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ANALYSIS ARTICLE

Trends in global herbicides research during 2011-2020: A web of science-based scientometric study

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ABSTRACT

Herbicides are continuing to be an integral part of weed control in global agriculture and hence the research related to herbicides have paramount importance. Therefore, the present study attempts a scientometric analysis of global herbicide research undertaken during the last decade (2011 to 2020). For this, we collected the bibliometric data on published literature from the ISI Web of science core collection database in March 2021. A combination of search strings was used to obtain the appropriate data on herbicide research and VOSviewer was used for analyzing the networks among authors, organizations, journals, and countries. The study showed that 9,980 research papers were published on herbicide research with an average citation per article of 9.94 during this period. The volume of publications exhibited an increasing trend over the years. Further, the leading countries involved in the herbicide research domain were the USA, China and Brazil. The co-occurrence analysis of author keywords indicted "herbicide resistance" as the most focussed field in the herbicide research domain.

Keywords: Bibliometric analysis, Herbicide research, Scientometric study, VOSviewer, Web of Science

INTRODUCTION

Weeds cause crop yield losses and increase the cost of cultivation to farmers. Being a botanical pest, its adaptability to the cropping system and damage potential is significantly high (Ramesh *et al.* 2017, Swanton *et al.* 2015, Rao *et al.* 2020). Before the introduction of selective herbicides, farmers adopted a combination of different methods like crop rotation, cover crop, proper tillage *etc*. to control the weed menace (Bolliger *et al.* 2006, Mishra *et al.* 2016). Considering the drudgery of manual weeding in agriculture, research continued across the globe and the late 1940s witnessed the introduction of selective herbicides. Subsequently, several new herbicides were developed and this provided a new tool of weed management called 'Chemical hoe" to the farmers (Kudsk and Streibig 2003). Herbicides reduced the farmers dependence on the manual weed control operations. Further, the contribution of herbicides along with other pesticides was very crucial in the success of the green revolution, particularly in developing countries of Asia (Pimentel 1996). The discovery of different molecules of selective herbicides revolutionized the modern agriculture system as it is more productive-oriented (Hamill *et al.* 2004). However, the public realized it as a double-edged sword because of the environmental issues that emerged in the late 1980s due to the over usage of herbicides. Henceforth, public consciousness increased and many countries brought the stringent policy of registration process for herbicides. This along with other factors like rising costs of herbicide development are partially responsible for the decline in the introduction of new herbicides over the years (Kudsk and Streibig 2003, Sharma and Singhvi 2017).

Herbicides are most simpler and more economical technology for weed management in agriculture and this hastened the wider adoption of the same (Johnson *et al*. 2009, Rao *et al*. 2014, Chauhan *et al.* 2017). Although herbicide dependent agriculture production benefitted the farmers in many ways, the heavy reliance on herbicides resulted in many issues like herbicide-resistant weeds, changing spectrum of weed flora, environmental pollutions *etc*. (Duary 2008). Several studies describe these kinds of issues in various parts of the world. The presence of multiple herbicide-resistant weed species in pulses,

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oilseeds and cereals constrained the options of available herbicides (Beckie and Tardif 2012, Heap and Duke 2018). Glyphosate-resistant *Sorghum halepense* evolved in Argentina and the dispersal of resistant biotypes was reported (Heap and Duke 2018). The advent of imidazolinone-tolerant rice resulted in the evolution of resistant weedy rice (Kraehmer *et al.* 2016). Herbicide contamination of soil and water negatively impacted soil health through the interference of important microbial and enzymatic activities in the soil (Hussain *et al.* 2009). Overdose of herbicide could disrupt the earthworm ecology in the soil, N-fixation and mineralization (Chauhan *et al.* 2017). Further, as a result of climate change, herbicide dependent weed control is facing several issues. There is evidence of declined efficacy of herbicides due to higher CO_2 concentration. The CO_2 induced morphological and anatomical changes in plants resulted in dilution effect and thereby less efficacy of herbicides (Ziska *et al.* 2004; Ziska and Goins 2006). Frequent shower increases leaching and subsequent groundwater contamination (Ramesh *et al.* 2017).

The herbicide research domain is spread across multi-dimensional fields such as herbicide efficacy, herbicide residue, herbicide-tolerant (HT) crops, toxicology, environmental sciences *etc*. The weed research is more oriented towards herbicide research and more funding is routed in this direction (Wyse 1992, Harker and O'Donovan 2013, Rao and Chauhan 2015). Nevertheless, this changing scenario necessitated scientists across the globe to address emerging issues related to herbicides because weed management has to stay and need to be strengthened in the agricultural system. Therefore, the challenge before the scientists is to develop cutting edge technologies for weed management through scrutiny of existing issues of herbicide dependent agricultural production systems to deal with the growing concerns about environmental pollution and safe food production.

