



# Contributions of Open Biomass Burning and Crop Straw Burning to Air Quality: Current Research Paradigm and Future Outlooks

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### Specialty section:

This article was submitted to  
Atmosphere and Climate,  
a section of the journal  
Frontiers in Environmental Science

**Received:** 12 January 2022

**Accepted:** 24 January 2022

**Published:** 08 March 2022

### Citation:

Mehmood K, Bao Y, Saifullah, Bibi S,  
Dahlawi S, Yaseen M, Abrar MM,  
Srivastava P, Fahad S and Faraj TK  
(2022) Contributions of Open Biomass  
Burning and Crop Straw Burning to Air  
Quality: Current Research Paradigm  
and Future Outlooks.  
Front. Environ. Sci. 10:852492.  
doi: 10.3389/fenvs.2022.852492

Since open biomass burning (OBB) and open crop straw burning (OCSB) could pose a great risk to human health via altering the air quality, these practices have grabbed considerable attention from the scientific community and policymakers in recent years. In order to have a greater and deeper understanding of the contributions of both OBB and OCSB on air quality, a bibliometric analysis was performed using the Web of Science core collection to understand the research developments and future perspectives of these issues between 1991 and 2021. VOSviewer software 1.6.15 and R version 4.0.3 were employed to determine the annual scientific production trend and the role of countries, institutions, authors, and journal metrics network analysis. The findings showed that the interest in the study of OBB and OCSB pollution related to air quality has increased significantly over the last decade. A total of 1,021 publications were retrieved, with English as the most preferably used language. Among all documents, research articles were the most commonly appearing document type, and the researchers mainly emphasized environmental science, meteorology, atmospheric sciences, energy fuels, and environmental engineering fields. In terms of article analysis, *Atmospheric Chemistry Physics*, followed by *Atmospheric Environment*, was found to be the leading journal in this research domain, whereas the most frequently utilized keywords in the documents were biomass, biomass burning, and PM<sub>2.5</sub>. In terms of countries, the United States emerged as the leader with the highest publication rate, followed by China and India. The Chinese Academy of Sciences was ranked first in the list of most productive institutions,

followed by the University of Montana and the US Forest Service. Based on the analysis, the finer spatial and temporal resolution and the characterization and understanding of the complex processes that are occurring in the atmosphere, such as clustering, oxidation, surface chemistry, and their impact on air quality, need to be explored in depth. Our research analysis can provide a baseline for future studies in air quality.

**Keywords:** bibliometric analysis, open biomass burning, air quality, visualization, network analysis

## INTRODUCTION

Crop straw and/or crop residues are among the richest sources of biomass, and the quantity of burning of open crop straw is growing with the intensification of agricultural practices (Kholif et al., 2017). It ultimately causes climate change and exacerbates crop productivity (Elahi et al., 2021a). Fire plays a key role in ecosystem services, such as maiden zones for livestock, pest control, and weed eradication (Shimabukuro et al., 2013). Presently, around half of the world's inhabitants use open crop straws for cooking and household heating, in addition to burning for removal from fields specifically in the countryside of the developing world (Nayek and Padhy, 2017; Sun et al., 2017). Unfortunately, fire utilized to remove crop straws from agricultural fields mainly in Southeast Asia produces heavy smoke (termed as haze pollution) that can spread to nearby regions or even countries, triggering transboundary pollution and attracting special attention to the atmospheric pollution episodes (Duan et al., 2004; Mehmood et al., 2020).

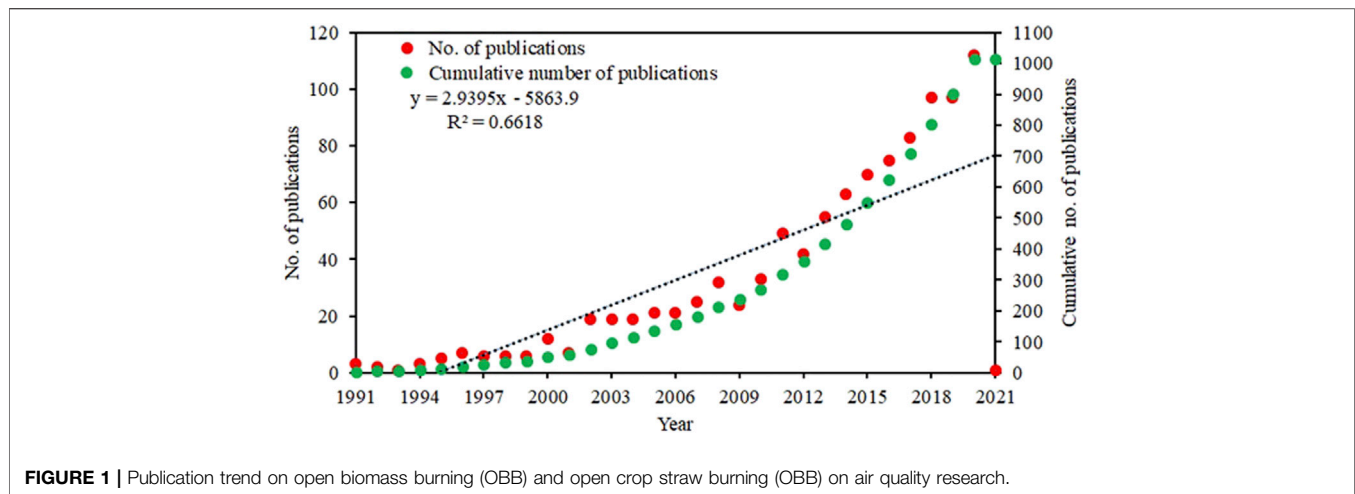
Open biomass burning (OBB) is a global phenomenon in which the practice of burning of forests, grassland, and residues from crops results in the heavy atmospheric emissions of particulate matter (PM), especially fine particles (PM<sub>2.5</sub>) and carbonaceous aerosols, including organic carbon (OC), elemental carbon (EC), and other gaseous pollutants (Van Der Werf et al., 2010; Wenlian et al., 2014; Qiu et al., 2016; Zhou et al., 2018; Mehmood et al., 2020). Globally, OBB contributes to around 40 and 65% of the annual average of EC and OC, respectively, and >45% of PM<sub>2.5</sub> concentrations (Deng et al., 2011; Bond et al., 2013). Each year, more than 25% of PM<sub>2.5</sub> emissions in the US originate from OBB (Kolden, 2019), while in China, it is around 15–24% (Song et al., 2007; Cheng et al., 2013), whereas in Southeast Asia and South China it is below 70% (Fu et al., 2012). The high emission of these pollutants poses a considerable risk on air quality, human health, and climate change at the regional and global levels (Andreae and Merlet, 2001; Bond et al., 2004; Akagi et al., 2011; Zhang L. et al., 2016; Mehmood et al., 2018)—for example, high PM<sub>2.5</sub> concentrations (200 µg/m<sup>3</sup>) with <90% of relative humidity for more than 4 h (Du et al., 2011) lead to a reduction in visibility below 10 km (Chen et al., 2017).

