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Review

Indoor Air Quality in Healthcare Units—A Systematic Literature Review Focusing Recent Research

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Abstract: The adequate assessment and management of indoor air quality in healthcare facilities is of utmost importance for patient safety and occupational health purposes. This study aims to identify the recent trends of research on the topic through a systematic literature review following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology. A total of 171 articles published in the period 2015–2020 were selected and analyzed. Results show that there is a worldwide growing research interest in this subject, dispersed in a wide variety of scientific journals. A textometric analysis using the IRaMuTeQ software revealed four clusters of topics in the sampled articles: physicochemical pollutants, design and management of infrastructures, environmental control measures, and microbiological contamination. The studies focus mainly on hospital facilities, but there is also research interest in primary care centers and dental clinics. The majority of the analyzed articles (85%) report experimental data, with the most frequently measured parameters being related to environmental quality (temperature and relative humidity), microbiological load, CO_2 and particulate matter. Non-compliance with the WHO guidelines for indoor air quality is frequently reported. This study provides an overview of the recent literature on this topic, identifying promising lines of research to improve indoor air quality in healthcare facilities.

Keywords: indoor air quality; healthcare units; hospital; patient safety; occupational health and safety

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1. Introduction

Air pollution is currently recognized as the single biggest environmental threat to human health [1]. In 2019, it was responsible for an estimated 6.7 million deaths globally, beside the cost in years of healthy life [1,2].

People spend 90% of their time in indoor environments [3], therefore maintaining adequate indoor air quality is essential to minimize negative health impacts [4]. Healthcare units are no different, as healthcare providers, medical practitioners, staff and patients spend long hours in the facilities subject to their inherent air quality [5,6].

Indoor air quality (IAQ) is a complex and dynamic issue that is affected by different factors:

- outdoor air quality;
- indoor activities;
- indoor occupant density;
- ventilation practices;
- indoor intrinsic emissions (e.g., equipment/furniture/coatings).

The presence of vulnerable individuals and the characteristics of the ongoing activities highlight the importance of adequately managing IAQ in healthcare facilities. Headaches, fatigue, dryness and irritation of the eyes and skin are common complaints of healthcare professionals, which have often been associated with poor IAQ [7–11]). In addition, hospitals operate on a full-time basis (24 h per day, seven days a week), with no idle time to recover from activities' emissions and consequent impact on IAQ.

Chemical contamination may be originated by cleaning, disinfectant and sterilizing products containing ethylene oxide, glutaraldehyde, formaldehyde and alcohols, as well as by the use of anesthetic gases and other chemical agents used in medical procedures [12,13]. Indoor biological contamination arises from the aerial dissemination of microbiological pathogens in the clinical environment, with the potential to cause nosocomial infections and work-related respiratory diseases [14–16]. Air temperature and relative humidity are frequently monitored in healthcare facilities due to the direct association of these parameters with microbial growth [12,17–19].

Studies focusing on IAQ in hospitals or other healthcare facilities are scarce when compared with IAQ studies in residential buildings, schools, or commercial buildings [12,20,21]. In healthcare environments, many scholars support the assessment that less attention is given to the monitoring and analysis of chemical pollutants when compared with biological contamination studies [13]. There is also a recognized difficulty in conciliating strategies to address different indoor air pollutants occurring simultaneously [22]—recent concern has arisen regarding the formation of secondary indoor pollutants from the reaction between primary pollutants and/or other compounds present indoors or introduced by ventilation [23]. There is an increasing research interest in the design and rehabilitation of healthcare infrastructures, given the influence of construction and finishing materials in IAQ [9,24–27].

Given the importance of this research topic, the main objectives of the present review are:

(i) to provide an overview of the recent literature on indoor air quality in healthcare facilities;
(ii) to identify the major determinants of indoor air quality in healthcare facilities;
(iii) to identify future research paths on this topic.

Through a systematic literature review focusing on recent research (2015–2020), the present review aimed to answer the following research questions:

RQ1: Which healthcare facilities are being studied?
RQ2: What is the contribution of each country to the research on this topic?
RQ3: Which IAQ parameters are being analyzed?
RQ4: What is the research trend on this subject?

The results obtained suggest that IAQ in healthcare facilities is an important research topic, with promising lines of research that may lead to improvements with impacts on patient safety and occupational health.

This paper is structured as follows: after this introduction, Section 2 presents the research methodology. Section 3 presents a general overview of the results obtained, analyzing information in order to answer all the research questions. Finally, Section 4 presents the conclusions of the review, highlighting directions for further research.

2. Methodology

A systematic literature review (SLR) was performed to find, select, analyze and systematize information published in recent research works focusing indoor air quality in healthcare facilities.

SLRs are based on a replicable, scientific and transparent process comprising a sequence of stages [28]: (i) plan the review process; (ii) conduct the review process; (iii) report and disseminate results. Through a SLR it is possible to synthesize knowledge on a given research field, identifying research trends as well as existing gaps and areas in need for further investigation [29].

In the first stage of the SLR, the planning of the review process was made by selecting the search strings to be used. Three databases were consulted—B-on, Science Direct and Web of Science. In accordance with the aim of the present study, the search strings used were {'indoor air' or 'IAQ' or 'IEQ'} combined with {'hospital' or 'healthcare' or 'clinic' or 'health care'}. Since studies focusing on IEQ (indoor environmental quality) may include IAQ, the term was a search string in the analysis. The selection criteria were: peer-reviewed articles, written in English, published during the period 2015–2020, and presenting the combination of the selected search strings in the abstract section.