In this context, the present study was conducted to undertake a scientometric assessment of herbicide research in the world during the period from 2011 to 2020. Efforts were made to find out scientific productivity, author contribution and collaboration, major countries and organizations involved, important research themes and emerging research priorities in the herbicide research domain. This would help provide an overview of recent advancements in the herbicide research domain and aid in understanding the required research focus and way forward.

MATERIALS AND METHODS

The present study used metadata obtained from ISI Web of Science (accessed in March 2021). Web of Science database has comprehensive coverage of published literature (Ramanan *et al.* 2020) and several bibliometric studies relied on the Web of Science database (Zyoud *et al.* 2017). The search string used to select the publications were; ("herbicide" OR "weedicide") AND ("crop OR plant"). This string was used in advanced search options available in the Web of Science in three fields TOPIC, TITLE and ABSTRACT. Then combined using appropriate Boolean operators which resulted in a total of 9980 studies. Three exclusion criteria were used; year=2011-2020, Language=English and Document type=article. Bibliometric data on author names, title, publication year, citation, journal name and references of all the retrieved publications were collected.

The h-index of authors would indicate the research performance or productivity for the period considered (Huang 2012) and the h-index was obtained from Web of Science through individual search after sorting the top authors from the downloaded bibliometric data. The Web of Science inbuilt "Analyze result" option is used for the first step analysis. Thereafter, a full record of citation report metadata was downloaded in the text format. This data was used for network analysis with the help of VOSviewer software. It is a free and open software used for constructing and visualizing bibliometric networks. VOSviewer enables the visualization of bibliometric data in an easily interpretable manner (van Eck and Waltman 2014).

Network analysis was carried out to understand the co-citation of authors and journals, co-occurrence of the author keywords and co-authorship of countries and organizations involved in herbicide research. Fractional counting option were chosen to get proper visualization of the results. This analysis would help to identify existing collaboration and emerging thrust areas in the research domain considered. Since in this study we have only considered articles published in journals indexed in web of science (as mentioned in the title, it is a web of science-based scientometric work). Hence, many of the Indian journals including Indian Journal of Weed Science (IJWS), which are yet to be indexed in WoS, were not a part of this analysis.

RESULTS AND DISCUSSION

Temporal trends in research publications

The number of published articles on "herbicide research" witnessed an increasing trend during the

period from 2011 to 2020 (**Figure 1**). By 2020, a cumulative number of 9980 research articles were published with an average citation per article of 9.94. The Web of Science (WoS) indicated an h-index equal to 84 for this whole volume of publications. Similarly, citations also indicated an increasing trend over the years and the total of citations recorded 99,224 in 2020, of which 73,992 were without self-citations. Year-wise record indicated that both citations and number of published articles were highest in 2020 (23,318 and 1392, respectively) with an average citation per article equal to 16.75. This increasing trend of herbicide research could be due to the various issues that emerged out of continued and over usage of herbicides for weed management and increased consciousness about ecologically balanced methods for weed control (Rüegg *et al.* 2007, Rao and Ladha 2011).

The percentage share of articles belonging to each research field out of the total articles published on herbicide research indicated that among the top 10 research fields wherein herbicide research related articles appeared during 2011-2020, the agriculture field showed the highest per cent share (43%) followed by plant science (31%) and environmental sciences ecology (20%) (**Figure 2**). The least share of articles among the top 10 fields was noticed in toxicology (3%). The herbicides are important to agriculture and the demand for the same is increasing over the years particularly in developing countries due to the labour shortage for manual weeding. As demand for herbicide increases in agriculture, undoubtedly research and development would continue to be an important domain of research (Hossain 2016).

