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Plant Allelopathy Research and Development: 60 Years (1960-2019)

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ABSTRACT

Plant allelopathy is a biological phenomenon in which plants adapt to defend against the pests (weeds, insects, nematodes and pathogens) adverse environment. It is one of the hotspots in Ecology and Agronomy. In this paper, we have retrieved from the Web of Science (WoS) SCI-E database the allelopathy-related studies (1960-2019). The Annual Number of Publications, Authors, Countries, Institutions, Journals and Keywords were analyzed by the bibliometric method to determine the research trends and hotspot changes in this field over the past 6 decades. From 1960-2019, the WoS database included 4,114 studies in the field of plant allelopathy. During this period of 60 years, the number of publications has gone through three stages: (i). Initial Stage (1960-1990), (ii). Growing Stage (1991-2009) and (iii). Stable Stage (2010-2019). The studies were conducted by 9,956 authors at 2,166 institutions across 100 countries. The United States, China, and Japan have the highest number of publications. The top three institutions with the highest number of publications are the Chinese Academy of Sciences, Kagawa University and USDA, USA.

The top three authors are H. Kato-Noguchi, F.A. Macias, and C.H. Kong. The major Journals in this field are: (i). *Allelopathy Journal*, (ii). *Journal of Chemical Ecology* and (iii). *Plant and Soil*. The results of keyword clustering showed that the main research directions in this field are: (i). Metabonomics undergoing allelopathy, (ii). Functions of allelopathy substances, (iii). Molecular biology, (iv). Allelopathy of

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aquatic plants, (v). Alien plants invasion and (vi). Application of plant allelopathy in agroforestry production. Plant allelopathy is a research field that aims to maintain stable development. Future studies should focus on strengthening the cooperation among international scholars in plant allelopathy research and improving the output in frontier and hotspot areas.

Keywords: Allelopathy, bibliometric analysis, collaborative allelopathy Research, Development, keyword analysis, plant allelopathy, Research, Web of Science.

1. BRIEF ANCIENT HISTORY OF ALLELOPATHY RESEARCH

The oldest record about the Allelopathy originated in 594 BC in Laws of Solon (c638-C 559cBC), which suggested that trees should be planted at spacing of at least 5-9 feet, without harmful effects on each other due to their effluvia (41). R.J. Wills (2007) book '*History of Allelopathy*" gave detailed History from ancient Roman, Greek, Indian, Chinese and Japanese Literature till 1957.

Prof. Hans Molisch in 1937 coined the term Allelopathy *"Allelopathy refers to all biochemical interactions (stimulatory or inhibitory) among plants, including micro-organisms"*. It was modified by E.L. Rice as *"Allelopathy is inhibitory or stimulatory effects of one plant on another"* and the IAS (1996) gave the New definition *"Allelopathy refers to any process involving secondary metabolites produced by plants, microorganisms, viruses and fungi that influence the growth and development of agricultural and biological systems"* being used presently. However, the establishment of Scientific Societies and organization of Conferences on Allelopathy started > 50-Years after 1937 (i.e. after the definition of Allelopathy was coined).

2. MODERN ALLELOPATHY RESEARCH

The term allelopathy, coined by Molisch (24) in 1937, is derived from two Greek words 'allelo' and 'pathos' means reciprocal sufferings of two organisms (14). In 1974, Rice (31) defined allelopathy as a phenomenon in which a plant directly or indirectly damages another kind of plant or microorganism by releasing chemicals into the environment. Some studies showed that chemicals released from the plants may be harmful not only to other plants but also to themselves (26), or may be beneficial to other plants (30). In 1984, Rice (32) redefined allelopathy as the beneficial or disadvantageous effects of the metabolic secretions of plants or microorganisms on other plants or microorganisms in the environment. Plant allelopathy is a model of interaction between receptor and donor plants and may play positive (e.g., weed control, crop protection, or crop reconstruction) and negative roles (e.g. autotoxicity, soil disease, or biological invasion). In the past several decades, plant allelopathy has been one of the research hotspots in Botany, Ecology, Agriculture and Forestry. Great achievements have been made in the allelopathy of invasive plants (7), control of harmful algae, such as algal blooms and red tides (11), agroforestry production (17,35,43), restoration and reconstruction of grassland vegetation (4), and medicinal plant cultivation (16).

The bibliometric method, which integrates mathematics, statistics, and philology, is an important means of statistical and visual analyses of literature. This method aims to explore the changing laws of literature-based information through data analysis to predict the future development trends and research hotspots in a certain field (33). In recent years, a large number of studies have analyzed the research status and progress in different disciplines by bibliometric analysis. For example, based on the Web of Science (WoS) database, bibliometric analysis has been adopted to analyze environmental economics (10), biological diversity (2), and ecological networks (6). Bibliometric analysis can be used to

evaluate the developmental history and current research situation in a certain field, reveal the research directions and hotspots in this field, and predict future developmental trends. Although many papers review the progress of plant allelopathy research (9), no work has revealed the international research trends and hotspots of plant allelopathy based on bibliometric analysis.

Based on the WoS SCI-E database, bibliometric analysis was conducted on the Annual Number of Publications, Authors, Countries, Institutions, Journals and Keywords of studies on allelopathy published from 1960-2019. These analyses were done to (i) Qualitatively and quantitatively analyze the bibliometric overview of plant allelopathy research, including annual number of publications, authors, countries, institutions, and journals, (ii) Describe the current situation and trend of the cooperation among authors, countries, and institutions and (iii) Reveal the research hotspots and development trends of plant allelopathy in past 60 years.

