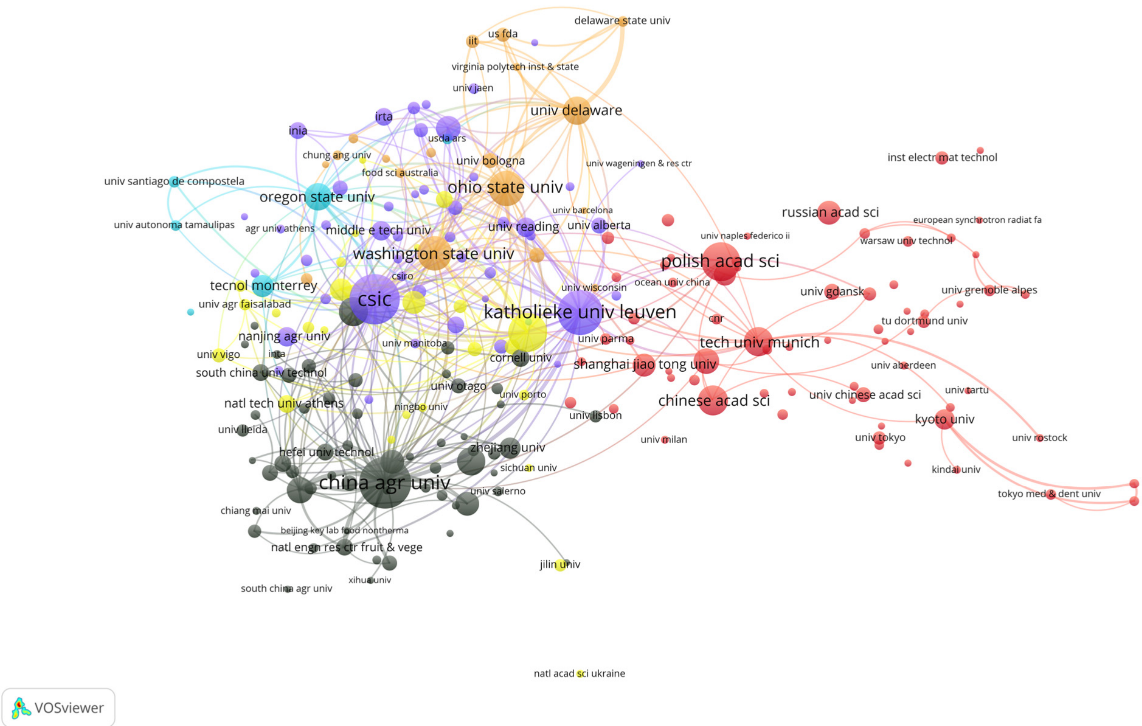

Figure 3. Citation by organizations.

The data processed from 23,241 authors shows that in Figure 4, 153 authors have met the threshold of 15 documents each. Out of those 153 authors, 149 have been distributed into 12 clusters with different colors. However, four authors were not related and were eliminated from the figure. The authors with the highest metrics are Saraiva, Jorge with 120 documents, 2678 citations, and a total link strength of 4733.9. Following him is Liao, Xiaojun with 114 documents, 3245 citations, and 5288.1 in total link strength. If we examine the color scale at the bottom of the graph, we can see how the relative importance of the authors varies over time.

Figure 5 is presented as a heat map plot and contains the co-citation ratio for the different cited sources included in the dataset, and this relationship occurs when two items are cited together by a third party. Of the 33,052 sources, 202 reached the threshold of 250 citations of a source. In the figure, three clusters can be observed. Cluster number 1, in red, groups 95 items, and the source with the highest metrics is *Applied and Environmental Microbiology* with 8144 citations, a total link strength of 6946.4, and 200 links. Cluster 2, in green color, groups 71 items and the journal that stands out the most is *Food Chemistry* with 17,962 citations and a total link strength of 15,633.5. The blue cluster contains 36 items where the most prominent source is *Journal of Food Science* with 11,457 citations and 10,294.5 in total link strength.

