Article

Examining Current Research Trends in Ozone Formation Sensitivity: A Bibliometric Analysis

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Abstract: The end of the 20th century brought about drastic changes in the tropospheric ozone (O_3) around the globe. It is, therefore, highly important to gain insight into O_3 formation mechanisms and their key precursors in order to assist policymaking to combat O_3 pollution. This article synthesizes a bibliometric analysis of O_3 formation sensitivity from 1965 to 2022, reported in English language journals available in the Web of Science Core Collection. This study shows that constant expansion in the number of publications has occurred since 2008, with the highest number occurring in 2021. Most publications are from the United States of America (USA), with 406 papers (42.7%), followed by China with 128 papers (13.5%), and the United Kingdom (UK) with 87 papers (9.1%). Citation burst analysis and significant and highly cited research work analysis are used to discover and assess evolving research tendencies. The thematic evolution of author-supplied keywords indicates that the terms "volatile organic compounds" and "ozone precursors" have recently emerged with a higher frequency. This suggests that there is a growing trend in research focused on these topics in the future. The objective of this study is to provide research primacies and future prospects for better analysis of O_3 sensitivity, thereby helping to manage O_3 pollution.

Keywords: O_3 formation sensitivity; O_3-NO_X-VOCs; O_3 precursors; bibliometrics; VOSviewer; Web of Science Core Collection

1. Introduction

Tropospheric ozone (O_3) is a harmful, invisible gas present in the atmosphere. This pollutant has detrimental effects on ecosystems and human health. It irritates the nose and eyes and causes respiratory problems [1–5]. Crop yield losses due to prolonged exposure to O_3 have been reported [6]. During the 1950s, it was discovered that O_3 is produced

secondarily by the photochemical reactions of anthropogenic emissions of volatile organic compounds (VOCs) and nitrogen oxides ($NO_x = NO + NO_2$) [7].

O_3 formation from VOCs and NOx precursors occurs in a non-linear manner in the presence of sunlight [8–10]. NO_x concentration can increase O_3 formation, and, in other cases, VOCs can enhance O_3 formation [11–13]. Tropospheric O_3 formation is a complex process that depends on precursor species and several other factors. The COVID-19 pandemic and subsequent lockdown measures resulted in emission reductions of VOCs and NO_x, but O_3 concentrations still increased in many regions [14–16]. Recent studies suggest this is due to the various factors (e.g., aerosols, meteorology and pollution source distribution) that govern atmospheric O_3 formation [12,17].

O_3 formation in the atmosphere occurs in one of three ways: (a) VOC-limited; (b) NO_x-limited; and (c) transition regimes. In the VOC-limited regime, O_3 production relies primarily on VOC levels, whereas in the NO_x-limited regime, O_3 formation depends on NO_X concentrations [18,19]. Insufficient precursor emission reductions can lead to enhanced tropospheric O_3 production. Therefore, accurately identifying O_3 sensitivity regions is necessary to cultivate effective control strategies to combat O_3 pollution. The situation is more complex in China, particularly as the ozone concentration has not shown a reduction in its level since the implementation of China's National Air pollution prevention plan in 2013. This is due to the production of O_3 via complex heterogeneous processes [15,20,21].

Given the complex relationship between O_3 precursors and O_3 formation sensitivity, we provide a comprehensive overview of the current research trends of O_3 precursors and their formation sensitivity. A bibliometric on ozone formation sensitivity from 1965 to 2022 is presented to elucidate the patterns of research and offer perspective into the present advancement and forthcoming paradigm of research. Rapid developments in scientific research result in the increased importance of bibliometric analysis. This sort of investigation is exceptional, as it offers classified information on various aspects of a scientific discipline, including publications, keywords, citations, and collaborations. This study utilizes distinct methods compared to previous research on ozone formation sensitivity. These methodologies enable the construction of a comprehensive research framework and facilitate the identification, organization, and analysis of the principal elements within the topic. To the best of the authors' knowledge, this is the first bibliometric study on ozone formation sensitivity and its precursors. Thus, the objective is to study recent global research trends and present content and citation analyses in order to recognize the leading studies in this domain. Furthermore, this study examined a wide range of research topics and analyzed the current emerging trends to identify potential valuable directions for further research.