2.1. METHODS USED

Data sources

WoS is the world's largest comprehensive academic information resource database, covers the largest number of disciplines and provides the deepest retrospective citation data. In this paper, subject-based retrieval is adopted using the SCI-E database in the WoS core collection as the data source. The retrieval type is TS= "Allelopathy" or "Allelochemicals" or "Allelopathic", and the time span is 1968–2017 (50 years). The abstracts of some studies are consulted to determine whether they are consistent with the research contents of plant allelopathy; unrelated studies are excluded. Ultimately, 3,732 papers are retrieved. The bibliographic information of each paper is extracted and recorded, including date of publication, author, journal, author's country and institution, and keywords.

Data analysis

The data from the literature are analyzed and processed using the WoS database bibliometric analysis tool and the professional bibliometric analysis software, BibExcel (29). The data are visualized using Pajek (25) and VOS viewer (40). BibExcel has the functions of co-citation analysis, citation analysis, clustering analysis, citation coupling analysis, and scientific knowledge mapping. Pajek is a package for analyzing and visualizing large-scale networks and society network analysis software integrating network drawing and network analysis. VOS viewer visualization analysis software is free software and can perform clustering and co-occurrence visualization analysis on literature, authors, countries, keywords, and so on. This software has strong graphics representation ability and can reveal the flow and transfer of knowledge among literature through the color and size of graphic as well as the thickness of lines to reflect the similarity, intimacy, and citation relationship among literature. The abovementioned software has been widely used in Bibliometric research (22).

Citation reports (including Titles, Authors, Journals, Publication Years, and Number of Citations) of 4,114 papers from1960-2019 were exported using a basic bibliometric analysis tool provided by the WoS database. The distribution map of the annual number of publications and total number of citations is drawn based on the relevant data. The number of journals involved in the literature and their publications are analyzed. The influential factors of journals refer to the Journal Citation Reports published by Clarivate Analysis in 2019. The journals with prominent influence in this field are determined by the number of papers published and the influential factors of journals. The information on authors, countries, and research institutions involved in the literature are extracted using the BibExcel software for frequency analysis. The cooperative relationship among different countries is drawn using the Pajek software. The cooperative relationship

among authors and institutions is drawn, and their cooperative strength is calculated, using VOS viewer. In addition, VOS viewer is used to make statistical analysis of the frequency of keyword occurrence and the intensity of correlation among keywords. The distribution of keywords is presented by circle size, thickness of lines, and color.

2.2. RESULTS

From 1960-2019, the global research on plant allelopathy showed trend (Fig. 1). Based on the number of publications in the past six decades, the research on allelopathy experienced three stages (Table 1):

I. Starting Stage (1960–1990): With a total of 123 papers over 31years, accounting for 2.99 % of the total number of publications and with an annual average of 3.97 papers published.

II. Growing Stage (1991–2009): With a total of 1,850 papers over 19years, accounting for 44.97 % of the total number of publications and with an annual average of 97.37 papers published.

III. Stable Stage (2010-2019): With a total of 2141 papers over10 years, accounting for 52.04 % of the total number of publications and with an annual average of 214.3papers published.

The total number of citations, 4,114 papers, shows a J-shaped increase (Fig. 1). Few papers and citations were made in the early stage. When the number of papers increased sharply, the number of citations also increased gradually. In 2019, the number of citations reached its peak. In 1984, Rice put forward a comprehensive concept of plant allelopathy (26). Afterward, scholars worldwide studied the functions of allelochemicals and allelopathy mechanisms (23); these results laid a solid foundation for follow-up studies. In 1991, relevant studies showed rapid development. In 2009, the number of publications reached its peak (239 papers). The number of publications has fluctuated slightly but is basically in a stable state, indicating that the study of plant allelopathy has entered a stable stage internationally. The research on plant allelopathy is expected to remain relatively stable in the future.

Table 1. Three stages of allelopathy research from 1960-2019

Allelopathy Research Stage	Duration (Years)	Research Papers published		
		Total	% of Total	Annual Mean
I. Starting Stage (1960-1990)	31	123	2.99	3.97
II. Growing Stage (1991-2009)	19	1850	44.97	97.37
III. Stable Stage (2010-2019)	10	2141	52.04	214.3

2.3. RESEARCH DISTRIBURTION

I. Principal authors

A total of 4,114 papers on plant allelopathy were written by 9,956 authors. As shown in Table 2 and Fig. 2, the top three authors in terms of the number of publications involving the allelopathy of common crops, function of allelochemicals, and interspecific and intraspecific chemical effects of plants are H. Kato-Noguchi, F.A. Macias and C.H. Kong. These authors have been cited many times and have a strong cooperative relationship with other scholars, and their research results have strong influence. In addition, R.M. Callaway has written relatively few papers published, but the total citation frequency of their papers related to invasive plants reaches 2,398, thereby ranking first.