Globally, farmers utilize fire as a tool for the clearance of open crop straw from their fields (McCarty et al., 2009). Compared with other methods, open crop straw burning (OCSB) is the most effective and least expensive tool to clear crop straw in the field, thus attracting farmers to follow this practice to get rid of crop residues. In their

seminal publication, Andreae and Merlet (2001) noted that OCSB was considered as the fourth major kind of OBB after charcoal making, charcoal burning, and biofuel burning. On a global basis, agricultural burning in China contributed to 3–6% of the global agricultural fires during the year 2000 (Charlesworth et al., 2003), while during 2000–2007, OCSB contributed to about 2/3 of the total biomass burning (Tian et al., 2011).

Recent estimates show that the pace of OCSB seems to have accelerated due to agricultural interventions, such as clearing of crop straw, managing pests, and providing short-lived ash fertilization (Cheng et al., 2014; Mehmood et al., 2020). Significant OBB, especially from OCSB, occurs during May to June and October to November due to harvesting of crops like rice, wheat, and maize and the subsequent burning of crop residues. It contributes to regional haze pollution and worsens the air quality in different parts of the world (Yu et al., 2014; Zhang K. et al., 2016; Qiu et al., 2016; Sipra et al., 2017), also harming the atmospheric environment both locally and at large distances downwind (Li et al., 2014; Zhang K. et al., 2016).

Generally, atmospheric pollution caused by OCSB is studied through the measurement of pollutants, the estimation of particulate species, and a numerical model simulation. Mittal et al. (2009) analyzed the variations in the concentration of aerosols, NO<sub>2</sub>, and SO<sub>2</sub> in the troposphere before and after the OCSB. Several researchers have employed levoglucosan (Titos et al., 2017), K<sup>+</sup> (Wu et al., 2016), and water-soluble organic carbon (Zong et al., 2015) as tracers to demonstrate the impact of straw burning on the downwind areas. These studies confirmed that the OCSB has a direct impact on air quality as well as the atmospheric composition by interacting with urban air pollutants which eventually convert into secondary pollutants (Grell et al., 2011; Singh et al., 2012). OCSB could also play a critical role in the deterioration of soil quality in terms of elevated pH after burning of crop straws with large deposition of black carbon (BC) and polyaromatic hydrocarbons (PAH) (Barreiro et al., 2016). Bikkina et al. (2019) suggested that large-scale open burning of post-harvest crop straw burning in surrounding rural regions is contributing to the severe haze pollution in Delhi especially during the winter and autumn seasons. Similarly, Nair et al. (2020) conducted a study to estimate the contribution of agriculture residue in air quality deterioration using multidisciplinary approaches over the region in Haryana, Punjab. Moreover, Irfan et al. (2015) developed a comprehensive emission inventory for pollutants released from crop straw burning, which covers pollutant emissions and their



sources in Pakistan. Furthermore, at a large scale, OCSB contributed not only to reducing the visibility but also to the temporary closure of highways and airports (Li et al., 2014; Hua et al., 2015).

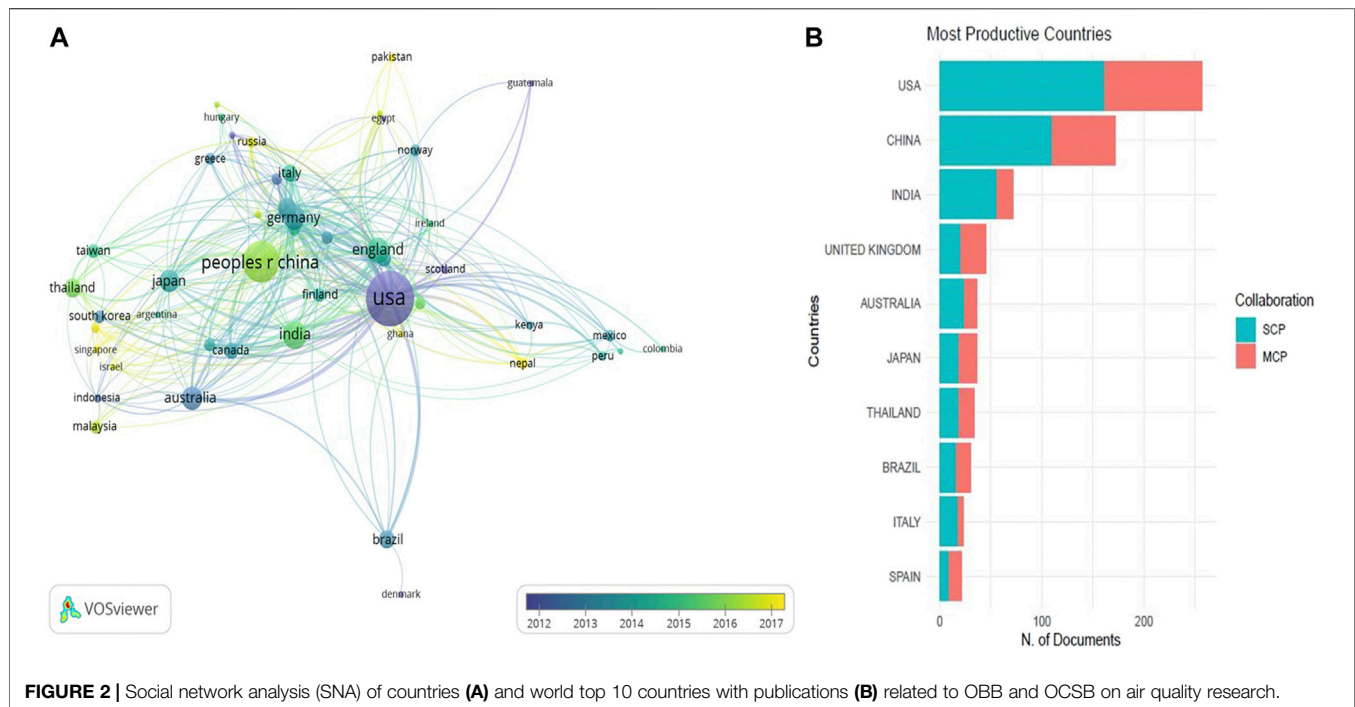
To date, a lot of research on OBB and OCSB has been conducted, which mainly emphasized emission inventory, emission characteristics, and the effects of burning on human health and the ecological environment. Bibliometric analysis is a well-established approach of library and information science, which is applied to evaluate and predict the new trends and development in the respective field (Bramness et al., 2013). Bibliometric research offers an imperative tool to estimate and measure the development of literature for a specific area of interest. Bibliometric analysis has been utilized in different perspectives to examine the data that illustrate the increase in publication frequency, identification of key authors, research funding agencies, research institutions, and countries (Xu et al., 2013). Although few studies on the bibliometric analysis of OBB have been investigated, there is a lack of inclusive and systematic analysis of research progress and future trends. Besides this, the relationship between OBB, OCSB, and air quality is rarely explored. Therefore, it is important to analyze OBB and OCSB concerning air quality and parallel to the development of necessary mitigation measures.

