Chapter 6
Comprehensive Analysis of Research Trends in Volatile Organic Compounds Emitted from Building Materials: A Bibliometric Analysis

Fatma Nur Eraslan, Mansoor Ahmad Bhat, Eftade O. Gaga, and Kadir Gedik

Abstract Volatile organic compounds (VOCs) are diverse compounds present in elevated indoor air concentrations, generally exceeding the outdoor levels. Indoor VOCs are emitted from various sources and activities, such as cleaning, cooking, paints, adhesives, furniture, carpets, and building materials, including wood and wood-based composite materials, reducing the indoor air quality. VOC emissions can significantly impact human health because people spend more than 80% of their time in the indoor environments and in recent years, the health effects of VOCs released from building materials have drawn tremendous interest. Moreover, there is no published literature showing the scientometric approach to explore the tendencies. This study aims to provide a bibliometric analysis of VOCs' research used in different building materials using the Web of Science Core Collection database from 1986 to 2020. According to bibliometric analysis results, 1,242 documents were printed in 475 different sources. The main language was English by far; China exhibited high collaborations, productivity, and influence on VOC and building material studies; the most productive journal was Building and Environment. Furthermore, "VOC" and "indoor air" were used most frequently in the author keywords in the early years of the research, the keywords "formaldehyde" and "building materials" increased to use more recently.

Keywords Building materials · Human health · Indoor air · Microplastics · Network analysis · Research trend · Scientometrics · VOCs · Web of Science (WoS)

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6.1 Introduction

Considering that most people spend their time indoors (households, office buildings, schools, etc.), the importance of indoor air quality is increasing. Various factors can influence indoor air quality, including microbiological, physical, indoor, and outdoor ventilation systems (Jones 1999). Building materials and different associated materials used in the construction industry, one of these factors, cause the release of various pollutants "COx, NOx, particles, volatile organic compounds (VOCs), micro-nanoplastics, etc." into the indoor air (Spengler and Chen 2000). Research has shown that pollutants from floors, ceilings, and walls have a negative impact on Indoor Air Quality (IAQ) in buildings (Harčárová et al. 2020). In most cases, indoor pollutants' level is substantially higher than outdoors (Batterman et al. 2007; Liu and Little 2012). One of the most important air pollutants are VOCs (Mujan et al. 2019; Rösch et al. 2014). VOCs enter the indoor environment as a result of release from the activities of the people (smoking, cooking, cleaning, washing, heating, etc.) (Buonanno et al. 2009; Mishra 2017; Morawska et al. 2017; Morawska and He 2006), home furnishings (Yrieix et al. 2010), household and building materials (sealants, plastics, paints, varnishes, solvents, adhesives, insulation materials, cleaning agents, disinfectants and cosmetics) (Harčárová et al. 2020; Hormigos-Jiménez et al. 2017; Kwok et al. 2003; Seltzer 1997; Spengler and Chen 2000). Also, photocopiers, printers, faxes, toners, and inks are essential sources in office buildings (Arı 2020; Lee et al. 2001). As is the case for construction materials and furniture, the newer the appliances, the higher the VOC emissions' potential rate is. VOC pollution concentrations from machines not requiring chemical suppliers, "e.g. computers" decline dramatically over time (Azimi et al. 2016; Chan et al. 2020; Kowalska et al. 2015). The indoor levels of these VOCs frequently exceed outdoor concentrations due to the widespread use of synthetic materials in the new building and interior finishing (Brooks et al. 1991). The occurrences of formaldehyde and other VOCs in building materials and emissions during the use phase are closely related to the manufacturing procedures. For example, manufacturing of widely used medium-density fiberboard consists of several steps: firstly, wood chips are milled into wood fibers; the wood fibers are then blended with adhesive resins, and the resulting mixture is dried by hot air; finally, the wood fibers after resin application are placed on a conveyer belt and hot-pressed into medium-density fiberboard (He et al. 2012). With low cost and good performance, urea-formaldehyde and phenol-formaldehyde resins are the most commonly used adhesives in wood-based panels (Liu and Little 2012). Acetaldehyde is present in laminates, cork, foam mattresses and linoleum in the form of polyester resins and basic dyes. Phenol is presented in materials, such as wall coverings and vinyl flooring, and dichloromethane is often used in adhesives (Harčárová et al. 2020). Therefore, lead to high emissions of VOCs such as formaldehyde when these products are used indoors. VOCs emanating from building materials includes: Adhesives "alcohols, amines, benzene, dimethylbenzene, formaldehyde, terpenes, toluene, xylenes," caulking compounds "alcohols, alkanes, amines, benzene diethylbenzene, formaldehyde, methyl ethyl, xylenes," ceiling tiles "formaldehyde," clipboard/particle board "alcohols, alkanes, amines, benzene, formaldehyde, terpenes, toluene," floor and wall coverings paints, "acetates, alcohols, alkanes, amines, benzene, formaldehyde, methylstyrene, xylenes," paints, stains & varnishes "acetates, acrylates, alcohols, alkanes, amines, benzene, formaldehyde, limonene, polyurethane, toluene" (Brooks et al. 1991; Kwok et al. 2003; Wallace et al. 1987). Among all the VOCs in the indoor environment, formaldehyde is one of the most common and best-known compound and a priority indoor air pollutant due to its wide distribution in indoor air and its highly toxic nature (Salthammer et al. 2010). The amount and composition of undesirable volatile organic compounds in the indoor environment depend on several factors. The most important ones include the number of people indoors, interior and technical equipment, relative humidity, the age of the building and its location within the urban unit, degree of air pollution, intensity and quality of ventilation, season and type of heat source (Harčárová et al. 2020).

The actual effect of VOCs indoor pollution on human health remains a topic of study, given the significant rise in types of cancer and associated diseases. The integration of new appliances and technology in homes and workspaces has led to higher levels and diversification of VOCs (Enesca and Cazan 2020). Ambient VOCs are usually complex mixtures of species from different sources, which may jointly contribute to the toxic effects (Hua et al. 2018). VOCs' health hazards associated with the use of building materials result from inhalation of fumes or vapours and skin absorption (Kwok et al. 2003). Short exposure to high values of VOCs can result in irritation of the eyes, nose, or mouth, headaches, nausea and vomiting, dizziness, allergy, and asthma (Singh et al. 2016). Long-term high VOC exposure values will lead to increased cancer risk, damage to kidneys, and adverse effects on the central nervous system (De Gennaro et al. 2014). The levels of exposure to VOC and the time spent indoors are causing increasing health hazards of volatile organics (El-Hashemy and Ali 2018).