Collaborative Authors: As observed from the cooperative relationship shown in Fig. 2, the authors from Japan and those working closely with them are mostly concentrated in the

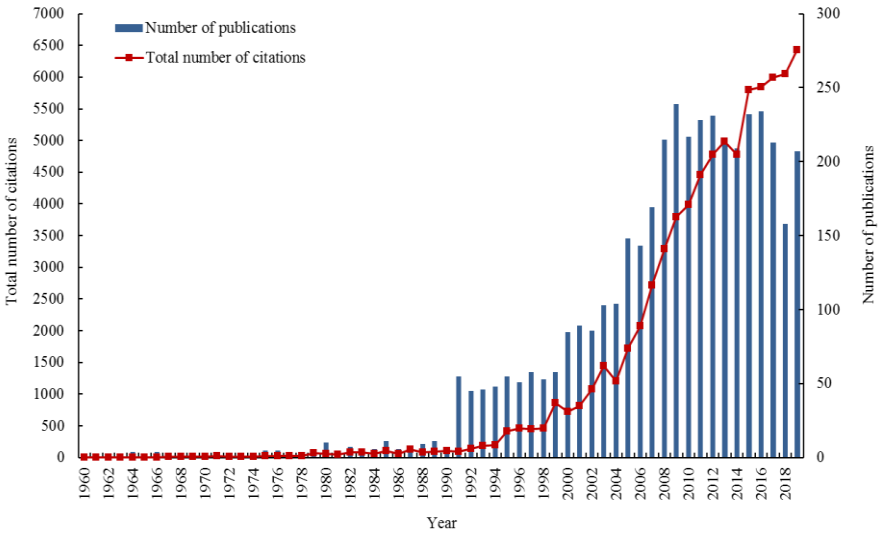

Figure 1. Number of allelopathy publications and total cited frequency distribution in 1960-2019.

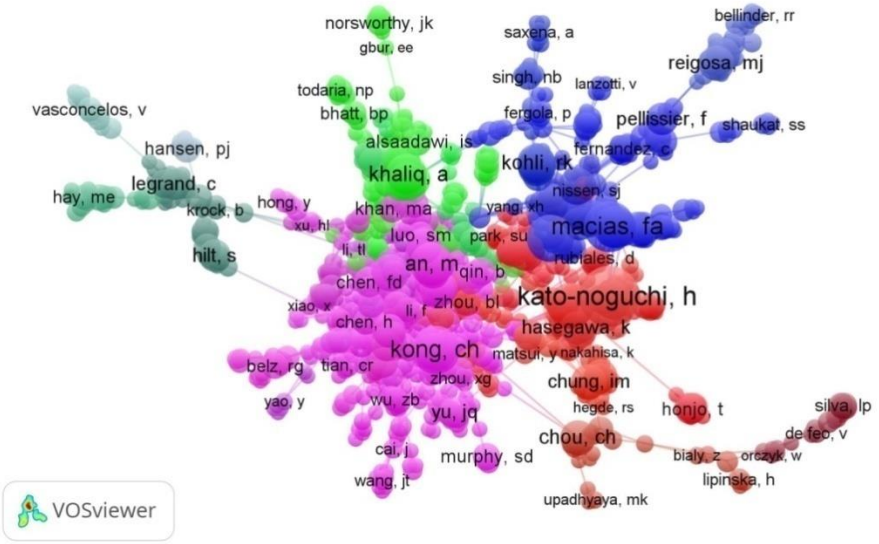

Figure 2. Distribution of all authors and their partnerships.

Note: Each circle represents an author, and the size of the circle represents the number of articles. A line connecting two circles illustrates a cooperative relationship between two authors. Circles with the same color indicate that the author is in a similar location or exhibits strong cooperation.

red areas; Chinese authors are concentrated in the pink areas; the authors from Spain and those who cooperated with them frequently are mostly found in the blue areas. F.A. Macias demonstrated the strongest cooperation with other authors among all the authors, followed by C.H. Kong and H. Kato-Noguchi. As far as the top 10 authors are concerned, H. Kato-Noguchi cooperates most closely with Y. Fujii, K. Suenaga, J.M.G. Mollinillo and F.A. Macias (Table 2).

Table 2. Top 10 most productive authors of allelopathy research papers

Order	Author	Number of publications	Number of citations	Total cooperation strength
1	Kato-Noguchi H.	94	873	181
2	Macias F. A.	57	1678	259
3	Kong C. H.	49	917	192
4	Fujii Y	48	619	157
5	Inderjit	43	1306	69
6	An M.	33	784	121
7	Molinillo J. M. G.	33	1022	162
8	Suenaga K.	32	127	93
9	Khaliq A	28	282	99
10	Callaway R. M.	25	2398	113

II. Main countries

A total of 4,114 studies on plant allelopathy were obtained from 100countries all over the world (Fig. 3, Table 3). The top several countries in terms of the number of publications are the United States (868 papers), China (743 papers), Japan (338 papers), Brazil (325 papers) and India (262 papers).

Table 3. Allelopathy Research Stages-wise Publications in top-3 countries and their Research Areas

Allelopathy Research Stages	Duration (Years)	Research Papers Published		
		Top 3-Countries	Research Areas (# Papers Published in each Area)	Number
I. Starting Stage (1960-1990)	31	USA	Biological suppression of weeds	16
		Canada	Allelopathy of common crops (wheat, rice, corn)	3
		Jamaica	Plant allelopathy	2
II. Growing Stage (1991-2009)	20	USA	Material and molecular basis of plant allelopathy	126
		Japan	Mechanisms of plant allelochemicals	43
		India	Ecophysiological aspects of allelopathy	37
III. Stable Stage (2010-2019)	10	China	Application of allelopathy	189
		USA	Allelopathy in invasive plants	127
		Brazil	Effects of allelochemicals on organisms	80

Collaborations: The United States, occupying the top position, cooperates closely with China, Japan, India, and Germany. China, in second place, cooperates frequently with the United States, Australia, Japan, and Pakistan; Japan, in the third place, cooperates closely with the United States, China, and Korea (Fig. 4). Approximately 10 publications were made without cooperation with other countries, such as Jordan, Serbia, and Sri Lanka, while only one study was made with cooperation with other countries, such as Albania, Libya, and Jamaica.