Major counties involved in herbicide research

The bibliometric analysis revealed that 71 countries published at least 10 articles on herbicide research during 2011-2020. Of the 71 countries, the top 10 countries involved most in herbicide research were identified and ranked based on the number of publications and total citations (**Table 1**). USA ranked first with 3056 published articles, followed by China and Brazil with 1067 and 1013 articles, respectively. In citations, the first ranked country was the USA (33282 citations) followed by the China and Australia with 11240 and 8688 citations, respectively. Brazil was 6th in terms of citations while it was in 3rd in the number of published articles. Australia was 4th in terms of the number of published articles but its citation was 3rd highest (8688) with an average citation per article equal to 14.60. In the USA, glyphosate use takes the major share of total herbicide application and the early adoption of herbicide-

Table 1. First 10 countries with highest number of publications and citations

Publications	Rank	Country	No. of publications
	1	USA	3056
	2	Peoples R China	1067
	3	Brazil	1013
	4	Australia	595
	5	Spain	510
	6	Canada	477
	7	India	468
	8	Germany	462
	9	Italy	358
	10	France	345
Citations	**Rank**	**Country**	**Total citations**
	1	USA	33282
	2	Peoples R China	11240
	3	Australia	8688
	4	Spain	8258
	5	Germany	7264
	6	Brazil	6124
	7	France	5585
	8	Canada	5201
	9	Italy	3986
	10	England	3962

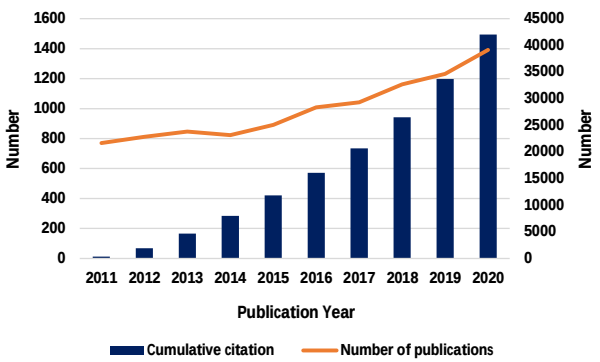

Figure 1. Year-wise number of publications and cumulative citation

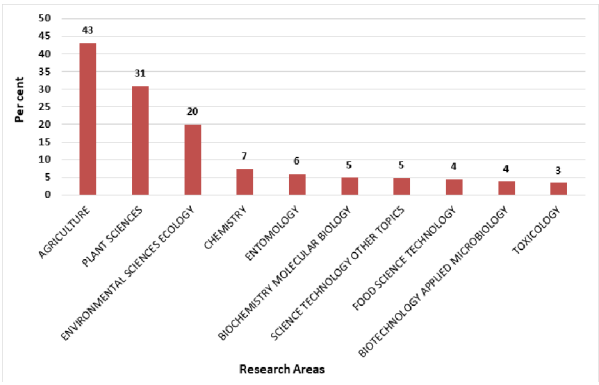

Figure 2. The per cent share of publications across major research areas

tolerant crops in the country could have led to wider use and increased research and development in herbicide research (Benbrook 2016).

The co-authorship network analysis of countries was done considering the minimum number of articles as 10 and the minimum number of citations as 20 to map the most important countries involved in the herbicide research domain. Out of 138 countries, 71 countries met the threshold for which the total strength of the co-authorship links with other countries was calculated. The countries with the greatest link strength were selected amongst which USA showed the highest link strength (687) and hence it was connected to many countries but closely to China and Canada (**Figure 3)**. The second and third highest link strength was found for China and Canada, respectively. The 4th highest link strength (279) was of Australia and it has a good cluster of networks with counties like England, Japan, New Zealand *etc*. Thus, the countries with better collaborations produced higher quality as well as volume of publications. India can perhaps take hint from this and attempt to collaborate more with countries engaged in advanced research on herbicides.

Most active organizations involved in herbicide research

There were 101 organizations with a minimum of 30 published herbicide research articles indexed in the WoS database. The USDA ARS ranked first amongst the top 10 organizations involved in the herbicide research with highest total publications (410) and citations (5469) (**Table 2**). The second and third ranking institutions were the University of Florida and the University of Western Australia with 197 and 178 published articles, respectively. Whereas in the case of citation ranking, the second rank was of The University of Western Australia (3506 citations) followed by the National Institute of Agricultural Research (NIAR) (2430 citations). One of the interesting findings is that, although, NIAR, France and Spanish National Research Council (CSIC) were