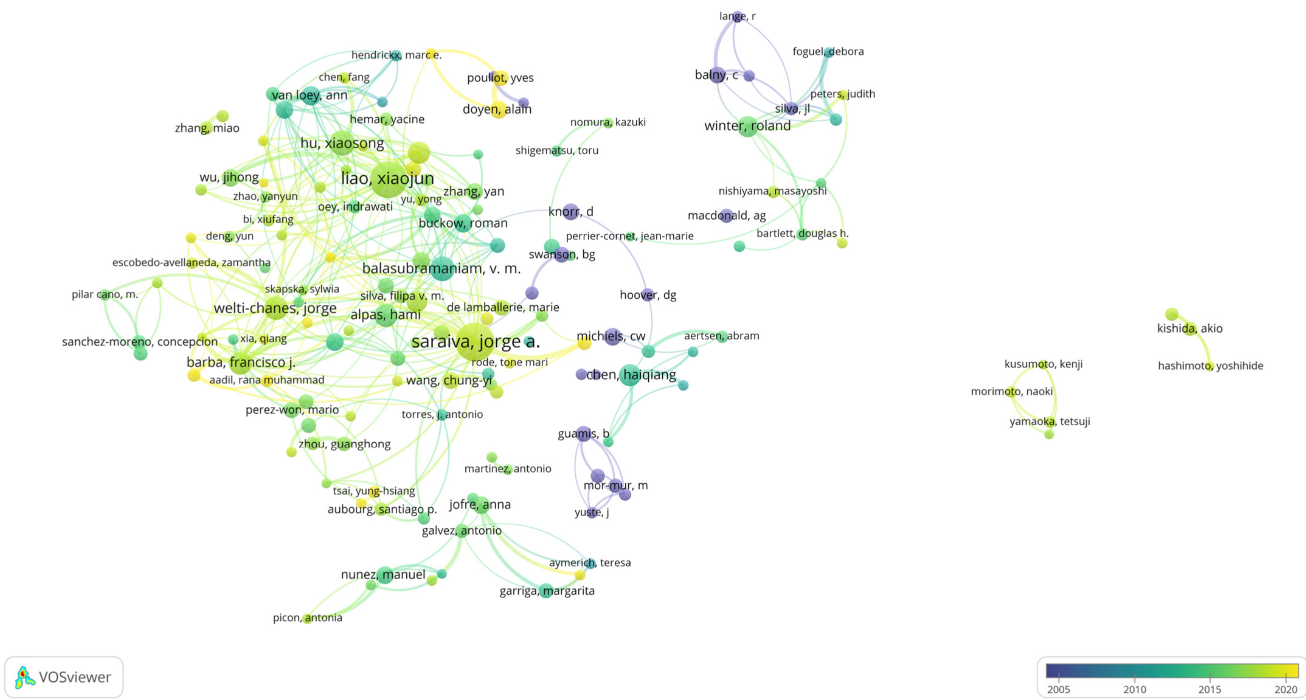

Figure 4. Bibliographic coupling by authors.