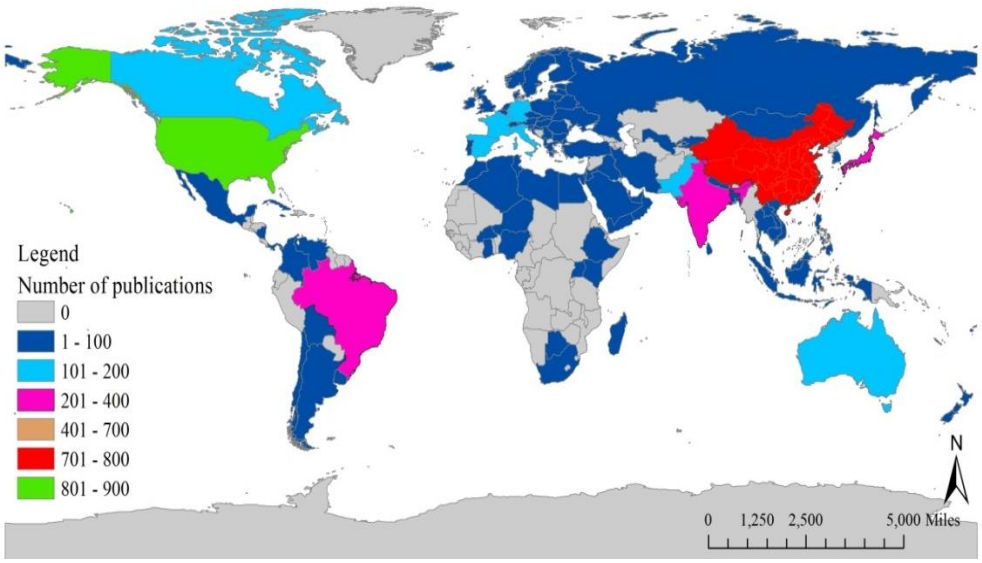

Figure 3. Number of allelopathy research papers published in different countries.

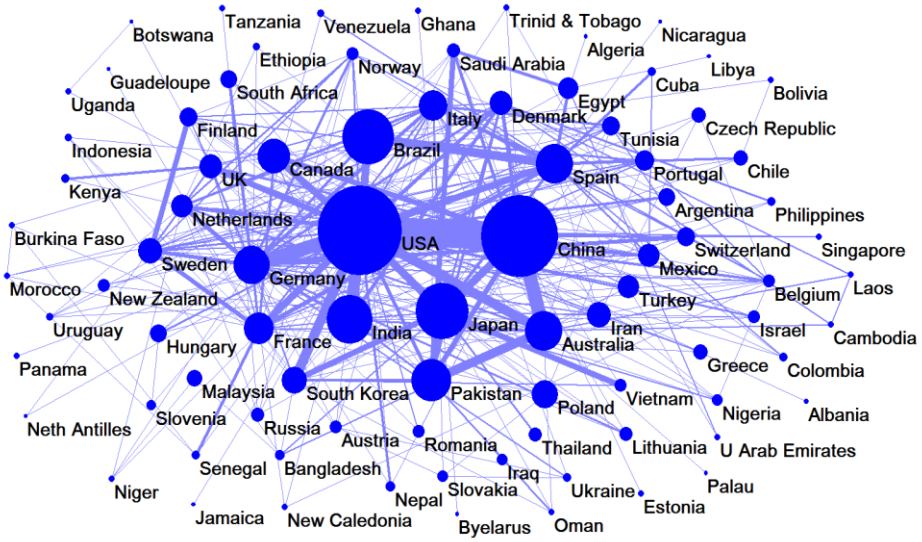

Figure 4. Visualization of cooperative relationships for allelopathy research between countries.

Note: Each circle represents a country/territory, and the size of the circle represents the number of articles. A line connecting two circles illustrates a cooperative relationship between two countries.

III. Main institutions

In the past six decades, 2,166 institutions participated in the study of plant allelopathy worldwide. The top three institutions in terms of the number of publications are: (i). Chinese Academy of Sciences (152 papers), (ii). Kagawa University (101 papers) and (iii). United States Department of Agriculture (89 papers) (Table 4). The aforementioned are the core institutions for the study of plant allelopathy in the world. Based on the total number of citations in papers (Table 4), the Chinese Academy of Sciences is ranked first (2,165), considerably higher than the University of Cádiz, which ranked second (1,339), and the United States Department of Agriculture, which ranked third (1,327).

Collaborative Institutions: The Chinese Academy of Sciences is the institution that published the most citations and the most papers on plant allelopathy, revealing that scholars from the Chinese Academy of Sciences have rich scientific research output and strong international influence in the field of plant allelopathy. Based on the collaboration among institutions (Fig. 5), the Chinese Academy of Sciences, with the strongest cooperative strength, cooperates strongly with China Agricultural University, the University of Chinese Academy of Sciences, Charles Sturt University in Australia, Montana University in the United States. The USDA (United States Department of Agriculture), ranking second in terms of cooperative strength, cooperates closely with Cornell University, Colorado State University, and other institutions. Kagawa University of Japan cooperates closely with University of Cádiz, Spain; University of Agriculture Faisalabad, Pakistan cooperates frequently with University of Tsukuba, Japan and the University of Western Australia.