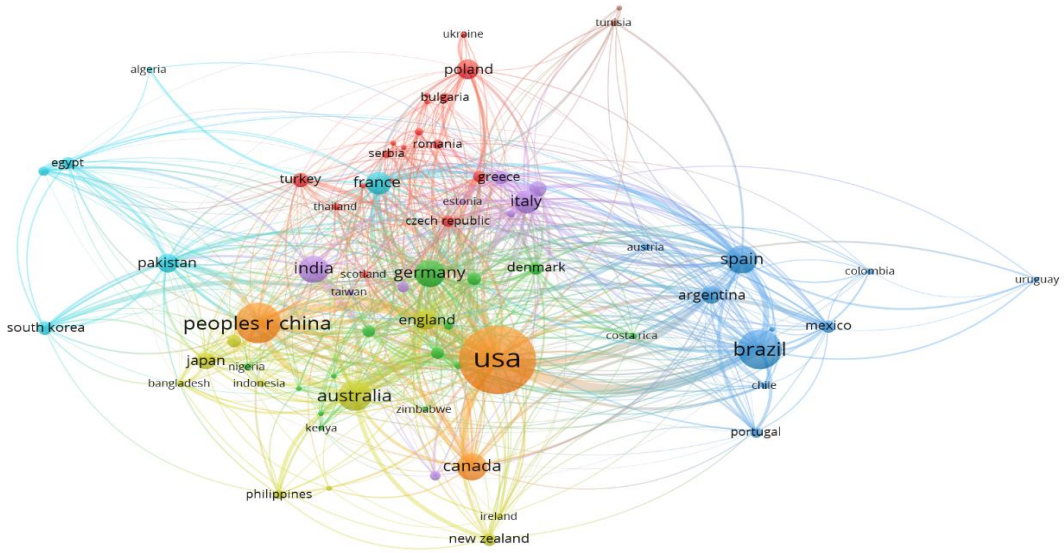

Figure 3. Co-authorship network of top countries involved in herbicide research

Table 2. First ten organizations with highest number of publications and citations

Publication			Citation		
Rank	Organization	No. of publication	Rank	Organization	Total citation
1	USDA ARS	410	1	USDA ARS	5469
2	University of Florida	197	2	The University of Western Australia	3506
3	The University of Western Australia	178	3	National Institute of Agricultural Research (INRA)	2430
4	University of Arkansas	177	4	Spanish National Research Council (CSIC)	2184
5	Mississippi State University	141	5	University of Arkansas	1910
6	University of California, Davis	140	6	The University of Queensland, Australia	1653
7	Agriculture and Agri-Food Canada	135	7	Iowa State University	1590
8	Federal University of Viçosa	134	8	Nanjing Agricultural University	1564
9	The University of Queensland, Australia	127	9	University of Illinois, Chicago	1551
10	University of Tennessee	126	10	Agriculture and Agri-Food Canada	1466

positioned at 3rd and 4th in the citations-based ranking, both of these organizations did not appear in the top 10 organizations based on the number of published articles. This could be due to the better quality of published articles from these organizations. There is a significant share of scientific man-years of USDA-ARS weed scientists out of total scientific man-years devoted to weed science in the country (Abernathy and Bridges 1994).

The co-authorship network of the most active organizations involved in herbicide research is depicted in **Figure 4**. The minimum number of published articles considered for an organization for this network mapping was 30 and the minimum citations were 10. Hence, 102 organizations among 6239 organizations met this threshold and network mapping have been done for these selected organizations. For each of the 102 organizations, the total strength of the co-authorship links with other organizations was calculated. The organizations with the greatest total link strength were selected. The USDA ARS (red) indicated the highest link strength (258) and hence, it has a large number of co-authorship networks with many other organizations. The USDA ARS has a close network with the University of California Davis, University of Illinois and University of Florida. This further suggests that better collaborations among organizations play crucial role in improving their research output.

Key authors contributing to herbicide research

The perusal of ranking of 10 key authors who published articles on herbicide research indicated that J.K. Norsworthy, University of Arkansas, USA was the author having the highest number of publications (108) during the period from 2011 to 2020 (**Table 3**). He is having a total citation of 1057 with an average citation per article equal to 9.79. As per the Web of Science database, he started research publication in 1998 and his h-index is 33 at present. The second-ranked author is P.H. Sikkema, University of Guelph, Canada with 73 articles and an average citation per article of 7.3. However, S. B. Powels, University of Western Australia is having the highest average