2. Materials and Methods

This section describes the data collection methods used in this bibliometric study of ozone formation sensitivity. Scientific literature can be systematically analysed using bibliometric techniques, retrieving data from online databases such as the Web of Science Core Collection (WoSCC) [22]. We have compiled a comprehensive list of keywords related to ozone formation sensitivity research to ensure maximum precision and recall. A query for WoSCC was formulated by connecting the keywords using Boolean operators. Specifically, the following query was used:

TS = ("ozone formation regimes" OR "ozone formation sensitivity" OR "O_3-NOX-VOCs Sensitivity" OR "ozone precursor*")

The search was performed through the 'Topic Field', which considers the 'Title', 'Abstract' and 'Keywords Plus®' of a record. "TS" stands for topic and restricts the search to the articles' title, abstract, and keywords and "OR" is a boolean operator that connects the various terms in the query. The initial query returned 972 documents. We examined the results from the publication of the first article to the date of the data retrieval (20 November 2022) to obtain a comprehensive, up-to-date understanding of the subject. We narrowed the search to 952 documents by restricting the document types to articles, proceeding

papers, and review articles. We downloaded the bibliographic data and imported it into EndNote to ensure there were no duplicate titles, authors, or years. One duplicate document was found and removed. An outline of the bibliometric study road map is shown in Figure 1. Finally, all the screened documents were examined carefully for their contribution to ozone formation sensitivity. The study used MS Excel, MS Access, Power BI, an online visualization platform (https://flourish.studio/ accessed on 20 March 2022), BiblioAnalytics, Citespace, VOSviewer software (version 1.6.15), and Biblioshiny software for the analysis [23].
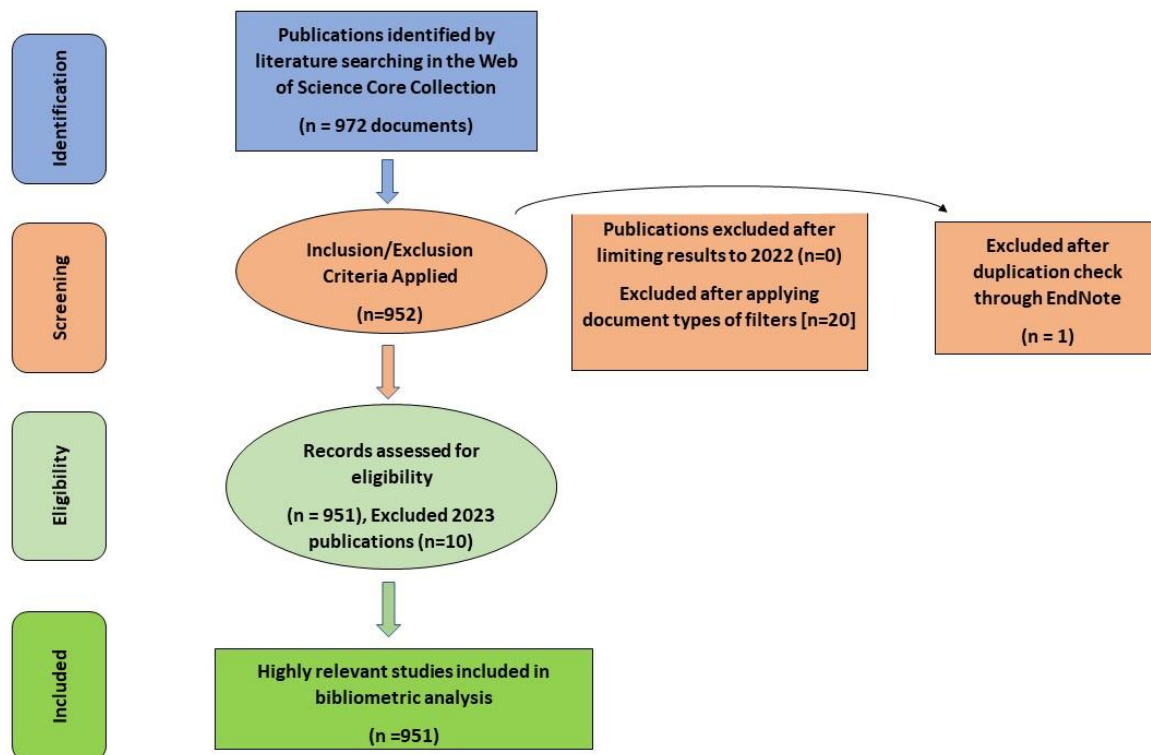

Figure 1. Flow chart of the steps of the study.