The use of plastics in construction materials has recently increased tremendously. Plastics are used for the manufacturing of goods and materials, like "insulation products, damp proofing, floorings, roofing, windows, and laminated surfaces of kitchen and other fitments." In addition, buildings have many structures and equipment containing plastics or made of plastics, like pipes. In comparison to plastics used in building materials, plastics are also used in the packaging. Plastics are often used as various types of coverings and in tarpaulins during building. Furthermore, "paints, varnishes, waxes and glues" also contain plastics. Additionally, plastics are usually used in furniture, e.g. cushions, textiles, glues, surface treatments and domestic appliances "refrigerators, washing machines, kitchen appliances, media devices etc." All of these contribute to the overall number of plastics used in the housing and manufacturing industries. Waste plastic bags, which are non-biodegradable, have been recycled to produce floor and wall tiles with lesser flammability and enhanced tensile strength (Dhawan et al. 2019). Plastics are wastes that cannot be decomposed by biological processes (Barnes 2019). Instead of disposing of these non-biodegradable wastes (NBW), reusing them as building materials has been an approach that has attracted attention, especially in recent years (Karthikeyan et al. 2020). Many researchers made concrete by adding NBW as a fiber or powder or in a scrap manner to obtain the best results (Al-hadithi et al. 2019; Foti 2019; Pešic et al. 2016; Silva et al. 2013). The addition of fibers in concrete would act as crack inhibitors and substantially improve the tensile strength, cracking resistance, impact strength, wear and tear, fatigue resistance, and concrete ductility (Malagavelli 2020). Concerning the plastic waste, "polypropylene (PP), polyethylene (PE) represents the most considerable fraction, followed by polyethylene terephthalate, most known as PET." This is due to their chemical resistance, relatively high melting point, and low price (Silva et al. 2013). Alternatively to PP, fibres from low-density PE (Alhozaimy and Shannag 2009) have been used to decrease the cracks of plastic shrinkage from concrete while slightly decreasing compressive power. Recycled polyethylene terephthalate (PET) fibres were also examined but were observed to decay after reaction to the alkalinity of concrete (Jean et al. 2012; Silva et al. 2005). The high-density polyethylene (HDPE), whose physical and chemical properties are most similar to those from PP, is another recyclable polymer candidate for mass fibre processing (Alhassan et al. 2017). It is manufactured in large amounts from plastic bottles which are used as "beverage and mineral water containers" (Karthikeyan et al. 2020). The manufacture of PET bottles has grown tremendously as a consequence of the dramatic rise in drink use, also due to the desirable properties of this plastic, including "low density, high resistance, weight ratio, high toughness, ease of design/manufacturing, and low cost" (Foti 2019). Today, plastics are used in fields such as furniture and carpet manufacturing, as well as building coatings, wall paints, insulation materials, building materials (Lin et al. 2009; Pešic et al. 2016; Silva et al. 2005; Vianello et al. 2019).

The microplastics can get released from the products used in different building materials and are the pollutants of environmental concern. Discussion of the potential negative effects of airborne microplastics on human health has only recently emerged (Prata 2018). It depends on the scale of the probabilities of airborne fibrous microplastics penetrating our air system. First of all, the words respirable and inhalable should be well defined (Gasperi et al. 2018). Plastics and microplastics capable of penetrating nose and mouth and depositing in the upper airways are inhaled, and the deep lung may penetrate and deposit. Deposition in the airway depends on aerodynamic diameter, and deposition falls over 5 μm diameter within the respiratory region (Donaldson and Tran, 2002). Therefore, microplastics can reach the alveoli in the nasal system due to their small diameter (Amato-Lourenço et al. 2020). However, the persistence of inhaled fibrous microplastics is related to the durability and clearance from the lungs (Greim et al. 2008). In the first study on the presence of inhaled microplastics in the lungs, it was emphasized that different types of microplastics are found in the lungs and show little signs of deterioration (Pauly et al. 1998). Fibre sizes play a part in toxicity in addition to persistence. Moreover, it is believed that microplastics that are inhaled or swallowed can be transferred to the circulatory system and other organs (Wright and Kelly 2017).

Bibliometric analysis is a literature analysis method that uses statistical methods (e.g. citation analysis) to analyze books, articles, reports and other publications. This technique has been progressively used to monitor various scientific disciplines' research performance and support appropriate policy action. A bibliometric analysis enables researchers to identify the publications' key research topics and interrelationships based on the collected publications' citations, bibliography, and text information. Bibliometric research is crucial for mapping research-related literature. As a valuable tool for literature analysis, bibliometric can effectively depict the rules of discipline development and has a wide application in different knowledge domains. Nowadays, many bibliometric studies are carried out in an attempt to analyze the process of collaboration between researchers and institutions. Digitalization of literature and the formation of online literature databases allowed researchers to explore the body of literature and research performance smoothly and efficiently. The Web of Science database contains the world-famous "Science Citation Index, Social Sciences Citation Index and Arts, and Humanities Citation Index." Also, the fundamental compendium of "Web of Science 1986–present" has numerous benefits: (1) The sources cited for all articles are completely indexed and accessible; (2) It is possible to get all the information about both authors and their respective affiliations; (3) Visually, the citation monitoring characteristic recognizes citation events and patterns, and (4) Developments of analysis and structures of publishing can be calculated by using the effects of empirical retrieval. According to the author's knowledge, few bibliometric analyses were carried out on the subject of VOCs (Cheng et al. 2019; Zhang et al. 2010), however, there have not been any scientometrics research undertaken in the release of VOCs from the building materials. The main aim of this work is to provide a bibliometric overview of findings of the VOCs used in different building materials by using the "Web of Science Core Collection database" from 1986 to 2020.

6.2 Methods

6.2.1 Search Strategy

All data used in the study have been obtained from the Web of Science (WoS) online database (WoS 2021). In scientometrics, selecting preliminary research data is of utmost importance, as these data directly impact the findings and results. For Bibliometric analysis, all publications from 1986 to 2020 were extracted using the keywords "Volatile Organic Compounds," VOCs*, VOC*, "Building Material," and "Building Materials" (In fact, building materials and VOCs the first relevant article was published in 1986). Before 1986 none of the articles was published regarding the above-mentioned keywords. The publication of articles started in the year 1986. Due to this reason, 1986 was considered as the starting year. The search was conducted in January 2021. Accordingly, the data consisted of 1,242 publications, and for each document, we selected "full records and cited references" and exported the results in a format for further analysis. The records were then downloaded in different files as Web of Science provides just 500 documents per download. Care was taken to analyze the gathered data to ensure their identification. Details on the paper included "authors, title, source, abstract, language, document type, keywords, addresses, cited reference count, times cited, publisher information, ISSN, page count, subject category, and citation report."