Based on the model of bibliometric analysis, this study aims at examining the frame of information in the field of OBB, OCSB, and air quality research during 1991–2021 through bibliometric analysis, social network analysis (SNA), Sankey three-field plot, and citation networks. Specifically, publications, authors, keywords, research funding agencies, research institutions, and countries were studied. The SNA and citation networks are very innovative in the exploration of this research domain. In the current study, a bibliometric analysis was conducted to (1) examine the research landscape of OBB and OCSB on air quality in terms of journals, author's domains, keywords, and cited work; (2) recognize the collaboration among research institutions; and (3) explore the burning issues and the future scenario.

## DATA SOURCES AND METHODS

The data for bibliometric analysis were retrieved from the Web of Science Core Collection (WoSCC) on May 11, 2021. The data also included the articles that were accepted for publication in 2021 and which were available online. The Web of Science (WoS) was selected due to its robust analysis and comprehensive information for bibliometric study as compared to other databases (Aghaei Chadegani et al., 2013; Yi et al., 2016). According to Journal Citation Reports from 2019, WoSCC was composed of 21,100 peer-reviewed high-quality scientific journals with more than 250 sciences. It covers Science Citation Index (SCI)—Expanded, Social Science Citation Index (SSCI), Arts and Humanities Citation Index (A&HCI), Conference Proceedings Citation Index (CCPI), Emerging Source Citation Index (ESCI), Current Chemical Reactions (CCR—Expanded), and Index Chemicus (IC). The search strategy employed for this work is illustrated in **Supplementary Figure S1**. The selection of keywords method was refined until the desired citation was completed. Afterward, the retrieved documents were screened based on our study scope and to ensure the purpose of this research, such that these completely cover the topic related to the contributions of OBB and OCSB to air quality. This study used the equation  $TS = [(open\ biomass\ burning) OR (open\ crop\ straw\ burning) AND (haze)]$  to retrieve the documents from WoS database. The period was selected from 1991 to 2021. The documents included research articles, review articles, reviews, early access articles, book chapters, editorials, abstracts, letters, proceeding papers, and reprints.

This study covers a total of 1,021 publications in 9 document types that were retrieved from the WoSCC database during 1991–2021. This study focused exclusively on the documents published in the English language. Of all document types, research articles (865) accounted for 84.72%, followed by proceeding papers (65, 6.36%), review articles (52, 5.09%), editorials (4, .39%), abstracts (3, .29%), letters (2, .19%), and others (2.54%) The most published document type was research articles, which is in line with other bibliometric analysis using the



SCI—Expanded database (Zhang K. et al., 2016; Dhital and Rupakheti, 2019).

The study of the global scientific literature on OBB and its effects on air quality was performed through a bibliometric network analysis, which syndicates both bibliometric and SNA to explore the specific area of science (Zou et al., 2018; Dhital and Rupakheti, 2019). The SNA is the method of studying social configurations through the application of a graph and network theory using data visualization software (Otte and Rousseau, 2002). The SNA and map-based analysis are helpful to identify pattern recognition in bibliometric science, allowing the construction of network maps as well as establishing statistical relationships among countries, journals, organizations, authors, and keywords pertaining to the research topic (Chen et al., 2016). In this study, we used h-index, g-index, and m-index metrics. The h-index is an author-level metric which measures both the productivity and citation impact of the researcher. The g-index is computed as the given set of articles ranked in decreasing order of the number of citations that they received. The m-index is another variant of the h-index that presents the h-index per year since its first publication.

This study employed VOSviewer software (version 1.6.15) and R version 4.0.3. for mapping, tabulation, and visualization (van Eck and Waltman, 2010). The visualization method could be illustrated as a network, overlay map, and density from 1991 to 2021. The network visualization utilizes different colors to represent different clusters, such as institutions, countries, and authors, and the linking lines indicate parameters, such as co-citation and collaboration. The size of the circle illustrates the magnitude of each parameter. The strength of co-citation is estimated by the thickness of linking lines and is mathematically denoted as relative link strength. **Supplementary Table S1** summarizes the main

technical terms used by the VOSviewer software and Sankey three-field plot. The analysis included co-authorship, co-occurrence, and citation used in this study (Van Eck and Waltman, 2019). In co-authorship webs, countries, researchers, and research institutions are connected, considering the number of document types such as research articles, proceeding papers, and review papers which they have authored jointly. The co-occurrence analysis includes the number of two keywords in the publications in which both keywords occur jointly in the keyword list, abstract or title, and citation analysis, if at least one cites the other.

## RESULTS AND DISCUSSION

### Annual Scientific Production Trend During 1991–2021

The life of scientific literature is linked to the number of citations. Both publication and citation trends can be helpful to illustrate the connections between citation per publication and the article lifespan (Chiu and Ho, 2007; Chuang et al., 2007). **Supplementary Figure S2** shows the average citation per year (a) and annual scientific production (b) during 1991–2021.

Lower citation scores were recorded during 1991–2005, primarily due to the lower number of documents published and, secondly, less frequent OBB events that occurred during this period. As evident from **Supplementary Figure S2A**, the number of citations increased from 2013 to 2019, suggesting that the topic gained significant attention presumably due to the increased OBB and OCSB events and their effect on air quality globally.

To better understand the publications and trends during the selected period, a linear regression model was applied.

**TABLE 1** | Countries with total citations and average article citations.

Country	Total citations	Average article citations	Country	Total citations	Average article citations
United States of America	20,311	79.031	Ireland	88	29.333
China	5,057	29.573	Israel	88	88.000
United Kingdom	1,752	38.933	Peru	84	28.000
Japan	1,404	39.000	Venezuela	55	55.000
Australia	1,375	39.286	Argentina	52	17.333
India	1,245	18.043	Indonesia	44	11.000
Thailand	957	28.147	Saudi Arabia	38	38.000
Korea	869	43.450	Egypt	25	12.500
South Africa	730	60.833	Kazakhstan	24	12.000
Brazil	707	23.567	Lithuania	24	12.000
France	660	33.000	Pakistan	24	6.000
Germany	627	31.350	Romania	24	6.000
Switzerland	622	77.750	Singapore	24	12.000
Sweden	589	39.267	Kenya	21	10.500
Spain	444	21.143	Slovenia	17	8.500
Finland	357	32.455	Cuba	15	15.000
Portugal	343	57.167	Sri Lanka	15	5.000
Norway	324	32.400	Lebanon	11	11.000
Italy	310	13.478	Slovakia	11	5.500
Mexico	296	26.909	Netherlands	9	3.000
Canada	274	15.222	Vietnam	9	1.800
Greece	273	24.818	Poland	6	6.000
Denmark	230	57.500	Iran	5	5.000
Belgium	222	74.000	Nigeria	5	2.500
Malaysia	179	9.944	Iraq	3	3.000
Russia	164	14.909	Colombia	2	.667
Austria	127	42.333	Nepal	2	1.000
Hungary	113	22.600	Philippines	2	2.000
Turkey	108	54.000	Serbia	2	1.000