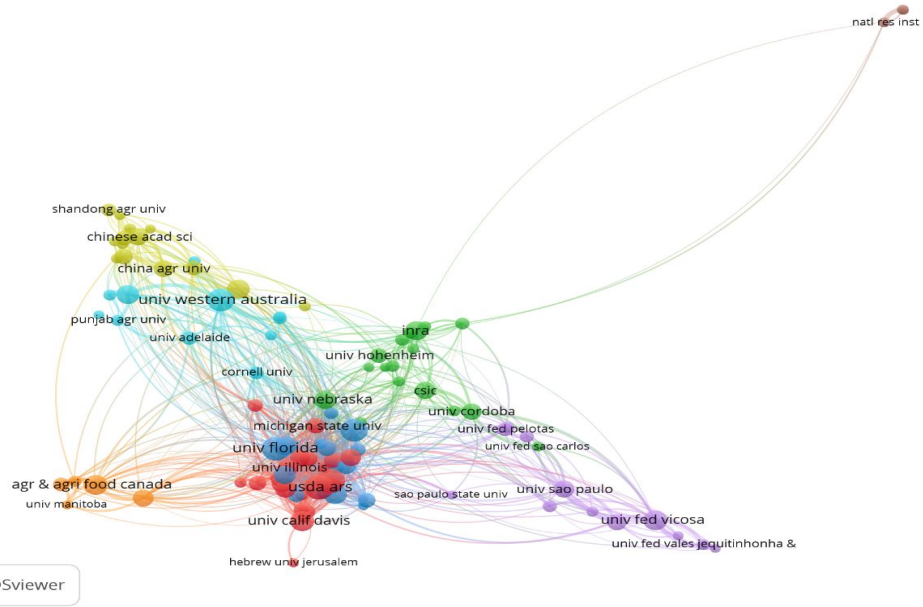

Figure 4. Co-authorship network of top organizations involved in herbicide research

Table 3. Ranking of 10 key authors based on number of publications

Rank	Author	Total publication	Total Citation	Average citation per paper	Country	Affiliation	h-index	Starting year of publication
1	Norsworthy, J. K.	108	1057	9.79	USA	University of Arkansas System	33	1998
2	Sikkema, PH	73	533	7.30	Canada	University of Guelph	21	1987
3	Powles, S. B	69	1609	23.32	Australia	University of Western Australia	62	1978
4	De prado, R.	61	796	13.05	Spain	Universidad de Cordoba	27	1982
5	Soltani, N.	52	336	6.46	Canada	University of Guelph	18	2003
6	Jhala, A. J.	51	459	9.00	USA	University of Nebraska Lincoln	18	2008
7	Young, B.G.	50	510	10.20	USA	Purdue University	27	1985
8	Scott, R. C.	46	715	15.54	USA	University of Arkansas System	29	2008
9	Jordan, D. L.	44	402	9.14	USA	North Carolina State University	3	2009
10	Preston, C.	43	606	14.09	Australia	University of Adelaide	41	1978

citation per paper (23.32) and h-index (62), among all the top 10 authors.

The authors' co-citation network analysis has selected 100 authors out of 13067 authors who meet the citation threshold of 50. For each of the 100 authors, the total strength of co-citations links with other authors was calculated and authors with the greatest link strength were selected. The network map has grouped the authors into 4 different clusters. The first cluster (green) was the biggest. I. Heap and S. O. Duke were the leading authors with respective citation figures of 1367 and 1314, and link strength of 1306 and 1000, respectively (**Figure 5**).

Lead journals publishing herbicide research

The ranking of the top 10 journals in which herbicide research articles were published during 2011-2020 was done based on the number of publications as well as total citations received. With respect number of publications, Weed Technology, published by the Weed Science Society of America (WSSA), was found on the top (648) followed by Weed Science (390) and Planta Daninha (339) (**Table 4**). Weed Technology publishes original research articles in the form of peer-reviewed articles focused on understanding weed management. In terms of total citations, Pest Management Science ranked first (4982) followed by Weed Science (4769) and Weed Technology (4507). Pest Management Science is an international journal focused on research in crop protection and pest control published for the Society of Chemical Industry by Wiley & Sons Ltd.

The Co-citation network analysis of journals considered the minimum number of citations of a journal source as 500. A total of 113 journals met the threshold out of 54,170 journals. For each of the 113 journals, the total co-citation link strength was calculated and journals with the greatest link strength were selected. The map depicted 4 major clusters, of which, the red one is having the highest co-citation networks in which the Pest Management Science was the leading journal with citation figure equal to