The performance review of research in this bibliometric analysis was centered on previously scientometric research (Cañas-Guerrero et al. 2014; Cheng et al. 2019; Geng et al. 2017; Li et al. 2017; Zhang et al. 2010). Web of Science database was employed as the resource to get all the scientometric statistical information concerning the scientific production in the subject of health effects of volatile organic compounds emitted from building materials. The Web of Science website has been chosen since it is the largest comprehensive citation and abstract platform of peer-reviewed articles. While various datasets can provide different findings, the most accurate literature sources for publications and citations are believed to be the WoS repository. Apart from this, the Web of Science is easy to use and has simple and advanced search tools. Moreover, WoS is the most frequently used database for empirical metrology for instance: in many bibliometric investigations, this Web of Science Databases have been commonly employed in different fields including VOCs and building materials (Can-Güven 2020; Cañas-Guerrero et al. 2014; Cheng et al. 2019; Factor et al. 2010; Harzing and Alakangas 2016; Kawuki et al. 2020; Li et al. 2017; Zhang et al. 2010).

6.2.2 Data Analysis

The bibliometric analysis of publications obtained from the database was analyzed using "Biblioshiny application" (using the R-studio) (Kawuki et al. 2020). Preliminary info regarding information includes: "Timespan, sources (journals, books, conferences), documents, average years from publication, average citations per documents, average citations per year per document, references." Meanwhile, the documents categories consist of: "article, article; book chapter, article; data paper, article; early access, article; proceedings paper, editorial material, editorial material; book chapter, meeting abstract, note, proceedings paper, review, review; early access." While as the article information consists of author's keywords. Furthermore, the authors' data include "author appearances, authors of single-authored documents, and authors of multi-authored documents." "Authors collaboration includes single-authored documents, documents per author, authors per document, co-authors per document, collaboration index". Graphics were created by considering the first 10 ranks (country, publication, author, word, journal). Besides, the VOS viewer (version 1.6.15) was used to visualize network analysis (Wang et al. 2020).

In order to include all documents published in all languages, the basic search method was used. Based on this, the 1,242 documents were published in ten languages, such as "English, German, French, Japanese, Chinese, Portuguese, Polish, Czech, Turkish, and Spanish." English was the leading written language. Papers written in the English language were 1,207 publications made up 97% of total publications, followed by German, French, Japanese, Chinese, Portuguese, Polish, Czech, Turkish and Spanish comprising 12, 6, 6, 3, 3, 2, 1, 1, and 1 publication respectively. This was expected because English is the international language of choice in building materials, VOCs, indoor environments and health impacts research. According to the WoS database, owing to English's global superiority, ethnic and language influences are less important in shaping publications, since it is the universal language for performing research investigations and the strict writing style for academic articles. However, topographical influences performed significant character in worldwide publication on building materials, VOCs, indoor environments and health impacts research.

The parameters included in the bibliometric analysis are:

Annual scientific production: It presents the number of publications published each year between the dates determined on the subject of interest. For this study, the yearly scientific output was calculated from (1986–2020); therefore, the relationship between the number of articles and scientific production can be assessed.

Collaborations: The analysis includes countries, institutes, and authors included in each article. It determines the most productive countries, institutes, and authors for research on the subject. The form of collaboration was decided by the addresses of the authors, where it was allocated independently if no partnership was identified. International collaboration was allocated if the article was co-signed by authors from more than one nation.

Journal: In this category, parameters such as the number of annual citations of journals, total citations, and yearly production dynamics were analyzed.

Authors: The authors' productions for the relevant topic over time and their cooperation with countries were examined.

Citations Index: The h-index is a citation index used to express the author's publication's quantity and significance, as first suggested by Hirsch (2005). "When a researcher's h-index is h, which means that there are at least h papers of this researcher that have been cited for h times" (Hirsch 2005). It is also used to explain the importance of h-index journals. In a study, the h-index calculated for journals showed a high correlation with the Thomson Institute for Scientific Information (ISI) impact factors, which are used as a standard to measure journal quality (Hodge et al. 2013). Also, the g-index and m-index of these articles and journals were calculated. These two indexes are used as a variant of the h-index. The g-index, first pioneered by Egghe (2006), is used to resolve the inconsistency in evaluating journals with the same h-index values. The g-index gives more weight to highly cited articles, and the higher it means, the more cited articles of that journal or author. Hence, g-index values are always equivalent to or greater than the h-index (Hodge et al. 2013). The calculated m-index is obtained by dividing the h-index by the number of years since the scientist's first published article. However, Hirsch thinks that the researcher's first published article may not always be a correct starting point (Hirsch 2005). Even though the h-index was considered in many studies (Dettori et al. 2019; Kawuki et al. 2020; Mingers et al. 2012) due to the ease of calculation, h, g, and m-indexes were calculated in this study.

Keyword analysis: The progression of the mainly significant research subjects over time is examined using keywords. In the study, the keywords described by the authors were analyzed separately. These keywords are called authors keywords.

6.3 Results and Discussion

The following topics have been studied by this bibliometric analysis: the history of research interest in the "Building material" and "Volatile Organic Compound" category; trends in publication and citation; the most productive countries and institutes, and their co-occurrence; authors' production over the time, total citations, and their impact values; the evolution of the journals in this category; the most global cited relevant documents and their author; the most important author's keywords. There were a total 1,242 publications that met the selection criteria mentioned, containing 9 document types "article, article-book chapter, article-data paper, article-proceedings paper, editorial material, editorial material-book chapter, meeting abstract, note, proceedings paper, review." The article was the most frequently used document type comprising 73.2% (910) of the total production, followed by proceedings paper 12.8% (159), review 7.4% (92), article; proceedings paper 4.1% (51), article; book chapter 1% (13) and others less than 1%. According to bibliometric analysis, the average years from publication was 8.84 while the average citations per document and the average citations per year per document were 22.6 and 2.57, respectively. Besides, the documents included in the bibliometric analysis contain a total of 34,437 references.

6.3.1 Trends in Publication

When calculating the annual number of publications, the analysis interval was set (1989–2020). Before 1989, there were only 2 articles (one published in 1986 and the other in 1987). The 1989 year was shown as the starting point as the topic's production increased in 1989 (Fig. 6.1). According to Fig. 6.1, while the number of publications had increased until 2001 and touched 27 publications, there was a decrease in 2002. There were almost twice as many publications in 2003 as the previous year. According to the Fig. 6.1, from the year 1989 to 1996, the number of published articles was below ten however after 1997 to 2020 the number of published papers per year was greater than 10. The other noteworthy point in the graph was in 2005–year data. As a result of the bibliometric analysis, it was determined that publications of relevant topics increased rapidly in 2005 due to the 10th International Conference on Indoor Air Quality and Climate (Fig. 6.1) (Indoor Air, 2005). This conference was held 4–9 September 2005 in Beijing, China and was attended by over 1,200 scientists and specialists in the subject of the indoor environment. Multiple keynote lectures were also offered by globally respected academics welcomed as plenary guests. Of all the