The analysis of bibliographic data is critical to identifying scientific research trends. The bibliometric analysis provides a quantitative means of evaluating scientific research and its impact by identifying the most influential authors and publications and finding research hotspots by analysing publication patterns and citation networks [24]. We systematically examine the existing literature on ozone formation sensitivity using bibliometric techniques. By identifying key research themes, we provide insights for future research directions.

3. Results

3.1. Temporal Analysis of Articles and Their Types

Scientific literature is usually evaluated on the basis of the number of publications and citations. The publication and citation trend can demonstrate the link between lifespan and citation per publication [22,25,26]. Figure 2 illustrates the growth in total publications (TP) and total citations (TC). The data show that the first research publication relating to ozone formation sensitivity was in 1965. The analysis shows little to no increase in publications in the early years, with only single-digit numbers and many years without any publications. Double-digit numbers appear between 1995 and 2008. After 2008, consistent publication growth was observed, with the highest number of publications occurring in 2021 (followed by 2020, 2012, and 2013). The results indicate that research into O_3 pollution gained attention relatively lately. This is due to the development of observation methods, including satellite and ground-based systems, over the past two decades, resulting in a

vast range of continuous data with wide area coverage and high precision. The number of citations dropped after 2017 and the reasons for citations dropping after 2017 could be explored further.
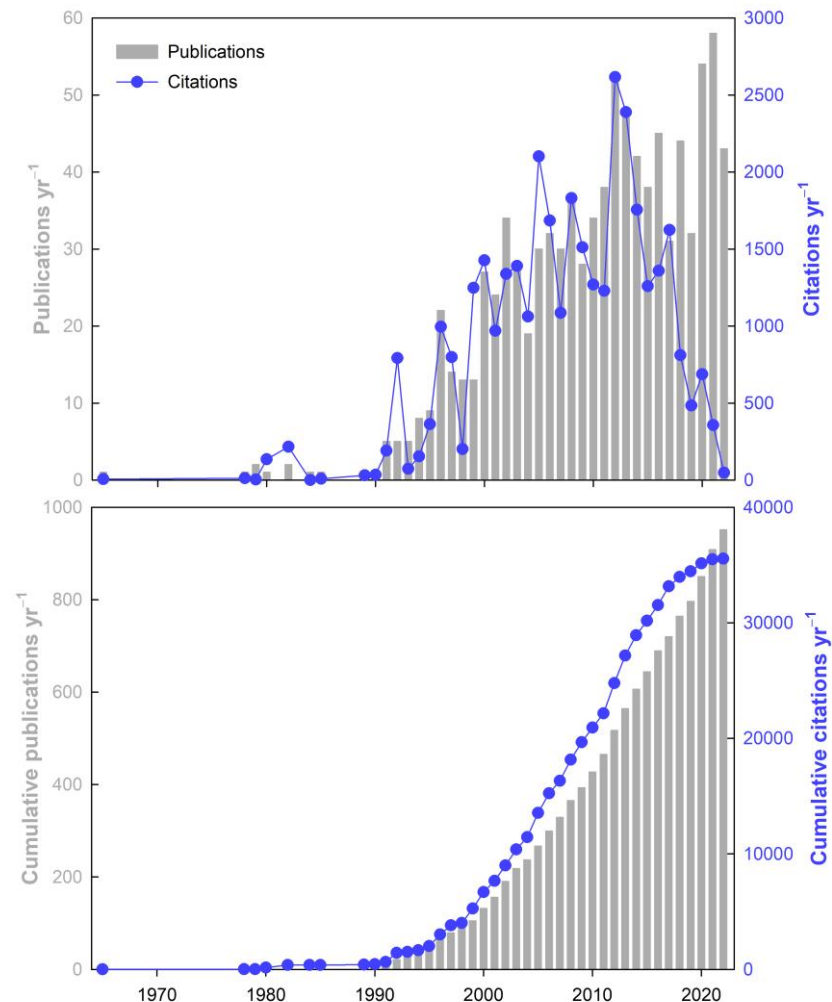

Figure 2. Yearly growth in ozone formation sensitivity research in terms of publications and citations.

The preferred document type for researchers working on ozone formation sensitivity is "article" with 876 TP, distantly followed by "proceedings paper" with 43 TP, and "review" with 32 TP. "Articles" also have the highest number of citations (29,274 TC), followed by "reviews" (4801 TC) and "proceedings papers" (1468 TC). The document type "review" has more impact (150 TC/TP) than "articles" (33.42 TC/TP) and "proceedings papers" (34.14 TC/TP).