**Figure 1** displays the trend of annual publications and cumulative number related to OBB and OCSB on air quality research from 1991 to 2021. The average number of publications was ~33 documents per year. A growing trend in the number of publications was noticed over the years which is estimated by the linear growth curve, resulting in the following equation:

$$y = 2.9395x - 5863.9$$

$$R^2 = 0.66$$

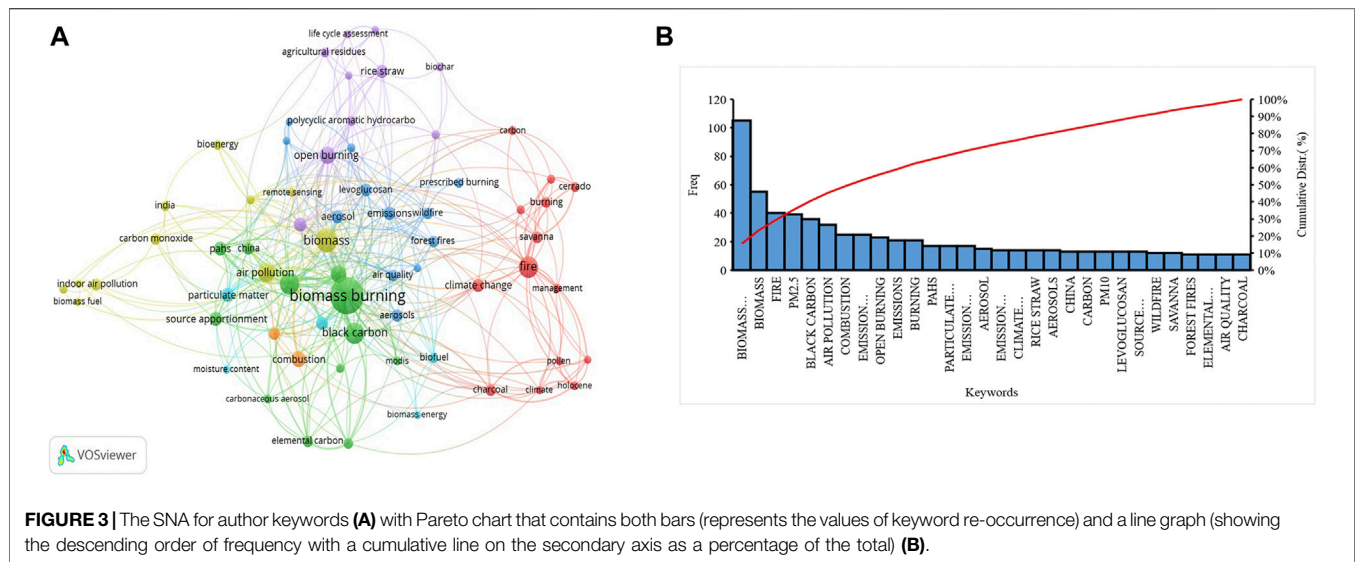
The highest productivity was observed in 2020 with 112 publications (10.96% of the total), although the minimum number of publications was recorded in 1993 and 2021 with

only one publication (0.19% of the total) during 1991–2021. The increasing trend of the number of publications since 2010 highlights the fact that the research on the role of OBB and OCSB on air quality has gained worldwide attention. From 1991 to 2001, the frequency of the publication was low (5.6%), which gradually increased to 41.33% during 2002–2014. However, in the last 5 years (2015–2020), a drastic growth in the frequency of publications was observed, with 52.30% of the total publications appearing during this period. The increasing number of publications in the last decade is primarily due to a large number of biomass burning events reported around the world, fueled by increasing awareness of global climate change among the community. Furthermore, it is also observed in the reports that the number of fire events was higher compared with the



**TABLE 2 |** Author keywords and author keywords plus network analysis.

Author keywords	Article frequency	Keywords plus	Article frequency
Biomass burning	110	Biomass	163
Biomass	47	Particulate matter	110
PM <sub>2.5</sub>	39	Emissions	107
Black carbon	36	Combustion	88
Fire	36	Source apportionment	80
Air pollution	31	Trace gases	67
Emission inventory	25	Black carbon	64
Open burning	24	Polycyclic aromatic hydrocarbons	62
Combustion	21	Air pollution	56
Emission factors	17	Carbon	54
PAHs	17	Air quality	53
Particulate matter	17	Aerosols	51
Source apportionment	16	Impact	47
Climate change	15	Pollution	46
Aerosol	14	PM2.5	45
Emission factor	14	Aerosol	42
Emissions	14	Chemical characterization	41
Rice straw	14	Forest	41
Aerosols	13	Particles	41
China	13	Fire	40
Levogluconan	13	Climate	39
PM <sub>10</sub>	13	Elemental carbon	39
Elemental carbon	12	Chemical composition	38
Wildfire	12	China	36
Carbon monoxide	11	Model	36
Charcoal	11	Dynamics	33
Forest fires	11	Vegetation	32
Indoor air pollution	11	Optical properties	31
Savanna	11	Transport	30
Air quality	10	Inventory	29
Burning	10	Light absorption	29
Organic carbon	10	Atmospheric aerosols	28
Agricultural residues	9	Brown carbon	27
Bioenergy	9	Emission factors	27
Biofuel	9	Energy	27
Cerrado	9	Management	27
India	9	Biomass burning emissions	26
Polycyclic aromatic hydrocarbons	9	Quality	26
Prescribed burning	9	Variability	26
Biomass open burning	7	Carbon monoxide	25
Brazil	7	Organic compounds	25
Carbonaceous aerosol	7	Organic carbon	24
Crop residue	7	Long-range transport	23
Grazing	7	Air	22
Holocene	7	Particle emissions	22
Household air pollution	7	Rice straw	22
MODIS	7	Smoke	22
Open biomass burning	7	Volatile organic compounds	22
Remote sensing	7	Asia	21
Smoke	7	Climate change	21



average over the 2000–2017 period (San-Miguel-Ayanz et al., 2018; Adam et al., 2020), while the burnt area was also increased. This implies that with the increase in biomass burning that occurred, research on this topic has also gained attention from policymakers and researchers.