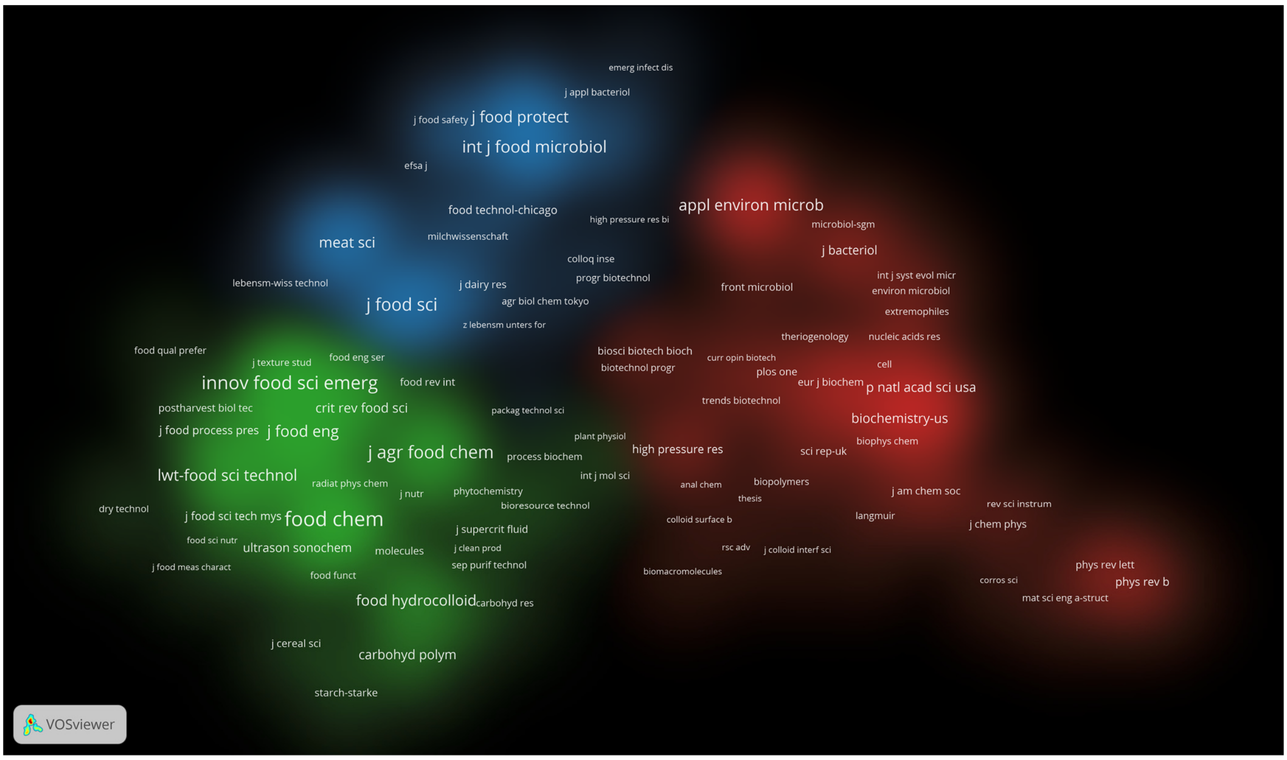

Figure 5. Co-citation, cited sources.

3.2.3. Keyword Frequency Analysis

Figure 6 shows a wordcloud graph showing the frequencies of words using the keyword plus field. The word with the highest frequency corresponds to 'inactivation' with

1034 occurrences given the high importance of topics related to the safety of high hydrostatic pressures. 'Temperature', with 845 occurrences, which may come from the evident relation and comparison of high hydrostatic pressures with classical thermal processes, and 'quality' also stands out with 792 occurrences. Conversely, it is important to highlight that words with lower frequencies could indicate new possibilities and research topics.

Figure 6. World cloud using keyword plus.

3.2.4. Foamtree WoS Areas

Figure 7 shows the article distribution in the different categories of the Web of Science. The figure shows that the groups with the largest number of publications are in the center and the smallest in the corners of the foamtree graph. The fiver groups with the highest number of publications are: *Food Science Technology* (55.8%), *Chemistry Applied* (9.93%), *Biotechnology Applied Microbiology* (9.06%), *Biochemistry Molecular Biology* (7.84%), and *Microbiology* (7.75%) with 4764, 848, 773, 669, and 662 publications, respectively.