3.2. Authorship Patterns and Most Prolific Scholars in Ozone Formation Sensitivity

Figure 3 shows the authorship patterns in ozone formation sensitivity research ranging from 1 to 41. The data analysis shows a collaborative research trend in this field of study. This analysis reveals the domination of two-author patterns with 139 publications, followed by five and four-author patterns with 136 and 132 publications, respectively. The citation analysis ranks four-author publications top, with 5042 citations, followed by six-author reports, with 4717 citations. Two-author papers have 4426 citations.
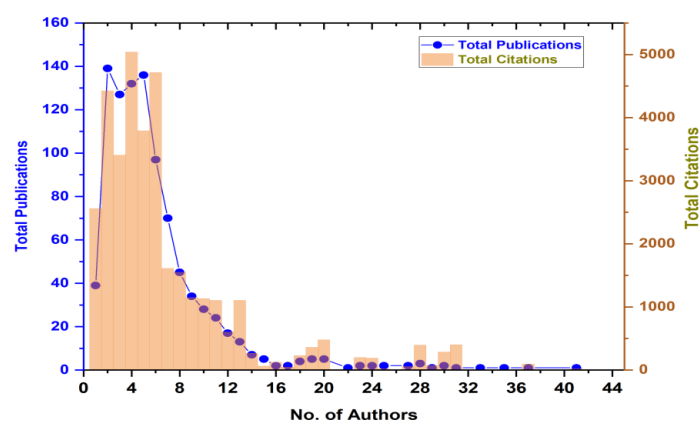
Figure 3. Authorship patterns in ozone formation sensitivity research in terms of publications and citations.

Table 1 gives the top 20 most prolific researchers in ozone formation sensitivity research. The data shows a trend for collaborative research among the most productive authors, as all authors among the top 20, except one (Shindell DT) published research which was the result of a joint effort. The most productive author, Wang JL, published five pieces of research on the topic as the first author. The second, Collins WJ, published five documents as the first author and 12 in other author categories. The third, Horowitz LW, maintained that position by contributing all publications in other author categories. The citation analysis ranks Shindell DT in the top position with the most citations, followed by Faluvegi G and Collins WJ.

Table 1. Top 20 most prolific authors.

Author	Publications by Authorship			TP	TC
	Single	First	Other		
WANG JL		5	18	23	776
COLLINS WJ		5	12	17	1692
HOROWITZ LW			16	16	1550
NAIK V		2	13	15	1400
DERWENT RG		6	8	14	572
PARRISH DD		3	10	13	842
THOURET V			13	13	743
CHANG CC		3	9	12	434
FIORE AM		1	11	12	715
NEDELEC P			12	12	750
STEVENSON DS		1	11	12	1174
SHINDELL DT	1	3	7	11	2081
SUDO K		1	10	11	1318
WEST JJ		2	9	11	767
ZENG G		2	9	11	1265
BEIG G		3	7	10	199
FALUVEGI G			10	10	1831
LAMARQUE JF		2	8	10	1488
PICKERING KE		2	8	10	494
THOMPSON AM		2	8	10	617

3.3. Most Productive Journals and Publishers

Identifying the distribution of journals is a crucial component of bibliometric analysis. This information is valuable for guiding future researchers in determining where to concentrate their efforts for finding literature and publishing their work. The top 20 most productive journals publishing on O_3 formation sensitivity are listed in Table 2. According to the analysis, Atmospheric Environment is ranked top for total publications (TP) with 169 and cited papers (CP) with 164. Atmospheric Chemistry and Physics, and the Journal of Geophysical Research-Atmospheres, take joint second place with a TP count of 100. The highest number of total citations are also from Atmospheric Environment, followed by the Journal of Geophysical Research-Atmospheres, and Atmospheric Chemistry and Physics. Geoscientific Model Development appears in 12th place; however, its impact (TC/TP) is the highest, followed by Environmental Science & Technology and Science of the Total Environment".

Table 2. Most productive journals.