### Scientific Contribution of Countries

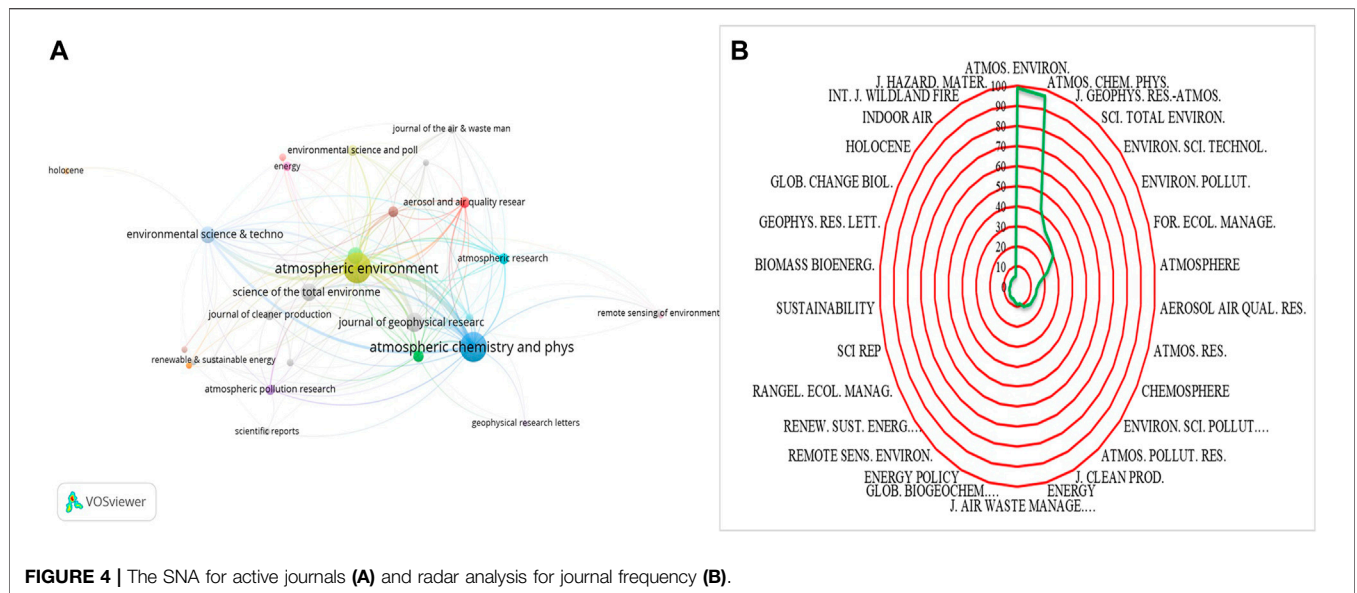
The contribution of different countries on this topic was determined by the affiliation of a minimum of one author listed in the publications. The 1,021 documents retrieved in the WoSCC included authors from 83 countries. **Table 1** shows the countries with total citations (TC) and average article citations (AAC), with the United States (20,311 citations; average citations of 79.03) ranked as the highest, followed by China (5,057 citations; average citations of 29) and the United Kingdom (1,752.38 citations; average citations of 38). **Figures 2A,B** presents all countries with publications and SNA related to OBB and OCSB on air quality research based on single-country publications (SCP) and multi-country publications (MCP). **Supplementary Table S2** presents a global analysis based on SCP, MCP, frequency, and MCP ratio. Researchers from Asian countries, such as China, India, Japan, and Thailand, and European countries, including Italy and Spain, have actively published papers on these topics. The United States contributed the maximum number of publications, with a total of 257 (25.17% of the total) documents, followed by China with 172 (16.84% of the total) and India with 72 (7.05% of the total), respectively. The number of publications, to some extent, represents the academic impact and research output of these countries. The United States had 46 links, with a total link strength of 3,465 with one cluster, and the strongest link was developed by China, with 46 links and a total link strength of 288 with four clusters (**Figure 2A**). Overall, both the United States and China were found to be the top two countries where OBB and OCSB research was extensively conducted.

An analysis of top institutions revealed that China and the United States were the most significant contributors to the research on air quality due to OBB and OCSB (**Figure 2B**), whereas the United Kingdom, Japan, Australia, India, Thailand, Korea, South Africa, and Brazil were in the list of the top 10 countries with the most productive institutions. The higher productivity of research in China and the United States are attributed to funding availability in these countries. On the other hand, the level of inter-institutional collaboration was found to be poorer than international collaboration. It is mainly due to the regionalized distribution of institutions in these countries and the lack of comprehensive research on the research topic at each institution. The data also indicate that the United States and China have put in significant research efforts to explore the possible effects of OBB and OCSB on air quality.

### Author Keyword Network and Research Hotspots

The analysis of words used in titles, abstracts, and author keywords can be useful when estimating the research areas because they cover the important information that authors want to present to their readership (Wang and Ho, 2016). The keywords were selected for analysis in this research, which can reasonably explore the depth of publication to reflect the focal areas of research and develop the direction, particularly the high-frequency keywords (Hamidi and Ramavandi, 2020).

Conversely, keywords plus could not completely cover the core content of the document by Thomson Reuters. Because some keywords with the same meaning have several variations, it is essential to homogenize these keywords before analysis—for instance, biomass burning and open burning were both aggregated to open biomass burning.



**FIGURE 4 |** The SNA for active journals (A) and radar analysis for journal frequency (B).

**TABLE 3 |** World journals with h-index, g-index, total citation (TC), number of publications (NP), and publication year start (py\_start).

Element	h_Index	g_Index	m_Index	TC	NP	py_start
<i>Atmospheric Chemistry and Physics</i>	34	68	3.090909	4,690	80	2011
<i>Atmospheric Environment</i>	24	38	2.181818	1,735	66	2011
<i>Environmental Science and Technology</i>	15	22	1.363636	1,314	22	2011
<i>Science of the Total Environment</i>	14	22	1.272727	511	29	2011
<i>Environmental Pollution</i>	13	19	1.181818	385	20	2011
<i>Atmospheric Research</i>	10	13	.909091	570	13	2011
<i>Journal of Geophysical Research—Atmospheres</i>	9	13	.818182	2,885	13	2011
<i>Atmospheric Pollution Research</i>	8	10	.727273	104	10	2011
<i>Chemosphere</i>	8	11	.727273	250	11	2011
<i>Energy</i>	8	9	.727273	225	9	2011
<i>Aerosol and Air Quality Research</i>	7	13	.7	196	13	2012
<i>Atmosphere</i>	7	10	.75	103	10	2014
<i>Environmental Science and Pollution Research</i>	7	10	.7	128	10	2012
<i>Renewable and Sustainable Energy Reviews</i>	7	7	.7	501	7	2012
<i>Journal of Cleaner Production</i>	6	9	1	194	9	2016
<i>Remote Sensing of Environment</i>	6	6	.545455	479	6	2011
<i>Energy Policy</i>	5	6	.625	99	6	2014
<i>Environment International</i>	4	4	.363636	112	4	2011
<i>Forest Ecology and Management</i>	4	4	.363636	65	4	2011
<i>Indoor Air</i>	4	4	.4	122	4	2012
<i>Renewable Energy</i>	4	4	.571429	20	4	2015
<i>Scientific Reports</i>	4	5	.571429	276	5	2015
<i>Atmospheric Measurement Techniques</i>	3	3	.272727	76	3	2011
<i>Biogeosciences</i>	3	3	.3	113	3	2012
<i>BMC Public Health</i>	3	3	.375	54	3	2014
<i>Energies</i>	3	3	.6	22	3	2017
<i>Energy Conversion and Management</i>	3	3	.6	43	3	2017
<i>Energy for Sustainable Development</i>	3	4	.6	35	4	2017
<i>Geoscientific Model Development</i>	3	3	.272727	885	3	2011
<i>Holocene</i>	3	3	.428571	28	3	2015