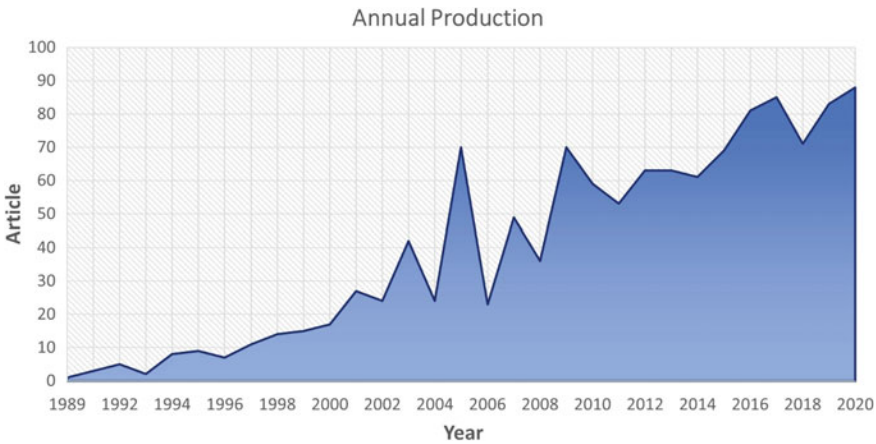

Fig. 6.1 The trend of literature publications annually

800 lectures, papers and exhibitions, the main presentation was the paper entitled "Carbon and cooling in UK office environments." Through this gathering, organizers plan to advance and expand their expertise on indoor environmental science and innovation with the goal of improving quality of life via better conditions in the buildings where people live and work. The total number of publishes articles in this year was 70, which was the highest number of published articles from (1989–2005). The year with the most increased scientific production (88) to date was in 2020. This is shown schematically in Fig. 6.1. Besides the analysis results, the annual growth rate of published articles was 16.1%.

6.3.2 Most Contributing Countries and Their Collaborations

Collaboration networks among various countries and institutions were developed on the basis of published studies from countries and institutions. As presented in Fig. 6.2, the outcomes of the study showed links between different countries or various institutions. The red lines are showing us the collaboration between the countries or institutions in terms of the published articles. The width of lines represents the strength in collaborations. The Most cooperation was between China and USA (35), followed by Canada and the USA (17), China and Korea (13), Canada and China (12), United Kingdom and China (12), USA and Denmark (12), Denmark and Germany (8),USA and Korea (7). While the collaborations among China and Japan, France and Italy, France and USA, United Kingdom and Korea, United Kingdom and the USA, USA, and Germany were the same as all these countries published 6 articles (Fig. 6.2). Also, shades of blue were used to show the total number of publications in the countries. In this case, the countries with the highest total number of publications were as follows: China (320), USA (233), South Korea (94), Germany (92), France (77),

Fig. 6.2 Geographical distribution of scientific publications based on countries and country collaboration

Canada (70), Japan (68), Denmark (62), Sweden (49), and England (39) respectively (Fig. 6.2).

Detailed statistics were given in the top ten countries commonly quoted (Table 6.1). The results revealed that China harbours the highest total citation (5,110), followed by the USA (5,106) and Denmark (2,211). However, Japan had the least number of citations (1,145) among all the countries (Table 6.1). Besides, when the relationship between the total number of publications in countries and citations was examined, it was seen that the country with the highest average article citation was

Table 6.1 Information of the top 10 frequently cited countries

Rank	Country	Documents	Total citations	Average article citations
1st	China	962	5,110	16.59
2nd	USA	626	5,106	28.53
3rd	Denmark	111	2,211	59.76
4th	Germany	206	2,137	26.06
5th	UK	113	1,536	45.18
6th	South Korea	285	1,411	15.85
7th	Canada	140	1,385	28.85
8th	Sweden	115	1,357	33.92
9th	France	235	1,227	19.48
10th	Japan	226	1,145	19.74

Denmark (59.76), followed by UK (45.18) and Sweden (33.92). In contrast, the least average article citations were seen in South Korea (15.85) (Table 6.1). Moreover, the highest numbers of articles were published in China (962) and USA (626) respectively, while at least a number of articles were published in Denmark (115). From Table 6.1 it gets clear Denmark was the most productive country in terms of average article citations plus total citations because its total number of published articles was just 111 which is almost nine times lesser than the articles published by the first rank country China which published 962 articles and six times lesser than the USA which published 626 articles.

From Fig. 6.2 and Table 6.1, it gets clear that China had the highest collaborations with other countries, the highest total number of publications and the highest total citations among all nations. In the future, more contributions are expected to increase from China in terms of collaborations, number of publications and citations. In China, the construction industry is expected to continue its dramatic growth due to ongoing rapid urbanization (Mao et al. 2015), and there is a massive demand for construction projects (Huang et al. 2018). Apart from this, the construction industry in China accounts for around one-half of the world's newly built floor area, which results in large volumes of pollution emissions and resource consumption (Huang et al. 2018). To mitigate these adverse impacts on the environment, Chinese government departments have taken steps to reform the construction industry towards sustainable development (Qi et al. 2010; Yu et al. 2019).

6.3.3 Most Relevant Institutions

This study seeks to assess the classification of the top universities in using keywords for analysis. Figure 6.3 shows the 10 most influential institutions from WoS in terms of published articles. 1,186 published the total of 1,242 articles from (1986–2020). Among the 1,186 institutions that participated in the analysis, the "Tsinghua University" leads the institutions' production with 151 publications and consists of 12% of the total global publications. Simultaneously, as the "Hong Kong Polytech University" had published the 44 articles having 3.54% of total publications. However, Concordia University had published 42 articles contributing 3.38% of total world publications. Meanwhile, the Seoul Natl University, Tongji University and University Calif Berkeley have published the least number of published articles individually (33) among the first ten affiliations. The total contribution of these universities individually is 2.66%. From Fig. 6.3, it gets clear only Tsinghua University contributed more than 10% in terms of total contribution while the contribution by rest nine affiliations was less than 4%. Moreover, only Tsinghua University published more than 100 articles; however, the rest of the universities published articles were less than 50 (Fig. 6.3). The top 10 institutes oscillate between 2.6 and 12% (number of published papers 33 to 151) (Fig. 6.3).