Journal	CP	TP	TC	Impact (TC/TP)
ATMOSPHERIC ENVIRONMENT	164	169	7192	42.56
ATMOSPHERIC CHEMISTRY AND PHYSICS	96	100	4311	43.11
JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES	98	100	5343	53.43
SCIENCE OF THE TOTAL ENVIRONMENT	31	31	1723	55.58
ATMOSPHERE	24	29	197	6.79
JOURNAL OF THE AIR & WASTE MANAGEMENT ASSOCIATION	27	27	704	26.07
GEOPHYSICAL RESEARCH LETTERS	24	24	915	38.13
ENVIRONMENTAL SCIENCE & TECHNOLOGY	19	21	1220	58.1
ENVIRONMENTAL POLLUTION	16	16	359	22.44
ATMOSPHERIC RESEARCH	14	14	555	39.64
ENVIRONMENTAL RESEARCH LETTERS	13	14	235	16.79
ENVIRONMENTAL MONITORING AND ASSESSMENT	11	12	219	18.25
JOURNAL OF ATMOSPHERIC CHEMISTRY	12	12	326	27.17
ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH	12	12	391	32.58
AIR QUALITY ATMOSPHERE AND HEALTH	9	10	133	13.3
INTERNATIONAL JOURNAL OF REMOTE SENSING	8	8	85	10.63
GEOSCIENTIFIC MODEL DEVELOPMENT	8	8	534	66.75
WATER AIR AND SOIL POLLUTION	8	8	84	10.5
JOURNAL OF APPLIED METEOROLOGY	7	7	132	18.86

The top publishers on the subject of O_3 formation are listed in Table 3, with Elsevier being on top, followed by the Amer geophysical union and Copernicus gesellschaft mbh. As well as the highest number of publications, Elsevier also has the highest number of citations, followed by Amer geophysical union and Copernicus gesellschaft mbh. The Nature Publishing Group has the highest impact (TC/TP), despite comparatively few publications, followed by Wiley-Blackwell and the Natl Acad Sciences.

Table 3. Most productive publishers.

Publisher	TP	TC	Impact (TC/TP)
ELSEVIER	312	11,866	38.03
AMER GEOPHYSICAL UNION	130	6279	48.3
COPERNICUS GESELLSCHAFT MBH	114	4931	43.25
SPRINGER	76	1849	24.33
MDPI	39	285	7.31
TAYLOR & FRANCIS LTD	35	706	20.17
AMER CHEMICAL SOC	24	1252	52.17
WILEY-BLACKWELL	17	1045	61.47
IOP PUBLISHING LTD	14	235	16.79
AIR & WASTE MANAGEMENT ASSOC	12	424	35.33
KLUWER ACADEMIC PUBL	12	394	32.83
NATURE PUBLISHING GROUP	11	1208	109.82
SCIENCE PRESS	11	224	20.36
AMER METEOROLOGICAL SOC	10	390	39
ROYAL SOC CHEMISTRY	9	459	51
NATL ACAD SCIENCES	7	400	57.14
TAIWAN ASSOC AEROSOL RES-TAAR	7	131	18.71
TURKISH NATL COMMITTEE AIR POLLUTION RES & CONTROL-TUNCAP	6	81	13.5
NATURE PORTFOLIO	6	334	55.67
INDERSCIENCE ENTERPRISES LTD	5	49	9.8

3.4. Countries and Organizational Productivity

Based on the author's affiliations, the regional research output on the subject of O_3 formation regime is presented. It is important to mention here that the number of publications in a particular area of interest is representative of the significance of that specific region for the subject. Figure 4 illustrates the contribution to research on the topic on a continental basis. Europe has the most publications (contributions from 29 countries), followed by North America (two countries) and Asia (23 countries). Europe also has the highest number of citations, followed by North America and Asia.