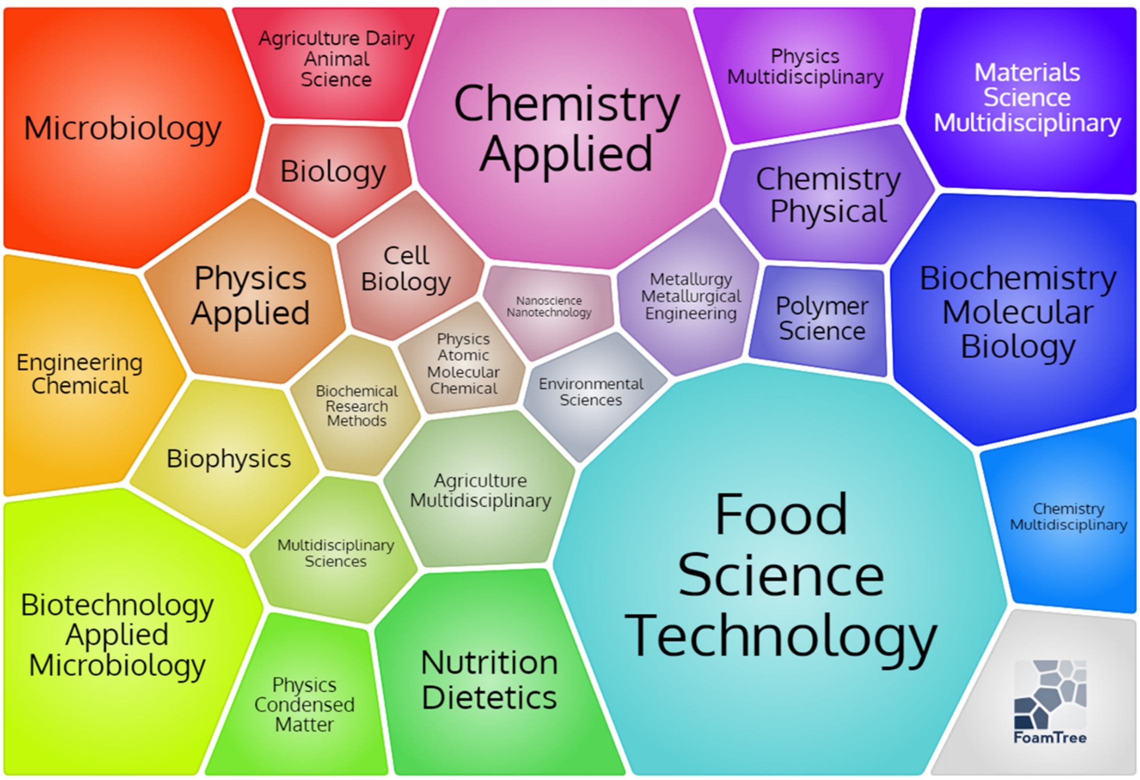

Figure 7. Foamtree WoS areas.

3.2.5. Sustainable Development Goals

Since 2023, the WoS database has considered associations between sets of micro-citations and the 16 Sustainable Development Goals outlined in the United Nations 2030 Development Agenda. In this way, it is possible to establish a link between which of the 16 SDGs the publications indexed in WoS are contributing to. Regarding goal number 17, "partnerships for the goals", it is important to mention that it is not included in the analysis.

Figure 8 below shows a foamtree containing the relationship between the scientific publications on the topic of high hydrostatic pressures and the U.N. SDGs. The figure shows that most of the publications are related to Sustainable Development Goal 3, "Good Health and Wellbeing" (66%), due to the relationship between the application of high hydrostatic pressures in food and food chemical composition issues, specifically the effect of high pressures on bioactive compounds, which is directly related to health and wellbeing issues. The h-index for publications in this SDG is 148, with a citation ratio per article of 32.04. The second SDG with the most publications is "Zero Hunger", with about 5% of the publications in the dataset, an h-index of 55, and 26.30 citations per article. Then comes SDG 07, titled "Affordable and Clean Energy", with a percentage close to 3%, an h-index 32, and 17.21 citation per article. The rest of the SDGs present a low number of relationships with the publications on high hydrostatic pressures in the period of 1975–2023. SDG 10, 1, and 16 (Reduced Inequalities; No Poverty; Peace, Justice, and Strong Institutions) showed no relationship with the publications on high hydrostatic pressures in the analyzed period.

Analyzing the relationship of publications to the SDG Sustainable Development Goals helps to establish roadmaps to guide future research in HHP and to understand that it contributes to sustainable development, specifically in the areas of food waste reduction, food safety, retention of bioactive compounds of interest for human nutrition, and energy-efficient food preservation methods.

Figure 8. SDGs and publications in HHPP.

3.3. Evolution

3.3.1. Authors' Evolution

Figure 9 shows that one of the authors with the greatest presence and influence during the time analyzed is the author Knorr, D., who has an important presence from 1989 to 2021. In addition to the aforementioned author, the author Barbosa-Canovas, with affiliation at Washington State University, stands out for his contribution to the topic of high hydrostatic pressures. Finally, in the most recent periods, the influence of the author from the University of Valencia in Spain, Barba, J., stands out as well.