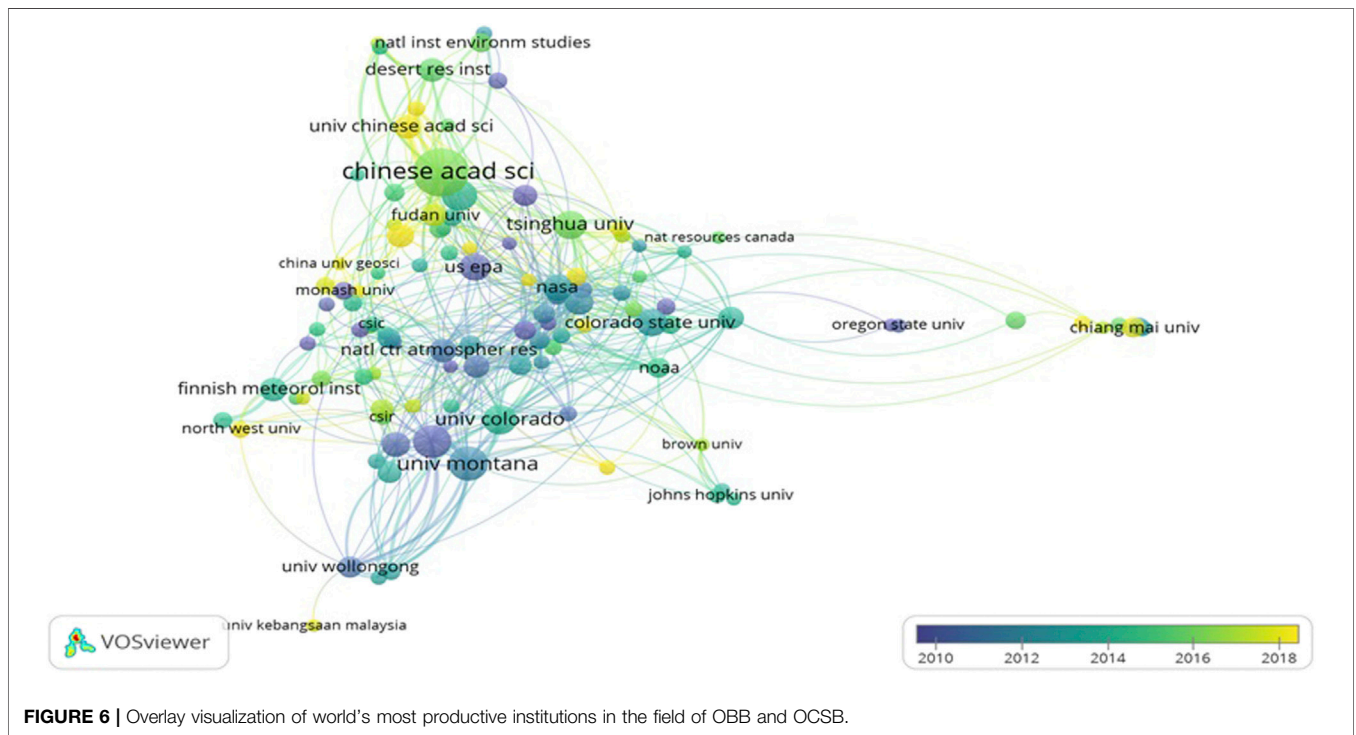
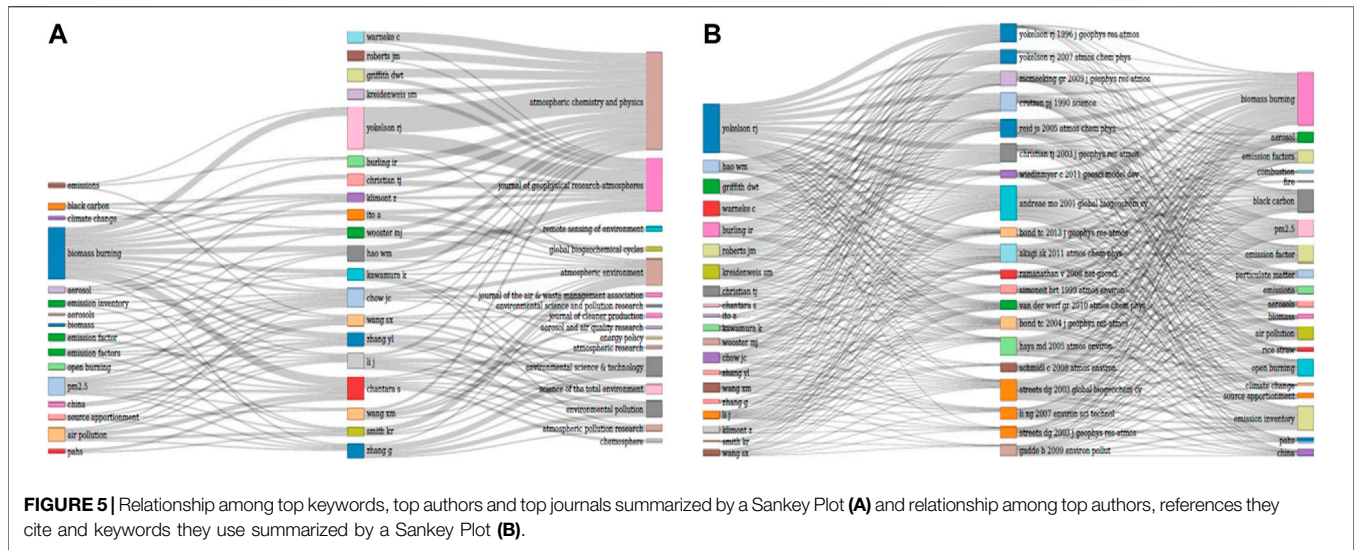


Table 2 shows the author keywords and author keyword plus networks related to OBB and OCSB air quality research. The results indicated that the most recurrently encountered author keywords and author keyword plus were “biomass burning” (110), “biomass” (47), and “PM<sub>2.5</sub>” (39) and “biomass” (163), “particulate matter” (110), and “emissions” (107), respectively. A keyword co-occurrence analysis was performed through VOSviewer 1.6.15 software by retrieving raw files from the WoSCC database, and a visual map was developed for better

illustration of the author keywords. The keyword “biomass burning” created 41 links, with a total link strength of 121 and with 2 clusters, followed by “PM<sub>2.5</sub>” with 27 links of a total of 59 link strength along with 2 clusters (Figure 3A). Figure 3B shows a Pareto chart that contains both bars (representing the values of keyword reoccurrence) and a line graph (showing the descending order of frequency with a cumulative line on the secondary axis as a percentage of the total). Supplementary Figure S3 shows the words cloud plot (a) and words cloud network data (b). Overall,

there was a total of 66 items with 7 clusters and 360 links and 579 total link strengths. Moreover, the recurrent occurrence of keywords such as “biomass burning,” “biomass,” “fire” “PM<sub>2.5</sub>” “black carbon”, and “air pollution” indicates that air quality caused by OBB and OCSB has drawn significant attention. Several studies employed keywords including “PM<sub>2.5</sub>,” “PAH,” “particulate matter,” and “PM<sub>10</sub>” from OCSB during cooking or heating in rural areas, which have a considerable impact on indoor air quality due to low combustion efficiency. Consequently, it has several adverse effects on the human lungs (Sarigiannis et al., 2015).