Figure 5 shows the most productive countries. The USA appears on top with 406 publications, followed by China (128) and the UK (87). The USA also has the highest number of citations. The UK, however, published the third-highest number of documents but is in second place for citations. Articles are regarded as publications from the United Kingdom (UK) if they are from Ireland, England, Scotland, Northern Ireland, and Wales. These countries are also among the most impactful in terms of the emission of gases and have greater resources to study the corresponding air pollution problems. There is greater mitigation concern for O_3, compared to other air pollutants, due to its complex non-linear photochemistry, especially in China [9]. Therefore, researchers in these countries have recently started working on this topic, resulting in a high number of publications.
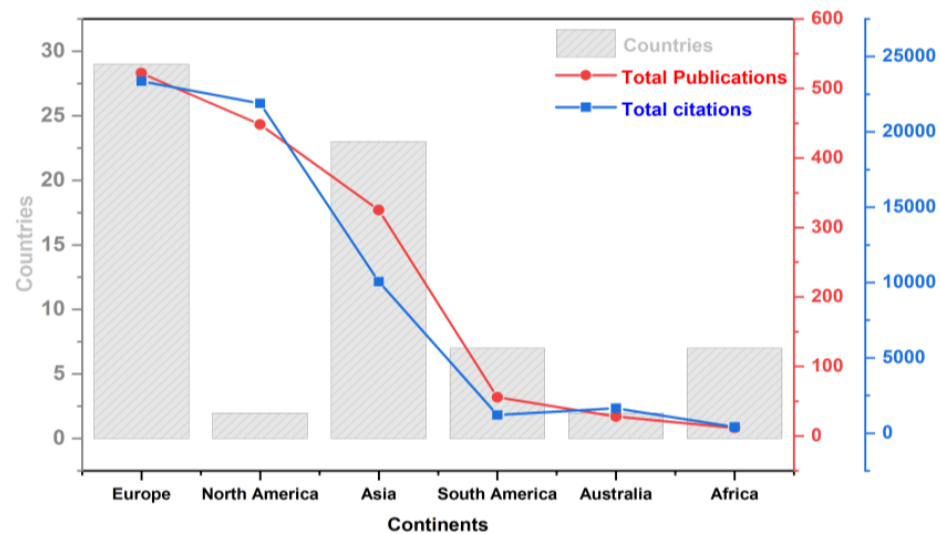
Figure 4. Most productive continents with number of countries and productivity (Publications and citations).
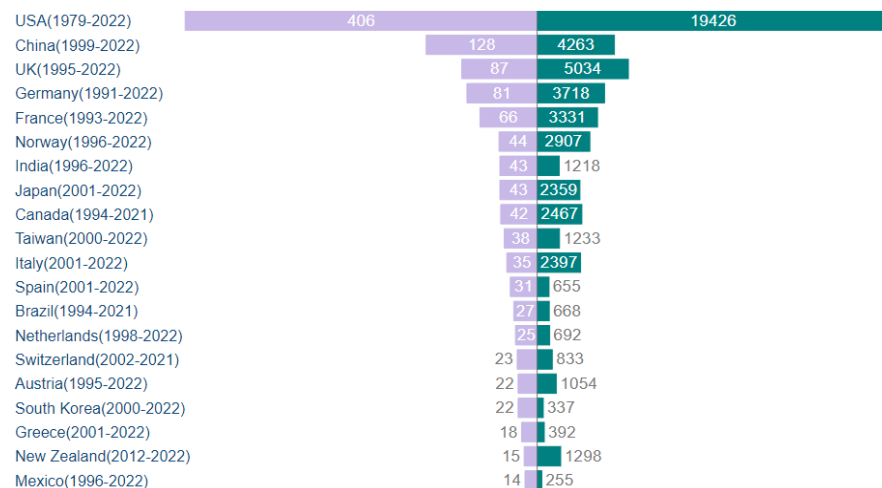

Figure 5. Most productive countries in terms of total publications and citations (Purple bar shows number of publications and green shows number of citations).

Bibliometric analysis offers insights into the leading institutions in various countries regarding the subject. This analysis is beneficial for researchers, as it helps them identify potential hubs for specific research, training opportunities, workshops, and post-doctoral study tours. By examining the most productive institutions in various countries, scholars can establish connections and collaborations to further their research endeavours [27].

Figure 6 shows the top organizations and their impact on publishing research on this topic. Ten of the top 20 organizations are located in North America, including the top three. The other ten come from Asia and Europe, with five from each. North American organizations also have higher impacts than those from other continents. The top four organizations, in terms of publications, are NASA (National Aeronautics and Space Administration), USA, NOAA (National Oceanic and Atmospheric Administration), USA, University of Colorado, USA and China Academy of Sciences, China. It can be inferred that these organizations are actively involved in studying the sensitivity of ozone formation.
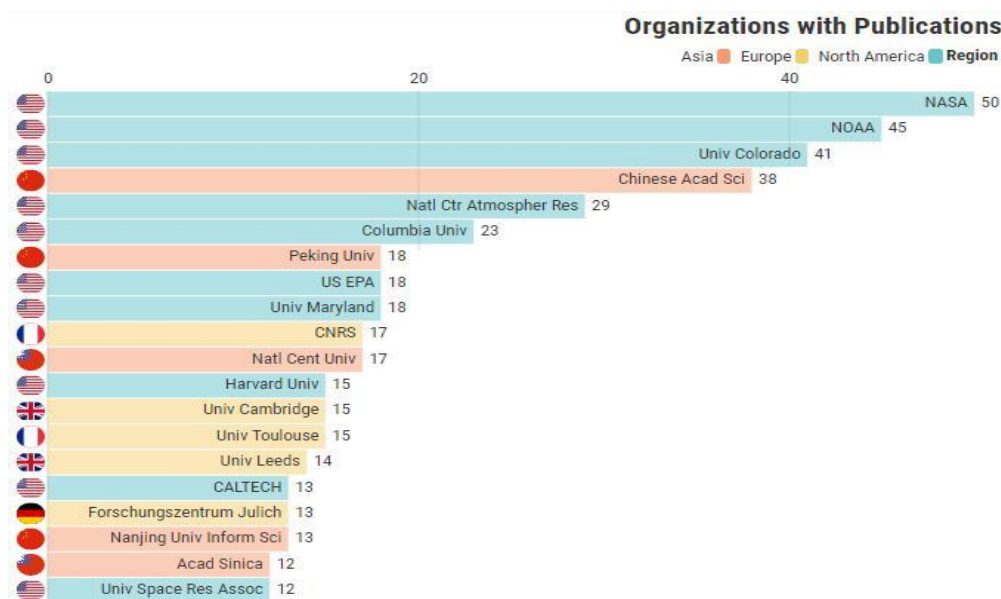
Figure 6. Most productive organizations in ozone formation sensitivity research publications.