Table 4. Top most productive institutions in Allelopathy Research

Order	Institution	Country	Number of publications	Number of citations	Total cooperation strength
1	Chinese Academy of Sciences	China	152	2165	192
2	Kagawa University	Japan	101	968	85
3	United States Department of Agriculture	USA	89	1327	94
4	University of Agriculture Faisalabad	Pakistan	80	687	113
5	China Agricultural University	China	66	1167	71
6	University of Cádiz	Spain	53	1339	54
7	Charles Sturt University	Australia	45	1059	69
8	Keio University	Japan	41	517	55
9	University of Tsukuba	Japan	39	621	57
10	Cornell University	USA	37	1256	29

IV. Journals Analysis

A total of 4,114 papers covered 677 journals. The top 10 journals in terms of the number of papers published are shown in Table 5 and Fig. 6. A total of 1,271 papers were published in the top 10 journals, accounting for 30.89% of the total number of papers. *Allelopathy Journal, Journal of Chemical Ecology* and *Plant and Soil,* with the most papers, are highly recognized and influential journals in this field. *The Journal of Agricultural and Food Chemistry* has the highest impact factor (4.192), followed by *Harmful Algae* (3.707), *Plant and Soil* (3.299), and *Planta Daninha* (0.46), which has the lowest impact factor. In addition, the statistics on the top 50 journals in terms of the number of papers published show that a total of 13 Journals were published in United States, with 576 papers published, while only one journal, *Allelopathy Journal*, was published in India, but its number of papers published is high up to 559; additionally, eight journals were published in Netherlands with 296 papers published.

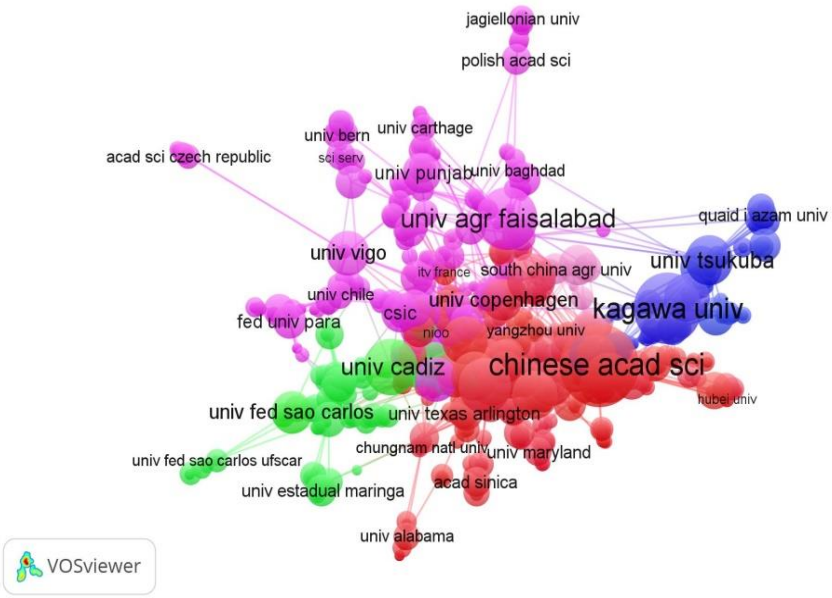

Figure 5. Visualization of cooperative relationships for Allelopathy Research between institutions.

Note: Each circle represents an institution, and the size of the circle represents the number of articles. A line connecting two circles illustrates a cooperative relationship between two institutions. Circles with the same color indicate that the institution is in a similar location or is characterized by strong cooperation.

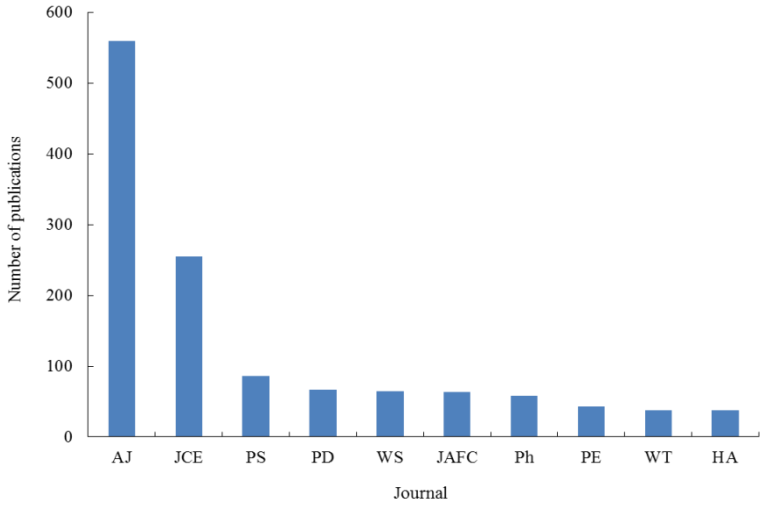

Figure 6. Top 10 Journals of total allelopathy papers published.