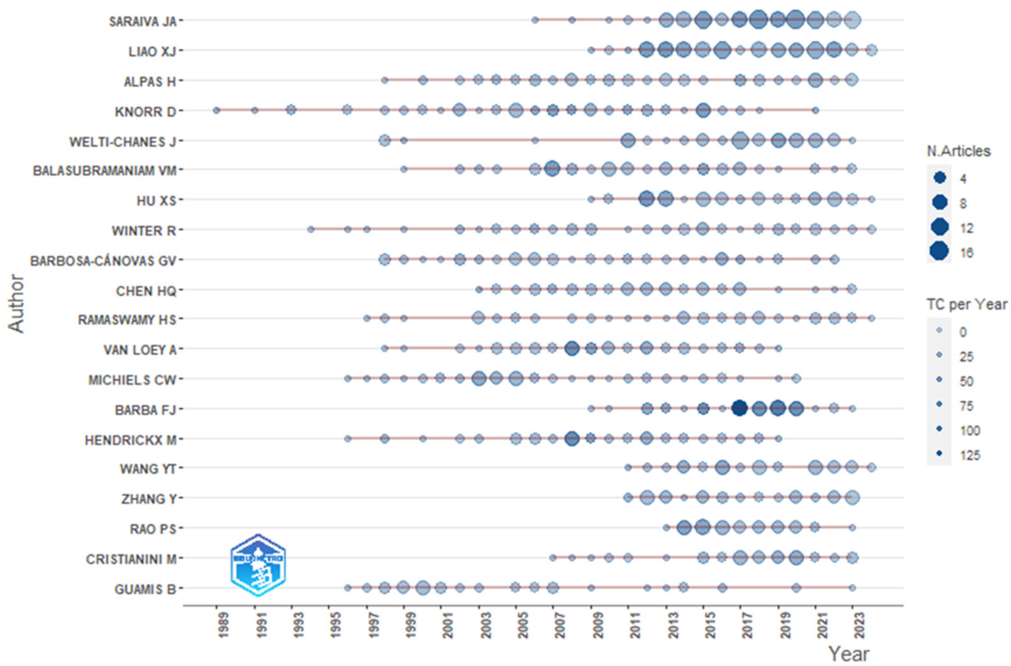

Figure 9. Authors' Production: 1975–2023.

3.3.2. Thematic Map

Figure 10 shows the distribution of the most important topics divided into four quadrants. In the niche quadrant (low frequency, high strength), the following concepts stand out: inactivation (1034), *Listeria monocytogenes* (587), and *Escherichia coli* (529). In the motor themes quadrant (high frequency, high strength), the most important themes are quality (792), antioxidant activity (461), and shelf life (420). The emerging or declining themes (high frequency, low strength) are functional properties (317), beta lactoglobulin (189), and rheological properties (175). Finally, the quadrant containing the basic themes (low frequency, low strength) has temperature (845), stability (446), and heat, with 367. There are no shared themes within the quadrants.