Figure S1 shows the top organizations in terms of citations in research regarding O_3 formation sensitivity. Figure S2 shows collaborations among countries. The USA has the most collaborations and published research on the topic, collaborating with the highest number of countries. The UK is the second most collaborative country, followed by Germany, France, and China. The USA collaborates most with the UK, Germany, France, China, and Norway. The UK collaborates most with Germany, France, Norway, and Japan.

3.5. Frequently Used Author Keywords

Author keyword analysis generates information about the words that appear in the titles or abstracts of publications. This kind of analysis is crucial for exploring research topics, as authors use keywords to convey specific ideas [28]. Based on author keywords, we investigate the areas focused on and give a topical analysis with an emphasis on O_3 formation regimes over the years. We investigate the shifts in the focus of authors dealing with the topic. Keywords with higher recurrence are chosen carefully to ascertain the key research scopes and related evolving dimensions [29,30].

Figure 7 shows the author keyword map, and Figure S3 shows the author keywords as a word cloud. The size of the circles in Figure 7 indicates the keyword search frequency use, with bigger circles implying more significant usage. Likewise, the word size in Figure S3 indicates the keyword use frequency. In both Figures 7 and S3, the author keywords "ozone", "ozone precursors", "air quality", "surface ozone", "tropospheric ozone", "nitrogen oxides", "climate change", and "air pollution" appear most frequently. Figure S4 shows the evolution of author-supplied keywords in ozone research and the author-supplied keywords with the highest frequency in the corresponding year. The keyword flow between nodes shows the evolutionary direction, while the node size indicates keyword usage frequency. Themes that have no connection with the evolved themes are not shown.

The keyword "ozone" remained the same from 1965 to 2000 but then evolved into new keywords, as shown in Figure S4. The keyword "biogenic emissions" evolved into "volatile organic compounds" and "ozone precursors".
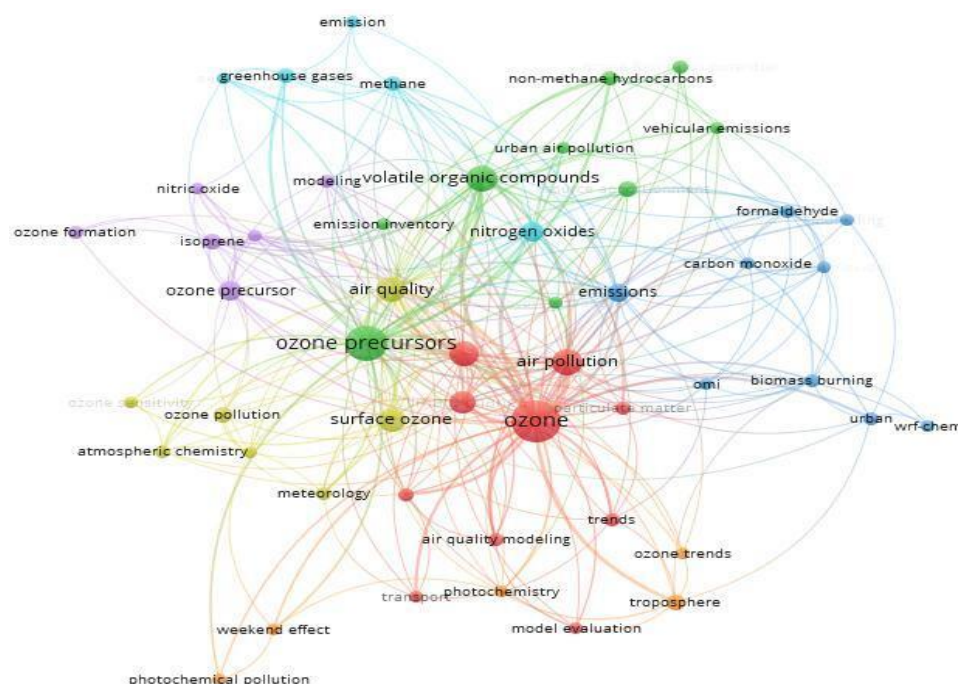
Figure 7. Frequently used author keywords network visualization in ozone formation sensitivity research.