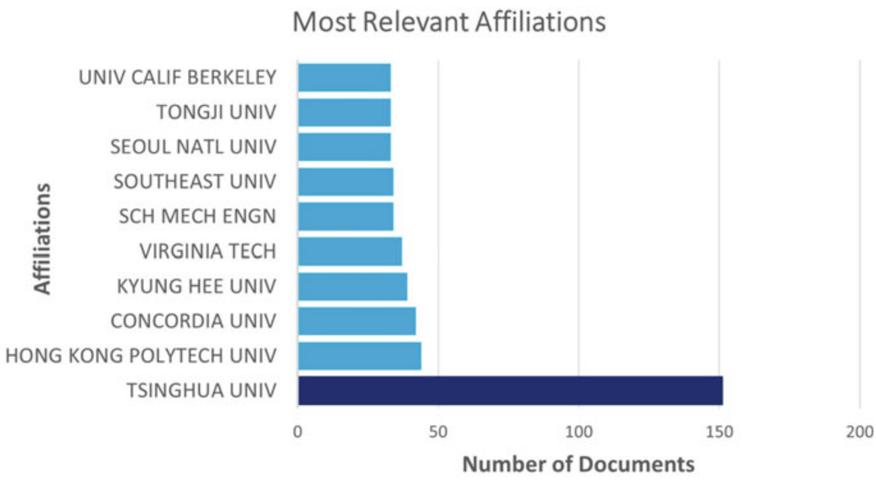

Fig. 6.3 Top 10 relevant affiliations in terms of their published number of documents

6.3.4 Most Contributing Authors

Several criteria are commonly used to assess scientists' influence, such as the total number of citations, and impact values (Patience et al. 2017). The analyzed publications from WoS were produced by 3,308 authors, while the total number of author appearances was 5,070. However, the authors of single-authored documents were 58. Meanwhile, authors of multi-authored documents were 3,250. Besides, single-authored documents were 77, while the documents per author and authors per document were 0.375, 2.66, respectively. On the other hand, the number of-authors per document was 4.08, and the collaboration index was 2.79. The total number of citations and impact values of the authors in the study was calculated. The results of the 10 most influential authors are given in Table 6.2. The three highest cited authors of the research included Wolkoff P (Total Citations, TC = 1,420), Salthammer T (TC = 1,305), and Zhang Y (TC = 1,052), while as the least cited Author was Little JC (TC = 660) (Table 6.2). Further, the results revealed that Zhang Y has the highest h-index and g-index (h = 20, g = 31) followed by Wolkoff P (h = 16, g = 23) and Xiong J (h = 16, g = 25) (Xiong J is not included in the top 10 authors in total citation (TC = 654) rankings). Conceivably for Wolkoff P and Xiong J with similar h-indexes, Xiong J has a higher g-index due to more citations or more paper (Table 6.2). In this case, Xiong J has more effective in terms of overall scientific impact than Wolkoff P. However, Marutzky R was having the least h and g-index (1). The Zhang Y published the highest number of articles (55), while as the least number of articles (1) was published by Marutzky R (Table 6.2).

Moreover, the top 10 authors' production over time was obtained with bibliometric analysis, as shown in Fig. 6.4. The figure shows the number of papers and total citations of the authors by years. The bubbles' size indicates the number of documents

Table 6.2 Most Cited Authors and their impact

Rank	Author	h-index	g-index	m-index	Total citation	Number of paper	Year
1st	Wolkoff P	16	23	–	1,420	23	1995
2nd	Salthammer T	14	21	0.583	1,305	21	1997
3rd	Zhang Y	20	31	–	1,052	55	1999
4th	Jones AP	2	2	0.087	839	2	1998
5th	Mentese S	3	4	0.231	820	4	2008
6th	Marutzky R	1	1	0.091	754	1	2010
7th	Norback D	9	9	0.346	697	9	1995
8th	Nielsen GD	6	6	0.25	697	6	1997
9th	Haghighat F	13	21	0.52	677	21	1996
10th	Little JC	13	22	0.65	660	22	2001

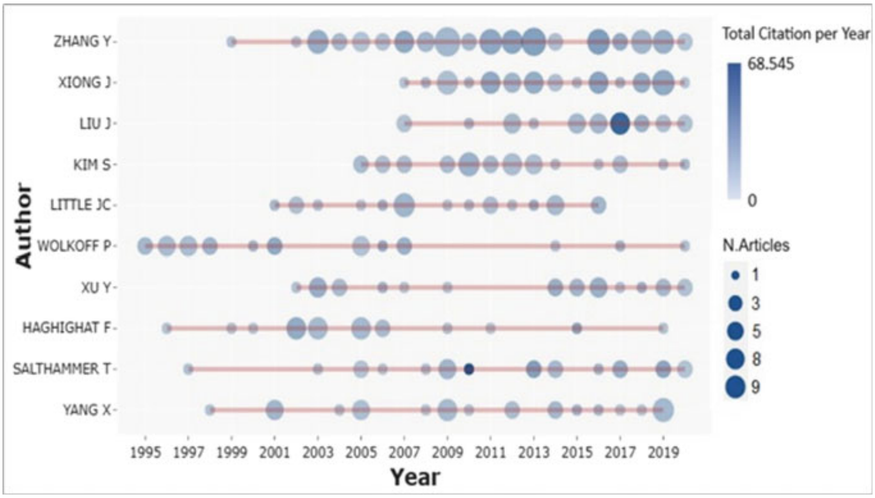

Fig. 6.4 Top-Authors' production over time

per year while with the increasing citations, the color fluctuates from light to dark blue. Salthammer T., published a paper in 2010 (only 1 paper), has the highest total number of citations per year to date (TC per year = 68.545) and followed by, Liu J., with his four papers published in 2017 is second on the total number of citations list (TC per year = 54) (Fig. 6.4). The most paper production per year belonged to Zhang Y in 2009 (number of papers per year = 9, total citations per year = 6.75) and in 2013 (number of papers per year = 8, total citations per year = 19.75). The least number of total articles (21) were published by Haghighat F, Salthammer T and Yang X, while the maximum number of total articles were published by Zhang Y (Fig. 6.4).

6.3.5 *Most Productive Journals*

From WoS, the analyzed documents were produced by 475 sources (journals, conferences and books). Information of the top 10 frequently cited journals are listed below (Table 6.3). The Atmospheric Environment journal topped the list having the total of 3,903 citations from the year of (1994–2020), which was followed by the Building and Environment journal having the total of 3,670 citations from the year of (1998–2020) however the Journal of Hazardous Materials was having the least number of citations (TC = 434) from the year of (2009–2020). The annual production of the 5 most active resources regarding the research topic is shown in Fig. 6.5. The Building and Environment journal, the second leading journal in terms of the total number of citations, however, it topped in the most relevant resource analysis (Fig. 6.5) with 140 papers. The Atmospheric Environment journal was the second leading journal in terms of published papers (69), followed by Indoor Air journal, consisting of a total 67 published articles, Indoor and Built Environment journal having a total of 44 published articles. The 10th International Conference on Indoor Air Quality and