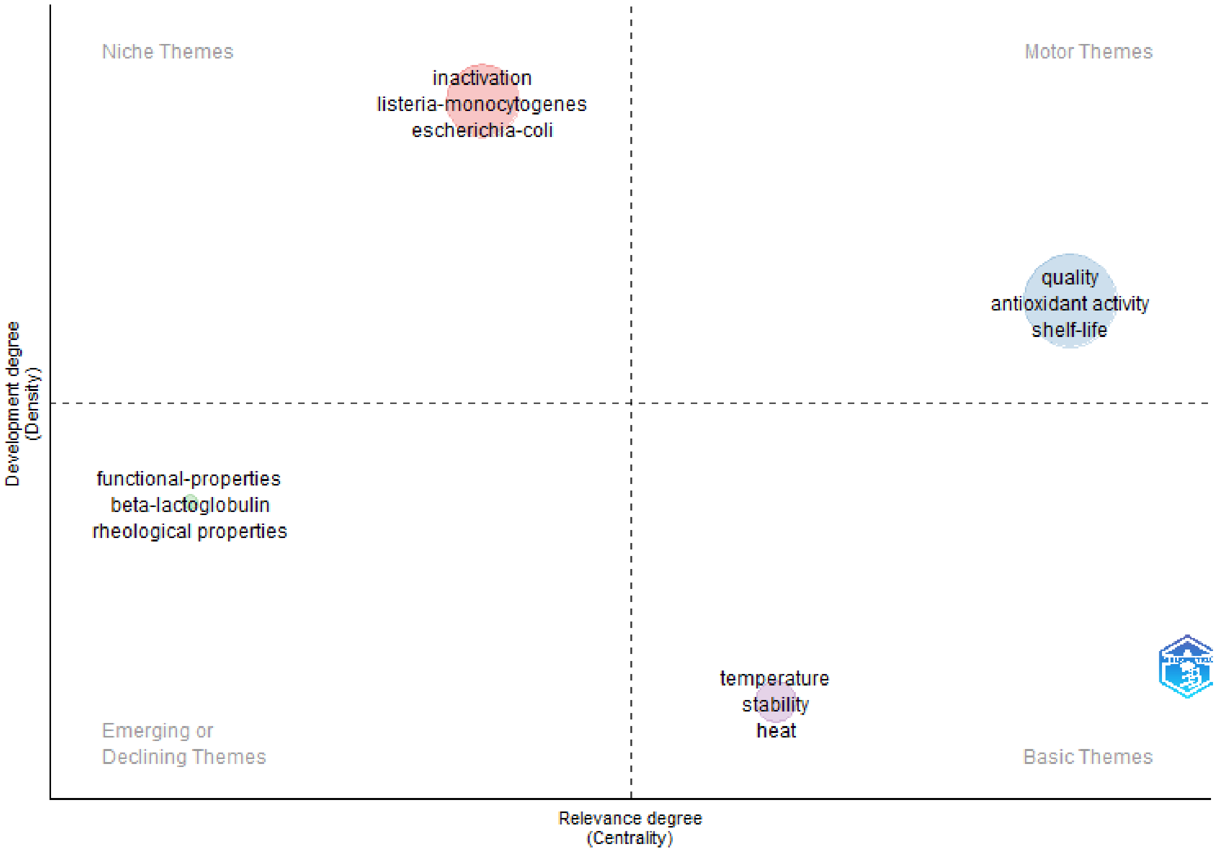

Figure 10. Thematic map using keyword plus.

3.3.3. Thematic Evolution

Figure 11 shows the thematic evolution of the publications on high hydrostatic pressures considering the author keyword field for the periods of 1975–1994, 1995–2004, 2005–2014, and 2015–2024. In the first period, the topics are more related to the phenomenon of application of high pressures as such, then, from the following period onwards, a greater diversification is observed. In the period of 1995–2004, topics related to the effects of the application of high pressures on physical and quality properties are observed; in the period of 2005–2014, comparison with thermal processes appears; and finally, between 2015 and 2024, quality characteristics and compounds with biological activity such as antioxidants are highlighted.

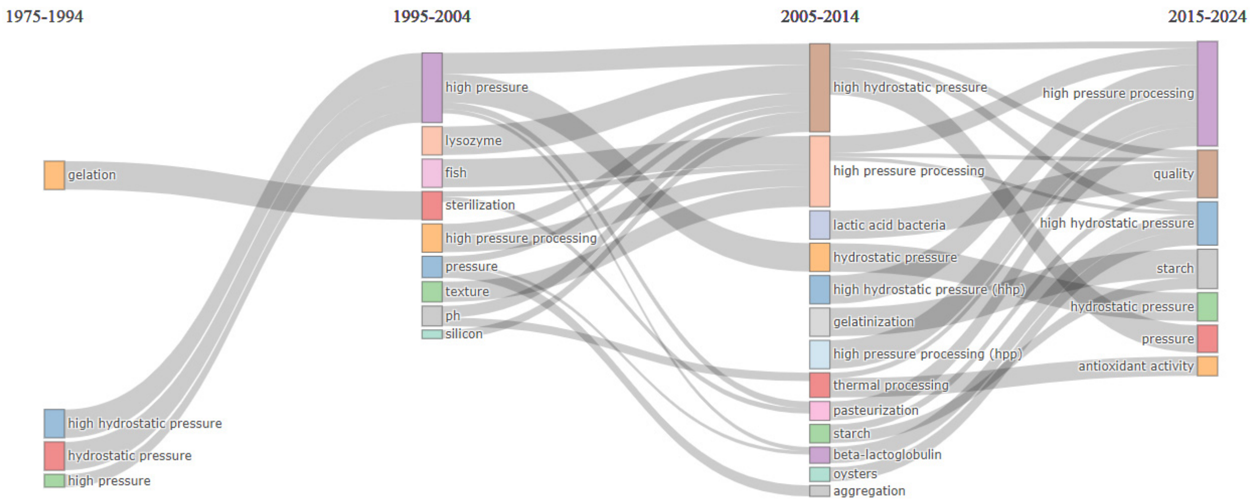

Figure 11. Thematic evolution.

3.3.4. Journals Evolution

Figure 12 illustrates the temporal evolution of the five main journals in the field of high hydrostatic pressures. In the early years, discrete progress is observed until the early 2000s, at which point the subject begins to gain relevance. The significant development of *Innovative Food Science & Emerging Technologies*, a specialized journal that was founded in 2000 and has experienced remarkable growth over time, is noteworthy. Similar progress can be seen in the journals *Food Chemistry* and *LWT-Food Science and Technology*, which have a more general focus. *Foods*, on the other hand, was created in 2012 and shows rapid development, especially from 2017, compared to the others. Finally, *High Pressure Research*, founded in 1998, is the journal that has experienced the most discrete growth over the years.