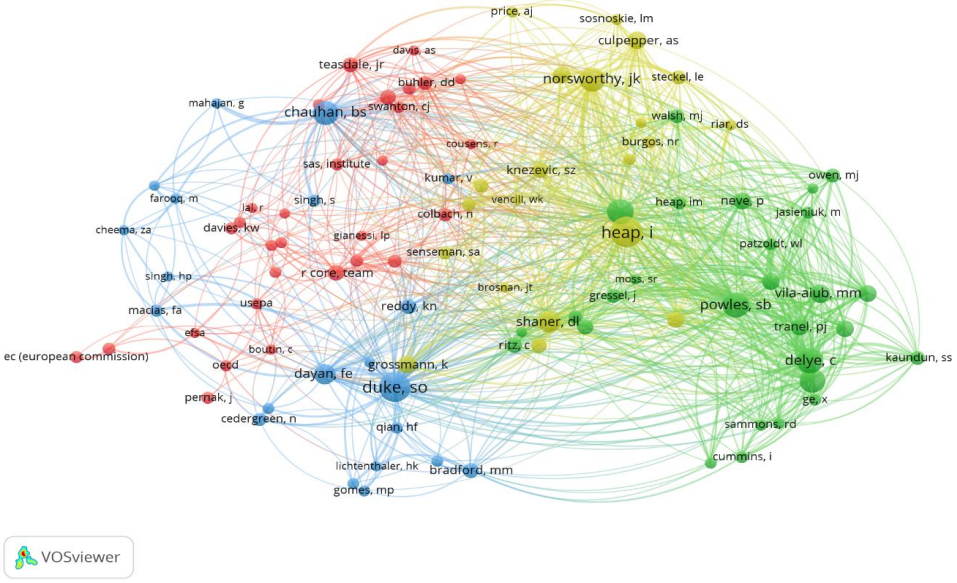

Figure 5. Co-citation network of authors of published articles based on herbicide research

Table 4. The first ten journals with highest number of publications and their citations

Number of publication			Total citation		
Rank	Journal	Number of publication	Rank	Journal	Total citation
1	Weed Technology	648	1	Pest Management Science	4982
2	Weed Science	390	2	Weed Science	4769
3	Planta Daninha	339	3	Weed Technology	4507
4	Pest Management Science	275	4	Science of The Total Environment	3178
5	Crop Protection	193	5	Journal of Agricultural and Food Chemistry	3161
6	Journal of Agricultural and Food Chemistry	175	6	Plos One	2900
7	Science of The Total Environment	164	7	Chemosphere	2387
8	Plos One	160	8	Crop Protection	2030
9	Weed Research	157	9	Weed Research	1961
10	Pesticide Biochemistry and Physiology	134	10	Pesticide Biochemistry and Physiology	1875

8,597 (**Figure 6**). Weed Science had the highest link strength (14664) and citations (19,063) followed by Weed Technology and Pest Management Science with total link strength equals 10,782 and 7, 586, respectively.

Most cited articles in herbicide research

The most important research articles in the herbicide research domain published during 2011-2020 were ranked based on total citations received. The article entitled "Trends in glyphosate herbicide use in the United States and globally" (Benbrook 2016), published in Environmental Sciences Europe journal, ranked first with a total citation of 487 (**Table 5**) with an average citation per year equal to 81.17. This paper discussed in detail herbicide use for agricultural and non-agricultural purposes in the US and the world. It suggested a rise in global glyphosate use (56%) after the introduction of genetically engineered herbicide-tolerant crops like "Roundup-Ready" crops (Benbrook 2016). This paper got wide acceptance due to the importance of the study carried out by the author. Though herbicide application data were sparse, the author managed to collect time-series data on the application of glyphosate in the USA and globally. He also advocated quantifying the human health impact due to the rising use of glyphosate as the way forward. The second-ranked article is titled "A combinatorial TIR1/AFB-Aux/IAA co-receptor system for differential sensing of auxin" (Calderon Villalobos *et al*. 2012) published in Nature Chemical Biology. It has a total citation of 308 and 30.8 as an average citation per year.

Focused areas in herbicide research

Bibliometric data on author keywords were downloaded and assessed to understand the priorities in the herbicide research domain in recent times. The frequency of occurrence of the author keywords in the 9,980 articles retrieved from the Web of Science indicated that the word "herbicide or weedicide" had the maximum number of occurrences (1298) followed by "herbicide resistance" (537), "glyphosate" (529), "weeds" (357) and "weed