3.6. Highly Cited Documents

Citation analysis is an essential bibliometric feature that demonstrates the significance and prestige of a research paper within the scientific community. A highly impactful article (HIA) is an indicator of a high-quality publication. Wang and Ho [28] propose that researchers should prioritize recent HIAs, taking into account their citation count. Sillman S [11] is the most cited document in ozone formation regime research, published in the journal Atmospheric Environment. This article provides an overview of the research into the relationship between O_3 and its primary precursors, volatile organic compounds and nitrogen oxides. The second most cited article is Wang et al. [31], published in the journal Science of the Total Environment. This study provides a review of studies on tropospheric O_3 in China and insight into the impact of meteorological processes and precursors on ozone formation. The third most cited document is Chameides et al. [32], published in the Journal of Geophysical Research. This study analyses concentrations of O_3, NOx and non-methane hydrocarbons to show the relationship between ozone and its precursors.

4. Implications and Limitations of This Study

The results of this study have vital implications for the scientific productivity surrounding the subject. The analyses pave the way toward a better understanding of how specific countries, institutions, authors and research hotspots contribute to ozone formation research. This study highlights the extensive work published over the years based on various metrics and illustrates the standing of various research institutions in terms of research output.

It is noteworthy that, except for China, Asian countries lag behind European countries in terms of research productivity. A detailed insight into current and prospective positions on the subject is provided, with an in-depth literature review of pioneering research articles and key research hotpots. A comprehensive analysis with detailed information on each parameter is conducted. A country's scientific productivity is, for instance, not only an indicator of the quality of research but of the potential for future collaboration networks. The high impact of published research is suggestive of the vitality of the subject for its specific audience. An important implication of the current analysis is recognizing faltering deviations in the research dynamics, which is crucial for policymaking in this domain.

Our study reveals some significant and interesting findings; however, there are certain limitations. Firstly, it is difficult to extract full information from keyword analysis maps generated by the bibliometric technique. A more comprehensive investigation could expand the information content to include the titles, abstracts and main text, not relying merely on keywords. Furthermore, we show that the subject lacks quantitative studies, which should be more of a focus in the future. However, such studies require objective data, which is either lacking or difficult to obtain. There is still uncertainty in some data sources and about data collection tools' ability to provide the desired datasets for analysis and research. Finally, this study only includes articles from the WOSCC search engine, which covers most articles, but some articles from other databases and search engines may be missing. Therefore, an analysis based on cross-comparison and multi-source searching would be more accurate and conclusive.

5. Conclusions

The current study uses a bibliometric technique to analyse the growth in the subject domain by finding recent trends and hotspots in O_3 formation sensitivity research. In order to meet the objectives, we perform an analysis of 951 publications and visualize the prospects of these publications in terms of prominent countries, research categories, institutions, authors, and journals. This study is a crucial indicator of the importance and contribution of research institutions that employ different research metrics across the globe. In terms of research output, the USA and China emerge on top. The USA has the greatest impact, followed by the UK, Germany, France, and China. On a territory basis, Europe is the most productive continent, followed by North America and Asia. Based on the analysis of the thematic evolution using author-supplied keywords, it is observed that the terms "volatile organic compounds" and "ozone precursors" have recently gained prominence with an increased frequency. This indicates a growing trend in research focused on these topics in the future. This analysis is crucial, as it has a substantial tendency to monitor indeterminate variations in research inclinations reflected in the literature, which act as crucial keys to assist policymaking. Using recent citation trends, the articles with the highest impact are identified.

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