Abbreviation: AJ: *Allelopathy Journal*, JCE: *Journal of Chemical Ecology*, PS: *Plant and Soil*, PD: *Planta Daninha*, WS: *Weed Science*, JAFC: *Journal of Agric and Food Chemistry*, Ph: *Phytochemistry*, PE: *Plant Ecology*, WT: *Weed Technology*, HA: *Harmful Algae*.

Table 5. Top 10 journals of total allelopathy papers published and their impact factors

Order	Journal	Country	Number of publications	2019 Impact Factor
1	*Allelopathy Journal*	India	559	1.275
2	*Journal of Chemical Ecology*	USA	225	2.117
3	*Plant and Soil*	Holland	86	3.299
4	*Planta Daninha*	Brazil	67	0.46
5	*Weed Science*	USA	64	2.258
6	*Journal of Agricultural and Food Chemistry*	USA	63	4.192
7	*Phytochemistry*	Holland	58	3.044
8	*Plant Ecology*	Holland	43	1.509
9	*Harmful Algae*	USA	38	3.707
10	*Weed Technology*	USA	38	1.259

V. Keywords analysis

A total of 13,318 keywords were found among 4,114 papers. After eliminating the keywords that occurred only once, the total was 4,177 keywords. The top three keywords were allelopathy (3,293 times), growth (931 times), and allelochemicals (684 times), accounting for 36.85 % of the total number of keywords. Based on their relevance (Fig. 7), the keywords can be clustered into three regions:

(i). Blue clustering regions: Identification, phenolic acids, bioassay, and the studies on metabonomics and molecular biology focusing on allelopathy and the function of allelochemicals are conducted in these regions;

(ii). Red clustering regions: Phytoplankton, dynamics, toxicity, and other keywords, and the allelopathy of aquatic plants is vigorously studied, including the application of allelopathy in inhibiting the growth of harmful algae;

(iii). Green clustering regions: Soil, plants, exotic plant invasion, and other keywords, and the allelopathy of the land plants in these regions is vigorously studied, including the research on the relationship between allelopathy and invasion by alien plants, the application of plant allelopathy in agricultural and forestry production, and the interaction between allelopathy and environmental factors.

2.4. DISCUSSION

I. Research Status and Trends

The annual changes in publications reflect the development in this field (20). From the annual changes in the literature in WoS, the research on plant allelopathy over the 31 years from 1960to 1990 was in its infancy, with fewer annual publications. This may be because the research was at the primary stage of understanding and the existence of plant allelopathy in nature and was being gradually accepted. From 1991-2009, the research was in the infant stage. The publications of papers constantly increased, and researchers paid more attention to the following aspects: (i). Material and molecular basis of plant allelopathy (19), (ii). Mechanisms of plant allelochemicals (37) and (iii). Interactions between the environmental factors and allelopathy (5,18). Moreover, due to the establishment of the Indian Society of Allelopathy in 1990 (organized 4-International Conferences: 1992,1994, 1998, 2004) and establishment of International Society of Allelopathy in 1994 in India due to efforts of its Originator Prof. S.S. Narwal and its Conferences in Spain, Canada, Japan, Australia, United States, China etc. gave momentum to allelopathy research worldwide.

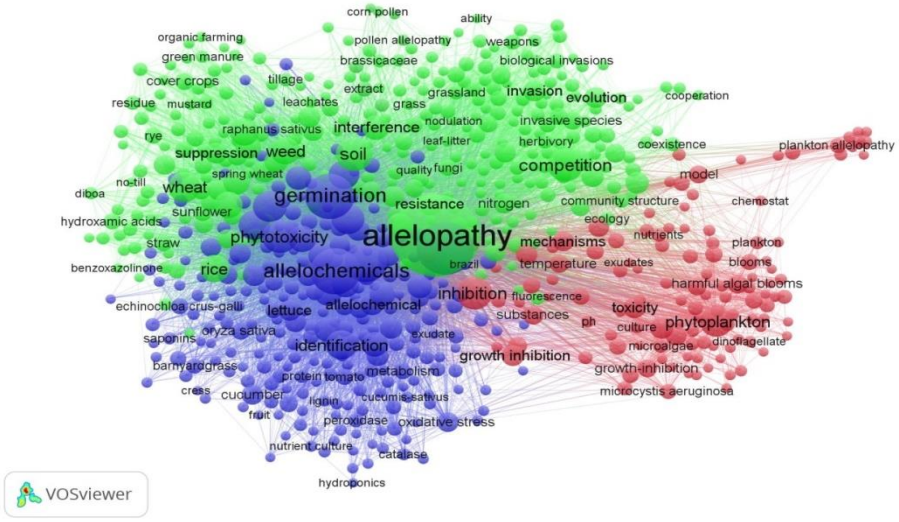

Figure 7. Distribution of keywords published more than 10 times.
Note: Each circle represents a keyword, and the size of the circle represents the number of citations of keywords. A line connecting two circles illustrates a relationship between two keywords. Circles with the same color indicate strong keyword correlation.

The academic circles attached great importance to research in this field, which led to rapid development of internationalization and became one of the most important scientific areas in Biology, Agronomy and Ecology (35). Thanks to the accumulation of research over the past 50 years, the research in this field entered a stable stage from 2010-2019. During this period, all aspects of research did comprehensive and in-depth investigations, and more notable achievements were made in scientific research (39). The research covered the interactions between (i). chemical-mediated plants and individuals or (ii). populations of the same or different species and (iii). above-ground and underground ecological interactions and microorganisms. In addition, many new perspectives have been opened up. For example, chemists have promoted the study of plant allelochemicals from identification to structural modification synthesis (28), soil and microbiologists have clarified the interaction and transformation of allelochemicals and microorganisms (21), and breeders devoted themselves to breed new allelopathic varieties of crops (13).