### Active Journal Distribution Analysis

The distribution of active journals is the primary part of a bibliometric analysis (Chiu and Ho, 2007). A total of 28 journals have published 1,021 research articles related to OBB and OCSB and their effects on air quality from 1991 to 2021. **Figures 4A,B** shows the SNA for active journals (4.a) and the radar analysis for journal frequency (4b). **Table 3** presents the world journals with h-index, g-index, TC, number of publications, publication year start. *Atmospheric Environment* was the most productive journal (100 articles, 9.5%), followed by *Atmospheric Chemistry Physics* (97 articles, 9.50%) and *Journal of Geophysical Research* (42 articles, 4.11%). However, *Atmospheric Chemistry Physics* scored the highest for h-index (39), g-index (72), and m-index (3.5454). **Figure 5A** shows the relationship among the top keywords, top authors, and top journals summarized by a Sankey plot.

The top 10 active journals that addressed the topic of this research covered the fields of environmental sciences, meteorology, atmospheric sciences, energy fuels, and environmental engineering. The most influential journal in these fields is *Atmospheric Chemistry Physics*, with an impact factor of 5.414 in 2019. This journal grabbed 6,050 citations with three clusters and 19 links and is dedicated to studies on the earth’s atmospheric and essential physical and chemical processes. The main core areas comprise field measurements and atmospheric modeling, clouds and precipitations, radiations, laboratory studies, remote sensing, and aerosols, whereas *Atmospheric Environment* was the second most influential journal, with an impact factor of 4.039 in 2019, capturing 4,568 citations with 4 clusters and 23 links. The major subject areas for *Atmospheric Environment* are atmospheric composition and its impacts on the ecosystem. In addition, this journal also covers atmospheric emissions and the deposition of gases and particulate compounds along with the impacts on air quality and human health. Both *Atmospheric Chemistry Physics* and *Atmospheric Environment* developed a total strength of 565 and 524, respectively.

### Active Journal Distribution Analysis

The institutional contribution analysis was carried out based on the author’s affiliation address. A total of 1,415 institutions contributed to 1,021 articles during 1991–2021. The most productive institutions in the field of OBB and OCSB are illustrated in **Figure 6**. Co-authorship with organization analysis indicated that the top four institutions have accounted

for 16.76% of the total 1,021 publications. It was also revealed that the Chinese Academy of Sciences (CAS), with 68 documents with 2,376 total citations and a total strength of 104, was the most productive institution. The CAS encompasses 100 sub-institutes nationwide, and all the data of these sub-institutes were aggregated into CAS research. This is one of the reasons that CAS ranked first in OBB and OCSB pollution research. The second most influential institution was the University of Montana (UoM) with 34 documents. The UoM received 3,697 citations, which was higher than the CAS, and had a total link strength of 92. The US Forest Services (USFS) received 2,402 citations with 33 documents and a total strength of 60. Citations and organization analysis indicated that the UoM was a highly productive institution with 34 documents and a total link strength of 2,044, followed by the USFS with 33 documents and a total link strength of 1,380. This study also shows that the top four institutions belonged to the United States except for the CAS. These institutions have several links with other organizations (**Figure 6**).

The publications from the United States institutions, however, showed a relatively low collaboration in terms of international research exchange with other institutions, especially in Asia. It is evident that the maximum number of publications was contributed by the United States and China, and only a few publications demonstrated international collaboration. In China and the United States, the most dominant institutions which are conducting research on OBB and OCSB are the CAS and the UoM, highlighting that the most productive institution in each country may help researchers explore potential avenues appropriate for their research exchange activities, workshops, training, and post-doctoral study tours (Vanzetto and Thomé, 2019).

### Authorship Analysis and Citations Network

The citation network analysis explains the citation scores of the author and is helpful to understand the importance of the research work on a specific topic. We used local citation scores (LCS) and global citation scores (GCS) for articles during 1991–2021. Akagi et al. (2011) received a GCS of 792 and an LCS of 103, followed by Streets et al. (2003) who received a GCS of 487 and an LCS of 81. Maximum citation (2,495) was observed for Bond et al. (2013) (**Supplementary Table S3**). **Figure 5B** shows the relationship among top authors, references that they cite, and keywords that they use summarized by a Sankey plot.

The total number of authors who contributed to the published documents was 110, with an average of 9.0 authors per document. The maximum number of documents were published by RJ Yokelson, followed by WM Hao and J Li. The top active authors were primarily from the United States, Germany, and China. Authors with a minimum productivity of five publications were also observed by utilizing the network visualization map, which presented research networking among active authors (**Supplementary Figures S4A,B**). This indicated that RJ Yokelson was the most active author with a maximum productivity of 14 publications in two clusters with seven links and 31 link strengths. Similarly, the maximum frequency (35) was

**TABLE 4 |** Highly impactful articles related to open biomass burning and open crop straw burning during 2011–2020.

Title	Author	Source title	Publication year	DOI	Total citations	Average per year
Bounding the role of black carbon in the climate system: a scientific assessment	Bond <i>et al.</i> (2013)	<i>Journal of Geophysical Research—Atmospheres</i>	2013	10.1002/jgrd.50171	2,602	289.11
Emission factors for open and domestic biomass burning for use in atmospheric models	Akagi <i>et al.</i> (2011)	<i>Atmospheric Chemistry and Physics</i>	2011	10.5194/acp-11-4,039-2011	815	74.09
The Fire INventory from NCAR (FINN): a high-resolution global model to estimate the emissions from open burning	Wiedinmyer <i>et al.</i> (2011)	<i>Geoscientific Model Development</i>	2011	10.5194/gmd-4-625-2011	666	60.55
Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010	Lu <i>et al.</i> (2011)	<i>Atmospheric Chemistry and Physics</i>	2011	10.5194/acp-11-9,839-2011	517	47
Global atmospheric emissions of polycyclic aromatic hydrocarbons from 1960 to 2008 and future predictions	Shen <i>et al.</i> (2013)	<i>Environmental Science and Technology</i>	2013	10.1021/es400857z	367	40.78
Global fire emissions estimates during 1997–2016	Van Der Werf <i>et al.</i> (2010)	<i>Earth System Science Data</i>	2017	10.5194/essd-9-697-2017	558	139.5
The collection 6 MODIS active fire detection algorithm and fire products	Giglio <i>et al.</i> (2016)	<i>Remote Sensing of Environment</i>	2016	10.1016/j.rse.2016.02.054	307	51.17
Effects of aging on organic aerosol from open biomass burning smoke in aircraft and laboratory studies	Cubison <i>et al.</i> (2011)	<i>Atmospheric Chemistry and Physics</i>	2011	10.5194/acp-11-12,049-2011	304	27.64
Impact of biomass burning on haze pollution in the Yangtze River delta, China: a case study in summer 2011	Cheng <i>et al.</i> (2014)	<i>Atmospheric Chemistry and Physics</i>	2013	10.5194/acp-14-4,573-2014	189	23.62
Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards	Jetter <i>et al.</i> (2012)	<i>Environmental Science and Technology</i>	2012	10.1021/es301693f	254	25.4

observed for RJ Yokelson, followed by J Li and K Kawamura (**Supplementary Figure S4A**). **Supplementary Table S4** shows the author analysis with dominance factor (DF) and rank DF based on single author, first author, and multi-authors. Ito A authors have gained the maximum DF (0.875) among all authors. **Supplementary Table S5** presents the year-wise analysis based on citations, mean total citation per article, and citable years. Highly cited articles with citable years were noted in 2004–2011. This indicates that these years were the most productive years in terms of citation analysis.