Table 5. Ranking of 10 most cited articles in herbicide research

Rank	Title	Author	Year of publication	Source journal	Total Citations	Average citation per year
1	Trends in glyphosate herbicide use in the United States and globally	Benbrook, Charles M.	2016	ENVIRONMENTAL SCIENCES EUROPE	487	81.17
2	A combinatorial TIR1/AFB-Aux/IAA co-receptor system for differential sensing of auxin	Calderon Villalobos, Luz Irina A.; Lee, Sarah; De Oliveira, Cesar; Ivetac, Anthony; Brandt, Wolfgang; Armitage, Lynne; Sheard, Laura B.; Tan, Xu; Parry, Geraint; Mao, Haibin; Zheng, Ning; Napier, Richard; Kepinski, Stefan; Estelle, Mark	2012	NATURE CHEMICAL BIOLOGY	308	30.8
3	A Meta-Analysis of the Impacts of Genetically Modified Crops	Kluemper, Wilhelm; Qaim, Matin	2014	PLOS ONE	293	36.63
4	Why have no new herbicide modes of action appeared in recent years?	Duke, Stephen O.	2012	PEST MANAGEMENT SCIENCE	265	26.5
5	Targeted base editing in rice and tomato using a CRISPR-Cas9 cytidine deaminase fusion	Shimatani, Zenpei; Kashojiya, Sachiko; Takayama, Mariko; Terada, Rie; Arazoe, Takayuki; Ishii, Hisaki; Teramura, Hiroshi; Yamamoto, Tsuyoshi; Komatsu, Hiroki; Miura, Kenji; Ezura, Hiroshi; Nishida, Keiji; Ariizumi, Tohru; Kondo, Akihiko	2017	NATURE BIOTECHNOLOGY	249	49.8
6	Herbicide cross resistance in weeds	Beckie, Hugh J.; Tardif, Francois J.	2012	CROP PROTECTION	243	24.3
7	Environmental fate of glyphosate and aminomethylphosphonic acid in surface waters and soil of agricultural basins	Aparicio, Virginia C.; De Geronimo, Eduardo; Marino, Damian; Primost, Jezabel; Carriquiriborde, Pedro; Costa, Jose L.	2013	CHEMOSPHERE	207	23
8	Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population	Pleasants, John M.; Oberhauser, Karen S.	2013	INSECT CONSERVATION AND DIVERSITY	207	23
9	Unravelling the genetic bases of non-target-site-based resistance (NTSR) to herbicides: a major challenge for weed science in the forthcoming decade	Delye, Christophe	2013	PEST MANAGEMENT SCIENCE	195	21.67
10	Metabolism-Based Herbicide Resistance and Cross-Resistance in Crop Weeds: A Threat to Herbicide Sustainability and Global Crop Production	Yu, Qin; Powles, Stephen	2014	PLANT PHYSIOLOGY	185	23.13

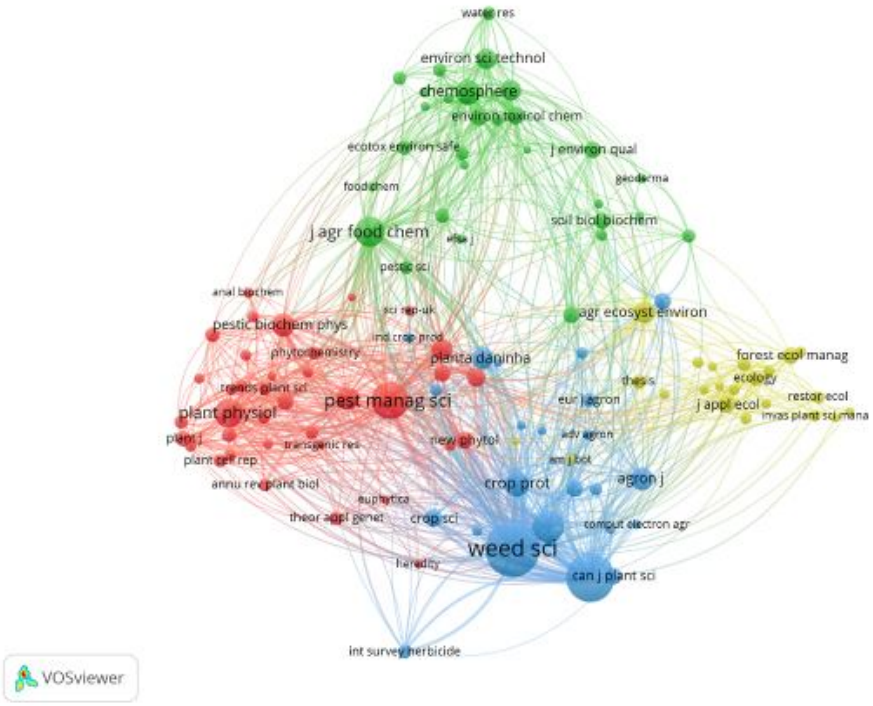

Figure 6. Co-citation network of leading journals publishing articles on herbicide research