II. Distribution of Research Forces

The publication of the study results of Authors, Institutions and Countries in a certain field reflects the research level of scientific researchers, as well as the research input and output of research institutions and the countries in this field, which is conducive to the timely tracking of research trends and promoting the academic exchanges and cooperation among different scholars, institutions, and countries (8). This research showed that the research on plant allelopathy had been carried out at 2,166 institutions in 100countriesby 9,956 scholars. Related research is primarily concentrated in the USSR, United States, China and Japan. The research institutions with outstanding contributions include the Chinese Academy of Sciences, Kagawa University Japan and the USDA (United States Department of Agriculture) in the United States. Scholars with high influence are spread

across many different countries and include H. Kato-Noguchi, F.A. Macias, C.H. Kong, Y. Fujii, Inderjit and R.M. Callaway. The research shows the United States, Britain, Australia, Canada, Poland and other countries contributed the most to the early study on plant allelopathy. This is related to the research interest in this field, scientific investment and comprehensive national strength of these countries, mainly in studying the role of allelopathy in vegetation succession and plant distribution (42), the inhibitory effects of allelopathy on weeds (32), as well as studies on allelochemicals in crops (3). After the rapid development of this field, more and more countries began participating in the research. The countries with the most publications include the United States, Japan, Spain, Britain and other developed countries, as well as China, India, Pakistan and some developing countries. This is closely related to the popularity of plant allelopathy research, the continuous development of various disciplines, and the development of research methods and techniques. The contents of these studies are extensive. The core countries in this field (USSR, United States, China, Japan, Brazil, India) are significantly different from marginal countries (Albania, Libya, Laos, Indonesia, Uruguay), which may be attributed to the importance of research on plant allelopathy and their scientific research strength.

Allelopathy Journal, the *Journal of Chemical Ecology* and *Plant and Soil* are the main journals that publish studies on plant allelopathy. Since *Allelopathy Journal*, an academic journal of plant allelopathy, was established in 1994, its publications gradually increased, but its Impact Factors are not high. This finding may be because it is a professional allelopathy journal. In a proceeding published by the International Society of Chemical ecology, the *Journal of Chemical Ecology* and have published more papers on plant allelopathy, because plant allelopathy has gradually become an important research direction of the International Society of Chemical ecology. Journal distribution on plant allelopathy is relatively concentrated geographically, mainly in the United States, the Netherlands, Britain, and Germany. The journals with higher influential factors in the world have higher requirements for novelty of paper content, integrity of data and simplicity of writing. Therefore, scholars are encouraged to strengthen cooperation and exchange, as well as publish the results in journals with high influential factors to promote the development of this field.

III. Research hotspot changes

Keywords are an important source of information on the topics involved in the literature. They can directly reflect the research topics and contents, reveal the relationship between the research contents, achievements and characteristics of a certain field, and also reflect the research progress and hotspot changes in a certain field (20). Allelopathy, growth and allelochemicals, appeared most frequently, which indicates that allelopathic effects on plant growth and allelochemical analysis are the focus of allelopathic research. Allelopathy, plant, inhibition, succession, and other keywords appeared in the early literature more frequently. In the early stage of the study, most researchers focused on the interactive inhibition between plants and the role of allelopathy in plant succession due to the limitations of research methods and techniques (26,42). With the continuous development of various disciplines, the improvement and perfection of research methods and technologies, as well as the increase of investment in scientific research, in the past three decades, the frequencies of keywords phytoplankton, invasion, soil, weed, and microbial appearing in the literature increased yearly. As such, allelopathy of invasive plants, the interaction between allelopathy and soil microorganisms (7,11,21) have gradually become research hotspots. Scholars have focused on theoretical research in practice, such as the development of biological herbicides and the breeding of allelopathic crop varieties (13).

High-frequency keywords are indicators of research frontiers over a period of time (44). Except for three clusters of keywords (Fig. 7), some keywords appeared in the same cluster, which also reflects the hotspots of the research on plant allelopathy. The co-occurrence of the terms agroforestry, wheat, rice, weed, and herbicide indicates that the establishment of agroforestry ecosystems with disease-resistance using the principle of plant allelopathy has received wider attention (12). Therefore, the cultivation of newer allelopathic varieties of crops and the development of new fungicides and herbicides based on plant allelochemicals will be the focus of allelopathic research in the future. Frequent occurrence of bioassay, extracts, molecular biology, gene expression, and metabolites indicates that studying the molecular regulation of plant allelochemicals and the genetic characteristics of allelochemicals using the knowledge and technology of molecular biology and metabonomics is an inevitable trend (1,36). The occurrence of keywords such as continuous cropping, inhibition, soil, microbes and nutrients indicates the interactions between the allelochemicals and soil microorganisms; the regulation of soil nutrients cycling by allelochemicals has always been the focus of research (15). The increasingly frequent occurrence of climate, carbon dioxide, drought, adaptation, and diversity indicates that the research on plant allelopathy under global changes, especially the background of climate change (nitrogen deposition, warming), and the simulation and prediction of plant allelopathy under future climate changes are also important directions for future research on plant allelopathy (34). With the continuous development of relevant studies on plant allelopathy in the past six decades, the research focuses and hotspots have changed with the development of biology, ecology, and other disciplines.