Table 6.3 Information of the top 10 frequently cited journals: as per citations

Rank	Source	h-index	g-index	m-index	Total citation	Number of paper	Year
1st	Atmospheric Environment	34	62	1.26	3,903	69	1994
2nd	Building and Environment	34	52	1.48	3,670	140	1998
3rd	Indoor Air	30	51	–	2,675	67	1995
4th	Environmental Science & Technology	18	30	0.72	1,065	30	1996
5th	Indoor Air-International Journal of Indoor Air Quality and Climate	13	15	0.48	832	15	1994
6th	Chemical Reviews	1	1	0.09	754	1	2010
7th	Indoor and Built Environment	14	22	0.64	610	44	1999
8th	Science of the Total Environment	13	20	0.57	495	20	1998
9th	Environment International	11	14	0.34	440	14	1989
10th	Journal of Hazardous Materials	11	16	0.92	434	16	2009

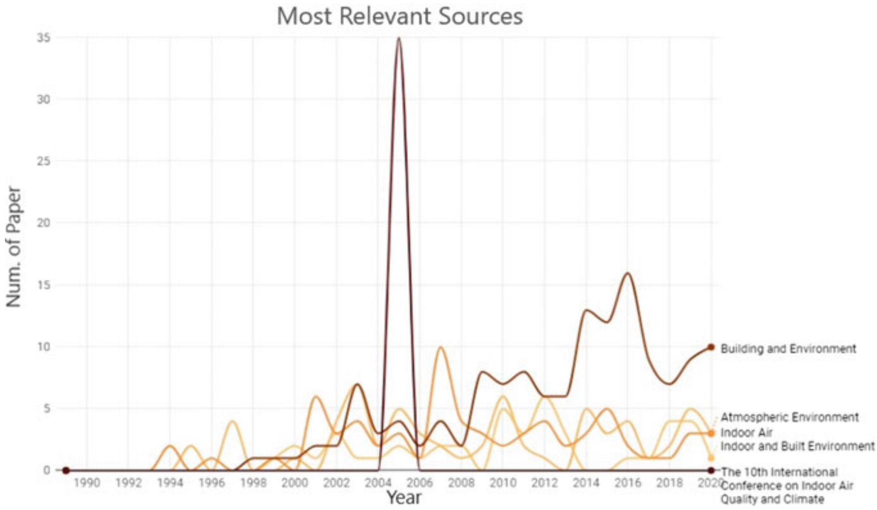

Fig. 6.5 Most relevant sources as per the number of papers published per year

Climate had the least number of published articles (35) (Fig. 6.5). All these articles were published during the year of 2005. The source that has made the most production every year since 2009 is the Building and Environment journal, while as the maximum number of articles (16) were published during the year 2016. However, from 1989–1997 none of the articles was published in Building and Environment journal. While as the least number of articles (1) were published during 1998–2000. From 1998–2020, the articles were regularly published in the Building and Environment journal (Fig. 6.5). In the case of the Atmospheric Environment journal, the maximum number of articles (10) were published during 2007. Meanwhile, during 1989–1993, 1995, 1997–1998 and 2000, none of the articles was published. However, the least number of articles (1) was published during 1996, 1999, 2006 and 2017–2018. From 2001–2020 articles were continuously published in the Atmospheric Environment journal (Fig. 6.5). In the Indoor Air journal, the maximum number of articles (7) were published during 2003. However, during 1989–1994, 1996, 1998, 1999, 2001 and 2013, none of the articles was published. While as during 2000, 2008, 2012 and 2017, the minimum number of articles (1) was published (Fig. 6.5). Meanwhile, during 2002–2012 and later from 2014 until 2020, articles were continuously published. In case of Indoor and Built Environment journal the maximum number of articles (6) were published during 2012 however from 1989–1998, 2009 and 2014–2015 none of the articles was published. While as during 1999, 2001, 2003–2004, 2006, 2016–2017 and 2020 least number of articles (1) were published (Fig. 6.5). It was seen from the last five years that articles have been continuously published in Indoor and Built Environment journal. The 10th International Conference on Indoor Air Quality and Climate was an exception compared to the other four journals. Under this publication house, only 35 articles were published during 2005 while as from 1989–2004 and 2006–2020 none of the articles was published as this conference happened only once (Fig. 6.5).

Further, the results revealed that the "Atmospheric Environment" and "Building and Environment" journals have the highest h-index (34) (Table 6.3). These two sources with similar h-indexes have different g-indexes due to the number of citations and papers. The Atmospheric Environment journal has 62 g-index, while as the Building and Environment journal has 52 g-index (Table 6.3). According to the results, it is determined that the Atmospheric Environment journal has more citations or papers. While as the second leading journal in terms of h-index (30) was Indoor Air. However, in terms of g-index (51), it occupied third place, followed by Environmental Science & Technology having h-index 18 and g-index 30. Meanwhile, Chemical Reviews journal had the least value (1) for both the h and g index (Table 6.3).

6.3.6 Most Cited Documents

According to the analysis results, documents had an average of 22.76 citations per document, while with 2.57 average citations per year per document. Relevant top 10 papers consist of 7 reviews and 3 articles (Table 6.4). The most cited article in WoS belonged to Jones and was published in Atmospheric Environment in 1999, under the title "Indoor Air Quality and Health" and was a review article with 790 TC in WoS. This was followed by a paper of Salthammer et al., published in "Chemical Reviews" during 2010 entitled formaldehyde in the indoor environment and was having the 754 total citations. This was also a review article (Table 6.4). These were the two leading articles in terms of total citations. Their total number of citations was almost 2–3 times more than the rest articles, while as in the rest of the articles, the minimum total citations were below 400 (Table 6.4). However, Norback et al., published an article entitled "Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings" in "Occupational and Environmental Medicine" during 1995 was having the least number 212 of total citations. This was a typical article (Table 6.4).

On the other hand, the most citations per year for two articles in WoS belongs to Salthammer et al. (2010) entitled formaldehyde in the indoor environment, published in "Chemical Reviews" (TC per Year = 68.55), and Yan, 2017 entitled lanthanide-functionalized metal-organic framework hybrid systems to create multiple luminescent centers for chemical sensing, published in "Accounts of Chemical Research" (TC per Year = 67) respectively (Table 6.4). However, concerning other authors, the total citations per year was almost (2–8) times lesser than the above mentioned two authors (Table 6.4). Norback et al. (1995) entitled "asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings" in "Occupational and Environmental Medicine" was having the least number of total citations per year 8.15 (Table 6.4).