## Highly Impactful Articles Related to OBB and OCSB

The number of citation analysis signifies its utmost key bibliometric features because it shows the importance and reputation of a study in the scientific community. The highly impactful article (HIA) is a measure of a high-quality publication. Wang and Ho (2016) suggested that researchers should emphasize on recent highly impactful papers by considering their citations in the most recent year. **Table 4** shows the list of the world's top 10 highly cited and impactful

articles during 2011–2021. The most highly impactful article was published by Bond *et al.* (2013) in *Journal of Geophysical Research-Atmospheres*, with 2,602 total citations and grabbing 289.11 average citations per year.

This article described the term BC and explained the framework which is used for quantifying climate forcing. Therefore, this paper has attracted significant attention from the scientific community. The HIA published by Akagi *et al.* (2011) in *Atmospheric Chemistry Physics* grabbed 815 total citations with 74.09 average citation per year. This study presents that individual OBB emits significantly more gas-phase non-methane organic compounds, which affect secondary organic aerosol and ozone formation. This study helped to improve the photochemical model performance. Overall, most of the studies emphasized the concerning OBB and OCSB emissions and the impacts on air quality, climate, and health over the globe, including the relationship to atmospheric dynamics and chemical processes. More specifically, OCSB is present in bulk form, and its plumes transport according to the weather condition. Therefore, it is highly recommended that OCSB campaigns should be planned during the harvest seasons. This will help to quantify the

aging and complex chemical process and optical properties of OBB.

## CURRENT STEPS AND FUTURE PERSPECTIVES

The review of literature, the analysis of results combined with abstracts, titles, author, and keywords, and the content of the documents suggest that further research is necessary to characterize OBB and OCSB emissions and their negative impact on the atmospheric environment and public health (Bikkina et al., 2019; Nair et al., 2020). Research trends in both OBB and OCSB pollutions indicate further studies focusing on the following:

- quantification of OCSB emission and identification of spatial and temporal pattern at a finer-resolution level and
- characterization and understanding of the complex processes occurring in the atmosphere, *e.g.*, clustering, oxidation, and surface chemistry, and their impact on air quality

In the light of the above-mentioned points, an in-depth analysis of OBB and OCSB activities and their effects on air quality, especially on haze formation, is likely to play a key role in exploring new horizons and future research directions. However, as recent evidence has suggested that OCSB may have significant effects on air quality in China and other parts of the world, more relevant efforts should focus on the following key issues:

- large-scale real-time monitoring data and surveys updating the comprehensive OCSB, emission factors, and emission inventories especially across Asian countries to anticipate higher accuracy for OCSB atmospheric modeling,
- spatial-temporal comparison (like the diurnal patterns of pollutant concentrations in different seasons over the whole country) regarding OCSB emissions,
- evaluation of uncertainty in haze prediction events while taking into consideration the atmospheric, modeling, satellite, and laboratory studies, and
- detailed cross-sectional and longitudinal studies to elucidate the short-term and long-lasting air quality issues before it becomes a widespread issue. Moreover, studies are required to understand the socio-psychological behavior of people regarding adoption measures (Elahi et al., 2021b) to reduce environmental emissions.

## IMPLICATIONS OF THIS WORK

The findings of this work are attributed to several major implications for the analysis of scientific productivity on the

contributions of OBB and OCSB to air quality. These analyses highlighted a series of key information and data which enables researchers and policy makers to gain understanding on the role of countries, authors, institutions, and specific research hotspots on the theme of air quality in response to burnings. This study clearly illustrated the contribution of each country's research productivity, research institutions, and renowned scientist related to famous institutions at the global level. The cutting edge research and research hotspot collected from the literature offer detailed information on the current and future perspectives on this theme. We have conducted an extensive analysis which provides the in-depth information for each parameter being used in this study—for instance, in terms of country, scientific country productivity implies the research status of a particular country in the future. Similarly, highly impactful articles indicated the significance of the research for a specific topic of interest. These can be referred to other bibliometric parameters, such as collaborations, number of citations, *etc.* The demarcation of tentative changes in research domain and trend compared to existing literature is an auxiliary key implication of this analysis, so this type of study may be beneficial for environmentalists and policy makers to gain in-depth understanding of current and future research.

## CONCLUSION

Based on the 1,021 documents associated with OBB and OCSB research retrieved from the WoS database during 1991–2021, the current study executed a scientific study using a bibliometric approach, in which a literature review through academic documents published in English was conducted. The appropriate document types were analyzed quantitatively and qualitatively to investigate the connections between authors, countries, citations, keywords, and institutions. The results showed that the frequency of articles significantly increased in the last decade. The United States contributed the maximum number of publications, with a total of 257 (25.17% of the total) documents, followed by China with a total of 172 (16.84% of the total) and India with a total of 72 (7.05% of the total) documents, respectively. The most recurrently encountered author keywords were biomass burning, PM<sub>2.5</sub>, biomass, black carbon, air pollution, open burning, and fire. *Atmospheric Chemistry Physics* with h-index (39), g-index (72), and m-index (3.5454) was the most cited journal. Co-authorship with organization analysis indicated that the top four institutions included the Chinese Academy of Sciences, the University of Montana, the US Forest Services, and the Colorado State University, which, together, accounted for 16.76% of the total 1,021 publications. Previously, the research focused on the construction of an emission inventory of OBB and OCSB and examination of the effects of OBB and OCSB on atmospheric environment and public health. However, the most important topics, such as emission species, high-resolution inventories, and climate change, gained attention around the globe in more recent times.



## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

## AUTHOR CONTRIBUTIONS

KM and YB contributed to conceptualization. KM contributed to methodology and writing—original draft preparation. KM and MY contributed to software. SD, Saifullah, and SB contributed to validation. Saifullah, MA, and SB contributed to formal analysis. MA and SF contributed to investigation. YB contributed to resources. SB contributed to data curation. KM, Saifullah, SB, SD, MY, TF, and MA contributed to writing—review and editing. MY and PS contributed to visualization. YB contributed to supervision. KM and YB contributed to project administration. All authors have read and agreed to the published version of the manuscript.

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## FUNDING

This study was supported by the National Natural Science Foundation of China (41975046).

## ACKNOWLEDGMENTS

All authors would like to thank Nanjing University of Information Science and Technology for its computational resources.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.852492/full#supplementary-material>

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