2.5. SUGGESTED FUTURE AREAS OF RESEARCH

More research on plant allelopathy is therefore warranted. New technology by combining the Ecology, Chemistry, Genetics and Molecular Biology has been used to develop high-yielding crop varieties resistant to insects and diseases. The breeding of new varieties can be used to reduce the overgrowth of invasive plants and harmful algae, and further developing a sustainable agricultural and forestry ecosystem with natural chemical regulation. It is obvious that allelopathy requires further research for application in agricultural production worldwide. Researches in physiological and ecological mechanisms of allelopathy, which implicate an ecological and evolutionary significance, will also be important directions for future research. Therefore the areas, such as the molecular mechanisms and ecological implications of allelopathy, the applied aspects of allelopathy in agricultural systems and pest management, allelopathy and abiotic stress tolerance, host allelopathy and arbuscular mycorrhizal fungi, should be the focus of future studies.

2.6. CONCLUSIONS

The output of scientific research in this field is reflected comprehensively via bibliometric analysis, through searching 4,114 papers on the plant allelopathy research collected in the WoS database from 1960-2019, the collaboration among Authors, Institutions and Countries and their search development and changing trends in research hotspots in this field are realized. Our bibliometric analysis showed that plant allelopathy is a growing research field, having experienced three stages from 1960-2019, namely, (i). Starting period (1960-1990), (ii). Growth period (1991-2009, and (iii). Stable period (2010-2019). Hence, research in this field is still expected to maintain stable development in the future. A total of 4,114 papers were published in 100 countries from2,166 institutions and by 9,956 scholars. The United States, China, and Japan are the top three countries with the largest number of publications. The top three institutions with the most publications include the Chinese Academy of Sciences, Kagawa University and United States

Department of Agriculture. The top three scholars are H. Kato-Noguchi, F.A. Macias and C. H. Kong. *Allelopathy Journal*, the *Journal of Chemical Ecology*, and *Plant and Soil* are the most important journals in this field. Keyword analysis shows that cultivation of new allelopathic varieties, R&D of new fungicides and herbicides, molecular regulation of plant allelopathy and genetic characteristics of allelochemicals, plant-soil feedback, as well as the allelopathic law of plants under global change, are the research hotspots of plant allelopathy. In the future, further strengthening of cooperation among international scholars in plant allelopathy, exploration of new research methods and technical means, and greater focus on the changes in the fields of Biology, Ecology and Agroforestry will further enhance the output of high-quality results.

3. ALLELOPATHY ORGANIZATIONAL DEVELOPMENT

Development of Allelopathy Organizations was very slow. Prof. S.S. Narwal, India, has made significant Contributions for the Development of Allelopathy (27). He did following:

I. Established 4-Scientific Societies of allelopathy viz.,
(i). Indian Society of Allelopathy (1990),
(ii). International Allelopathy Foundation (1993),
(iii). International Allelopathy Society (1994),
(iv). Asian Society of Allelopathy (2004).

II. Organised 4-Internationsal Allelopathy Conferences in India (1992,1994,1998, 2004),

III. Started Publication of Allelopathy Journal (1994)**,**

IV. Got 3- Allelopathy Books Translated from German, Czech and Russian to English and got these published.

V. Authored/Editor 31- Books on Allelopathy.

Table 6. Chronological contributions of S.S. Narwal in development of allelopathy

Year	Academic Activity	Remarks
	Establishment of Allelopathy Societies	
1990	Establishment of Indian Society of Allelopathy, Hisar India.	Prof. E.L. Rice, said it was first National Society in World
1994	Establishment of International Allelopathy Society	Established in New Delhi
2004	Asian Allelopathy Society	Proposed, later established in Faislabad, Pakistan
	Organization of International Allelopathy Conferences	
1992	Organised I International Allelopathy Conference, Hisar, India	
1994	Organised II International Allelopathy Conference, New Delhi	
1998	Organised III International Allelopathy Conference, Dharwad	
2004	Organised IV International Allelopathy conference, Hisar	
	Other Academic Activities	
1994	Allelopathy Journal Publication Started	
2007	Organised International Short Courses on Allelopathy	Organised in 2007 (Italy, China), 2011 (China), 2014 (Tunisia)
	Books Translated from other languages published in English	
2001	Hans Molisch, *Influence of one plant on other*	German
2006	A.M. Grodzinsky. *Allelopathy in soil sickness*	Russian
2007	I. Lastrvka. *Coaction and competition in plants*	Czech
	Allelopathy Books: Authored/Editor	**30 Books on Allelopathy**

4. ALLELOPATHY RESEARCH IN USSR

In the former USSR during the period 1960-1990s, more than 300 researchers were studying the various aspects of allelopathic research (38). The studies ranged from (i). Simple study of chemical composition of certain plant species, (ii). Effects of chemical components on the physiology of another species, (iii). Modelling the allelopathic relationships (iv). Development of weedicides to control weeds in crops, (iv). Development of growth regulators etc. Unfortunately, despite the great scientific potential of Allelopathy Research, after the breakdown of USSR (i). the research funding was drastically reduced and (ii). the non-replacement of old equipments almost stopped the allelopathy research in USSR and Warsaw pact countries.

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