Table 6.4 The top 10 most global cited relevant documents from WoS

Author, year	Document title and journal name	Document type	Total citations	Total citations per year
Jones 1999	Indoor air quality and health, Atmospheric Environment	Review	790	35.91
Salthammer et al. 2010	Formaldehyde in the indoor environment, Chemical Reviews	Review	754	68.55
Brown et al. 1994	Concentrations of volatile organic-compounds in indoor air—a review, Indoor Air-International Journal of Indoor Air Quality and Climate	Review	370	13.70
Weschler 2009	Changes in indoor pollutants since the 1950s, Atmospheric Environment	Review	316	26.33
Qıu et al. 2012	Hybrid CuxO/TiO_2 nanocomposites as risk-reduction materials in indoor environments, ACS Nano	Article	269	29.89
Yan 2017	Lanthanide-functionalized metal-organic framework hybrid systems to create multiple luminescent centers for chemical sensing, Accounts of Chemical Research	Review	268	67
Wolkoff and Nielsen 2001	Organic compounds in indoor air—their relevance for perceived indoor air quality? Atmospheric Environment	Article	242	12.1
Korpi et al. 2009	Microbial volatile organic compounds, Critical Reviews in Toxicology	Review	239	19.92
Yu and Crump 1998	A review of the emission of VOCs from polymeric materials used in buildings, Building and Environment	Review	214	9.30

(continued)

6.3.7 *Keyword Analysis*

Based on the analysis, WoS documents had 2,891 author keywords. The authors' keywords' co-occurrence network was visualized and determined eight clusters through VOS Viewer software, as shown in Fig. 6.6. "Each circle in the network

Table 6.4 (continued)

Author, year	Document title and journal name	Document type	Total citations	Total citations per year
Norback et al. 1995	Asthmatic symptoms and volatile organic-compounds, formaldehyde, and carbon-dioxide in dwellings, Occupational and Environmental Medicine	Article	212	8.15

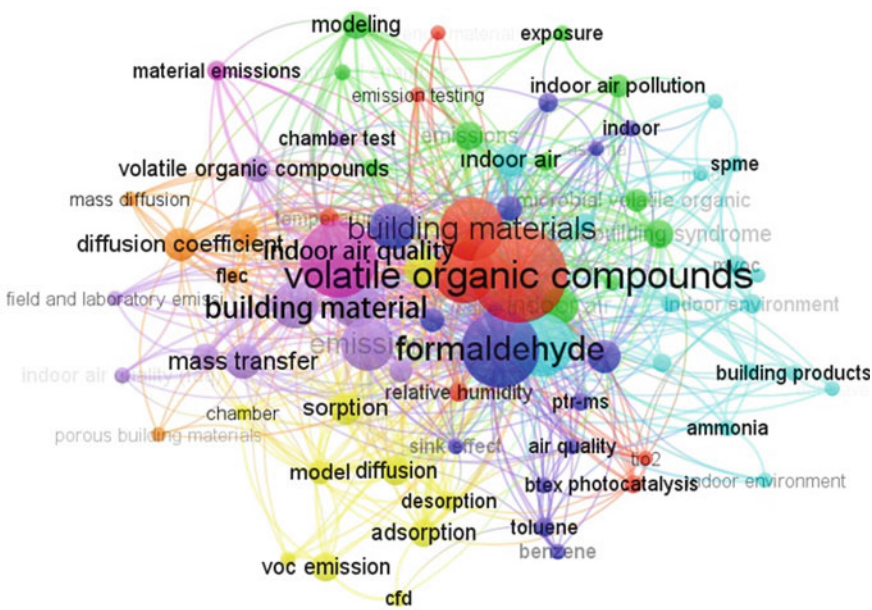

Fig. 6.6 Network visualization map of author's keywords co-occurrence

analysis represents a keyword, and the size of the circle indicates use frequency." The number and color of items in the clusters contain: 16 items in cluster 1 (cyan), 15 items in cluster 2 (dark blue), 11 items in cluster 3 (green), 10 items in cluster 4 (yellow), 10 items in cluster 5 (purple), 9 items in cluster 6 (red), 5 items in cluster 7 (orange), and finally 2 items in cluster 8 (pink) (Fig. 6.6). The co-occurrence keywords analysis revealed that the most frequent author keywords were "volatile organic compound," "building material," "formaldehyde," "indoor air quality," and "indoor air." These keywords formed a strong network and were having strong links with other keywords. While as the keywords which were away from the centre mean they were less used like "building products," "indoor environment," "exposure", "indoor air pollution," "modelling," "material emissions", "mass diffusion," and "VOC emission" etc. The

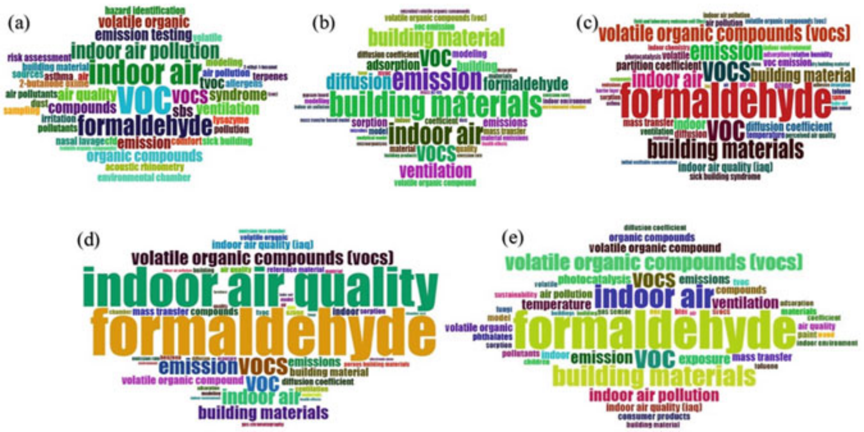

Fig. 6.7 Visualised word-clouds of authors keywords (**a** 1986–2000, **b** 2001–2005, **c** 2006–2010, **d** 2011–2015, **e** 2016–2020)

network formed by these keywords is weak and has weak links with other keywords than the keywords present in the centre (Fig. 6.6).

Besides, a word cloud of author keywords was created. The usage of a keyword depends on its size and centrality, frequency, and magnitude of the word (Kawuki et al. 2020). Figure 6.7 shows the author's keyword clouds for five different periods, and the authors' keywords are shown in Fig. 6.7a belonging to 92 documents published from 1986–2000. However, for another period authors, keywords are shown in Fig. 6.7b present in 187 documents published (2001–2005). While as for third–period authors keywords are shown in Fig. 6.7c existing in 237 documents published from 2006–2010, fourth-period authors keywords are shown in Fig. 6.7d belonging to 309 documents published from 2011–2015. As for final period authors, keywords are shown in Fig. 6.7e present in 409 documents published from 2016–2020. The most frequent authors' keywords used during 1986–2000 were "VOC" (8 documents), "indoor air" (6 documents), "formaldehyde" (5 documents), and "indoor air pollution" (4 documents) (Fig. 6.7a). However, the less regularly used authors keywords were "environmental chamber," "hazard identification," "comfort," "sampling," "volatile organic compound," "risk assessment," "sources," "air pollution," and "syndrome" etc. (Fig. 6.7a). While the most common authors' keywords used during 2001–2005 included "building materials" (19 documents), "emissions" (16 documents), "indoor" (16 documents), "VOC" (15 documents), and "diffusion" (12 documents) as visualized in Fig. 6.7b. However, during this period, the less often used authors' keywords are "dust," "microorganisms," "emission rate," "health effect," and "building product" etc. (Fig. 6.7b).