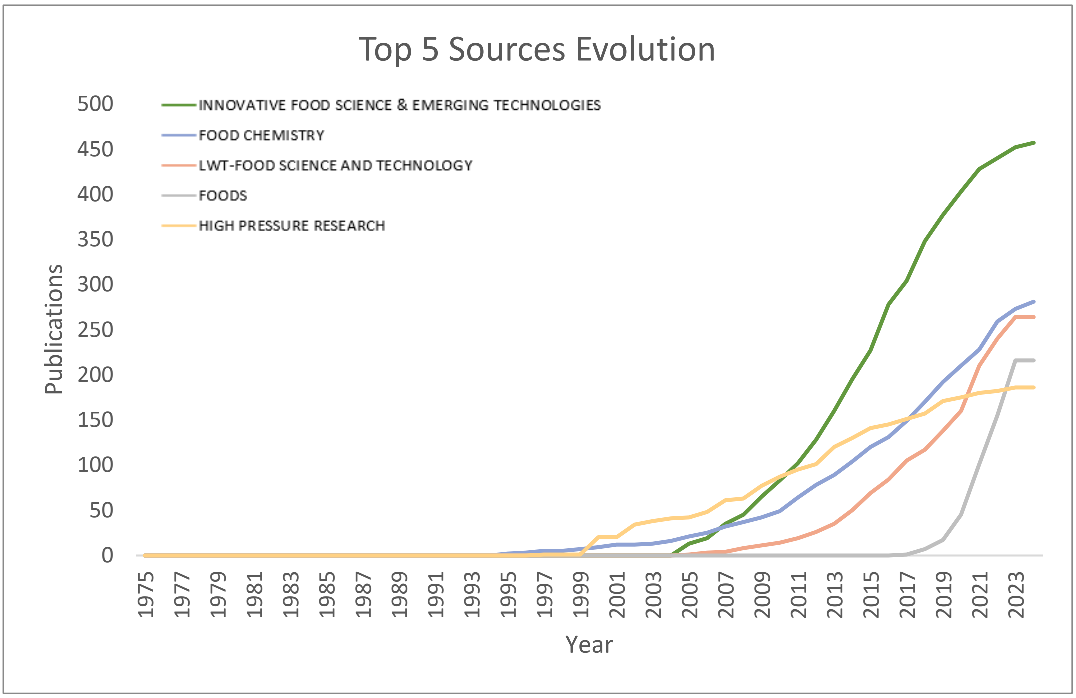

Figure 12. Evolution of top 5 journals in HHP publications.

4. Conclusions

The bibliometric analysis conducted for the articles published regarding high hydrostatic pressure has uncovered some interesting insights. The analysis revealed that the main areas of research belong to the fields of Food Science Technology, Applied Chemistry, and Applied Microbiology. Additionally, there has been a significant increase in publications on this topic from the year 2000 onwards, which has been sustained until the end of the period analyzed. This trend indicates the growing importance of high hydrostatic pressure research and also gives an idea of what we can expect in the coming years.

Furthermore, the analysis also sheds light on the most influential countries, institutions, and authors in this field. China, the USA, and Spain are the highest ranked countries in terms of research output, while Saraiva, J., Hendrickx, M., and Wang, T. are the most influential authors and highly productive. This information may be valuable for researchers interested in this area.

While the most productive countries in HHP are not necessarily the most productive in other fields. The People's Republic of China stands out as one of the top countries across various metrics. These metrics include productivity, authorship, funding agencies, and citations by organizations. In terms of bibliographic coupling by authors, it is evident that

Saraiva, J., from the University of Aveiro, Portugal, has the strongest link strength with Liao, X., from China Agricultural University, China.

In conclusion, the use of various bibliometric tools has enabled the identification of key trends and provided valuable information for researchers focused on the field of high hydrostatic pressure. The subject of high hydrostatic pressure is a field that has undergone substantial growth and has applications in diverse fields related to food sciences and nutrition, among others.

It is worth noting that this particular study relies on bibliometric analysis, which only takes into account publications indexed in the WoS database. Therefore, it may not encompass all relevant information and may exclude works published in journals not indexed in WoS, as well as other types of publications like technical reports and websites that could contain valuable insights.

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