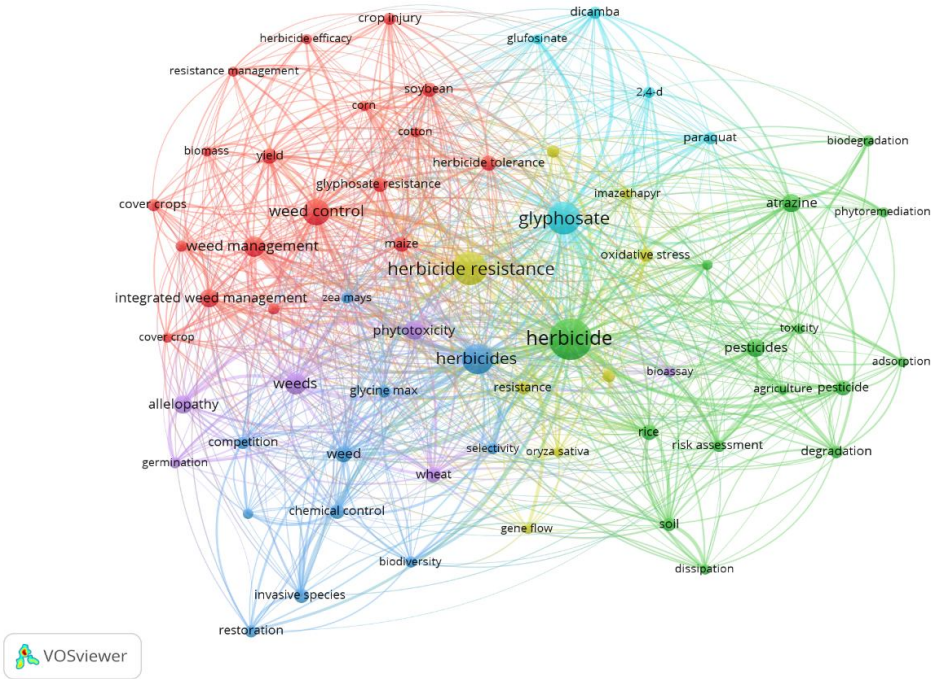

Figure 7. Co-occurrence network of the most frequently used author keywords

control" (329). Barring the keyword herbicide because, it is as obvious to appear with more frequency considering the search string used for the study, herbicide resistance was the dominating keyword. Other important keywords appeared in the descending order of frequency were "phytotoxicity", "photosynthesis", and "allelopathy". Further, a co-occurrence network of the most frequently used author keywords was constructed (**Figure 7**). The analysis indicated a total of 63 important keywords met the threshold of 50 as the minimum occurrence of a keyword. For each of the selected words, a total link strength of co-occurrence with other keywords was calculated and keywords with the greatest link strength were mapped. Four prominent clusters were found in the network wherein as an obvious fact "herbicide" was the keyword with the highest link strength (426). The keyword "weed control" was

observed as the leading word in the red colored cluster with the highest number of keyword networks (17) and those keywords include "glyphosate resistance, herbicide tolerance, crop injury, herbicide efficacy" *etc*. Another important cluster was the one in which "herbicide resistance" was the leading keyword with a link strength of 256 and other words connected in this cluster were gene flow, oxidative stress, and imazethapyr. Many recent studies opined in the similar line identified through this keywords analysis. Special focus needs to be given to fundamental research on evolved glyphosate resistance because of the global over reliance on this herbicide (Duke and Powles 2008). Herbicide resistance studies could be given more emphasis to minimize the resistance of weeds to herbicides because it is one of the limiting factors to food security in global agriculture (Busi *et al.* 2013). There is a great concern about glyphosate weed resistance among researchers as per keyword analysis of literature (de Castilhos Ghisi *et al.* 2020).

Conclusion

In summary, this study provides a comprehensive bibliometric review of global herbicides research. The various analysis undertaken, help to explore different dimensions from a scientometric perspective. Ranking of countries, organizations, journals, and articles help to know the leading entities in each category that are involved in herbicide research, publications and their contribution in terms of volume and citations. Different network analyses provided an understanding of the collaborations and cooperation prevailing in herbicides research across the globe. Overall, the study highlighted the present status of research in the herbicide research domain and hints at future thrust areas of research like herbicide resistance which has been appeared as the most focused field of research in author keywords analysis.

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