Whereas the most frequent authors' keywords used during 2006–2010, were "formaldehyde" (25 documents), "VOC" (18 documents), "building materials" (14 documents), and "emission" (13 documents) (Fig. 6.7c). Nevertheless, the least frequently used authors' keywords were "desorption," "asthma," "air," "adhesive," "material," and "gas sensor" etc. (Fig. 6.7c). The maximum current authors' keywords used during 2011–2015 included "formaldehyde" (49 documents), "indoor air quality" (41 documents), "VOCs" (21 documents), "emissions" (17 documents), and "building materials" (14 documents) as visualized in (Fig. 6.7d). However, the less often used authors' keywords during this period were "environment," "furniture," "fungi," "health effect," "chamber," and "gas chromatography" etc. (Fig. 6.7d). While the maximum common authors' keywords used during 2016–2020 were "formaldehyde" (33 documents), "indoor air" (20 documents), "VOC" (19 documents), and "building materials" (18 documents) (Fig. 6.7e). However, the least frequently used keywords during this period were "buildings," "air," "children," "sustainability," "volatile," "fungi," "compounds," "wood," "paint," "diffusion coefficient," and "sorption" etc. (Fig. 6.7e). From Fig. 6.7 it gets clear that literature changed into more specific research methods, from VOC to formaldehyde. The importance of chemicals containing (e.g. formaldehyde) is more influential for research purposes than other types of chemicals existing in building materials. The reason can be that the significant occupational exposure sources for formaldehyde include the "processing of resins for wood products, furniture and fixtures, the wearing of garments and textiles, chemicals and plastics" (Catalani et al. 2019). Furthermore, formaldehyde is revealed to be the cause of nasal cancer in animal studies at comparatively high concentration levels, "i.e., long-term exposures to concentrations greater than about 4 ppm" (Kamata et al. 1997; Kerns et al. 1983), and connections between occupational formaldehyde exposure and multi-type cancer risk are reported (Bachand et al. 2010; Bosetti et al. 2008; Erika et al. 2010). Subsequently, the "National Toxicology Program of the National Institute of Environmental Health Sciences Changed the classification of formaldehyde from anticipated to be carcinogenic in humans to known to be a human carcinogen" (National Toxicology Program 2016).

6.4 Conclusion

Evaluating scientific research production is a challenging task. In this study, a bibliometric method was employed to identify the historical dynamics of studies investigating VOCs' release from building materials. Bibliometric is widely recognized as a well-established research method in information science, particularly for evaluating academics and universities' research performance. It adopts quantitative analysis and statistical methods to analyze the quantitative relation and content information in a given field and further examine the featured research field's detailed characteristics and patterns. The bibliometric analysis assesses and validates the trends of publications covering a given topic and analyses features of articles such as authorships, quotations, and impact factor. In addition, a statistical viewpoint is offered by the scientometric framework to consider better features involved in global construction materials, VOCs, indoor habitats, and studies on human health. One of the most important fields of chemical and environmental science is research into VOCs. For the last few decades, empirical papers on VOC studies have seen an accelerated rise in quantity. In leading scientific journals, numerous articles reporting the latest science accomplishments have been written. Study into VOCs has attracted growing scientific interest, primarily because of their adverse effects on human health and the degradation of the environment. Firstly, in the environment, the office, and consumer goods, VOCs are pervasive and various. These VOCs are issued from various construction materials as well. In recent decades, the building industry has undergone rapid growth, possibly due to social and economic change. The building sector has a significant effect on the economy, on the environment and culture. For example, one of the main consumers of resources, especially oil, is the construction industry. Energy is the main input not only at the operating stage but also during the manufacture of construction materials during the entire life cycle of buildings. However, these building materials release different chemicals, particularly VOCs, affecting indoor air quality and human health.

This study's main contribution is to present an international image of research activity in the field of building materials, volatile organic compounds, human health, and indoor environment in the last few years. A total of 1,242 documents from 1986 to 2020 were collected and analyzed. This bibliometric analysis was presented based on "yearly publications, document types and languages, subject categories, journals, countries, institutions, collaborations, research keywords, authors and their impacts, and trends." The main language was English by far; although another ten languages were still used; consequently, this designated that with "VOCs" released from building materials research became more globally concerned. China exhibited high productivity and influence on VOC and building materials studies, standing "first in both the number of publications and citation times." China was also competitive concerning collaborations. In this study, the 1,242 technical documents were printed in 475 different sources "journals, books, conferences." The most remarkable journals included Building and Environment, Atmospheric Environment, Indoor Air, and Environmental Science & Technology. "Tsinghua University" is the utmost productive university followed by "Hong Kong Polytech University." Additionally, the results showed that Wolkoff P. was the leading author in the total number of citations (TC = 1,420, article no. = 23). Moreover, according to the top 10 authors' production over time Salthammer T., published a paper in 2010 (only 1 paper), has the highest total number of citations per year to date (TC per Year = 68.545), while as the most document production per year belonged to Zhang Y in 2009 (number of papers per year = 9, TC per Year = 6.75). The boom of scientific activity in the last few years has also increased researchers and institutions' interest in publishing their studies. We implemented a step-by-step study of the study emphases and patterns, from the single-dimensional keyword intensity to the keyword matrix and time series analysis, to define trends. The number of studies regarding volatile organic compounds, especially in indoor environments, is expected to increase as their consumption in indoor building materials and products are continuously rising. Apart from this, they create serious human health and indoor air quality issues and make them topics of concern for researchers.

The synthetic analysis of author keywords provided insight into VOC, and building materials research focuses. The time-series distributions of these keywords were divided into five phases: 1986–2000, 2001–2005, 2006–2010, 2011–2015 and 2016–2020. Also, while "VOC" and "indoor air" were used most frequently in the author keywords in the early years of the research, the keywords "formaldehyde" and "building materials" increased more since 2006. The network of the identified keywords showed that "formaldehyde," "VOC," "indoor air", "indoor air quality," and "building materials" had the strongest centralities and were considered to represent the leading edges of VOC and building materials research. The fields of these leading research keywords showed substantial growth in the number of publications over time and were expected to grow in the future. Furthermore, this study's results provide insights into patterns and trends in global VOCs, building materials, indoor environments and human health research and help expand our understanding of the situation of global VOCs, building materials, indoor environments and human health research. There has been a lot of research interest in this area, as evidenced by the continuing growth of scientific outputs. Moreover, this study's bibliometric approach can be applied to trend analyses of other research fields. Additionally, the study results can be of great utility for organization and research planning in terms of the chemicals present in different building materials and their impacts on human health.

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