The PRISMA flow diagram [29] for the present SLR is presented in Figure 1. The search was performed in January 2021, and a total of 1441 records was found, reduced to 668 articles after duplicates were removed. The first screening of the articles derived from a title analysis, excluding those that did not focus specifically on indoor air quality in healthcare facilities. This step reduced the sample to 241 articles, which were further analyzed through abstract reading. At this stage, 44 articles were excluded because they focused exclusively on lab-scale research or simulation studies. The full-text reading of the remaining 197 articles resulted in 26 of those being excluded from the sample, either because they were not accessible (eight articles), or because they were outside the inclusion criteria described above. Thus, the final sample comprised 171 articles (the complete list of references is available in Supplementary Materials.

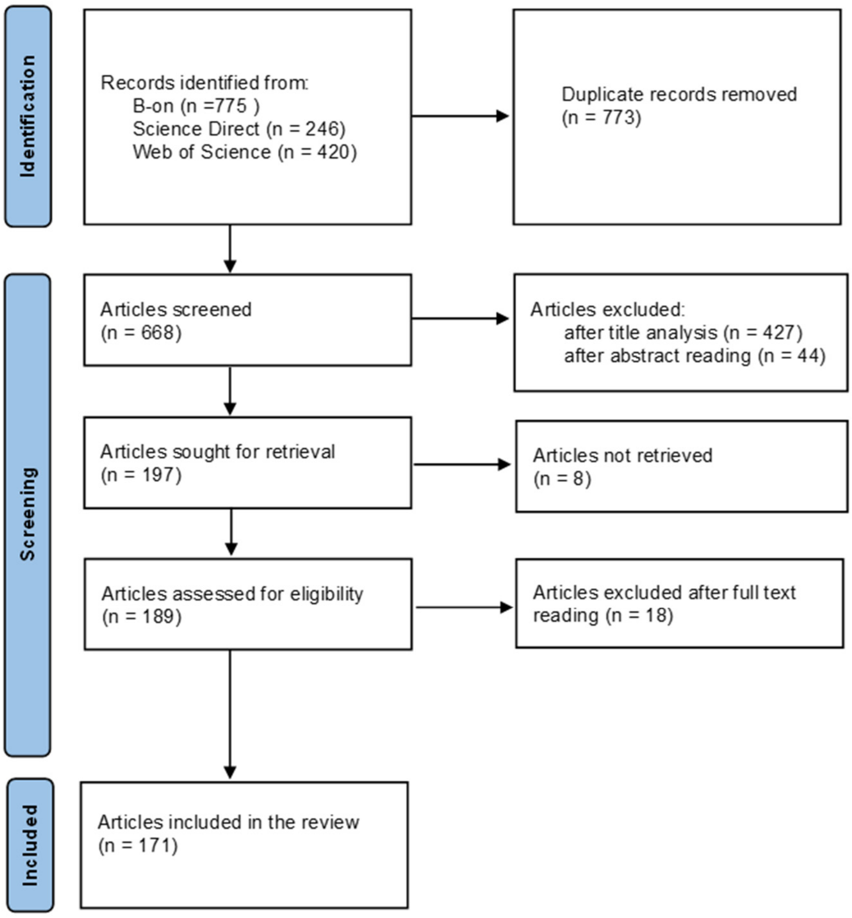

Figure 1. Flow diagram of the SLR.

The 171 selected articles were evaluated for their scientific quality according to the position in the Scimago Journal & Country Rank (SJR) of the journal where they were published. Only two indicators were used, the quartile and the H-index of the journal. If the journal was not part of the SJR base or was not ranked, it was flagged.

The second stage of the SLR comprised the content analysis to develop a dataset, registered on a spreadsheet. The following data was extracted from each paper: authors; publication year; title; journal; country where the study was conducted; type of healthcare facilities analyzed; study design; and indoor air quality parameters considered.

The IRaMuTeQ software was used as a tool to provide text analyses of the article's keywords and abstracts. It is anchored in the R Software and in the python programming language and it was developed in 2009 by Pierre Ratinaud [30].

The keywords of 159 articles (12 of the 171 articles were without keywords) were organized considering some uniformization: besides using the underscore to join compound words together, acronyms were standardized and synonymous were considered. A word cloud was obtained where the keywords most frequently used appear larger than the others.

The textometric analysis was also performed with the abstracts of the 171 articles. After creating the corpus, the text was corrected to avoid spelling mistakes and the use of some symbols and punctuation. A consistent use of acronyms and abbreviations and the use of underscore to join compound words together were also considered. A lemmatization process that replaces each word (occurrence) by its root word or its canonical form was applied. In the analysis, only active forms were considered, which include: adjective, adverb, common nouns, verbs and unrecognized forms.

Textual content analysis of the abstracts was performed using descending hierarchical classification (DHC) and confirmatory factorial analysis (CFA). The corpus was divided into homogeneous sections according to the chi-squared correlation between the categories and the frequency with which the active forms appear. The association strength is statistically significant ($p < 0.0001$) when the test value is greater than 3.84.

3. Results and Discussion

3.1. Descriptive Bibliographic Results

The trend on the number of publications on IAQ in healthcare facilities over time, for the period 2015–2020, clearly shows that there has been an increasing interest in the subject (Figure 2). Published articles more than doubled in number from 2015 (19 papers) to 2020 (40 papers).

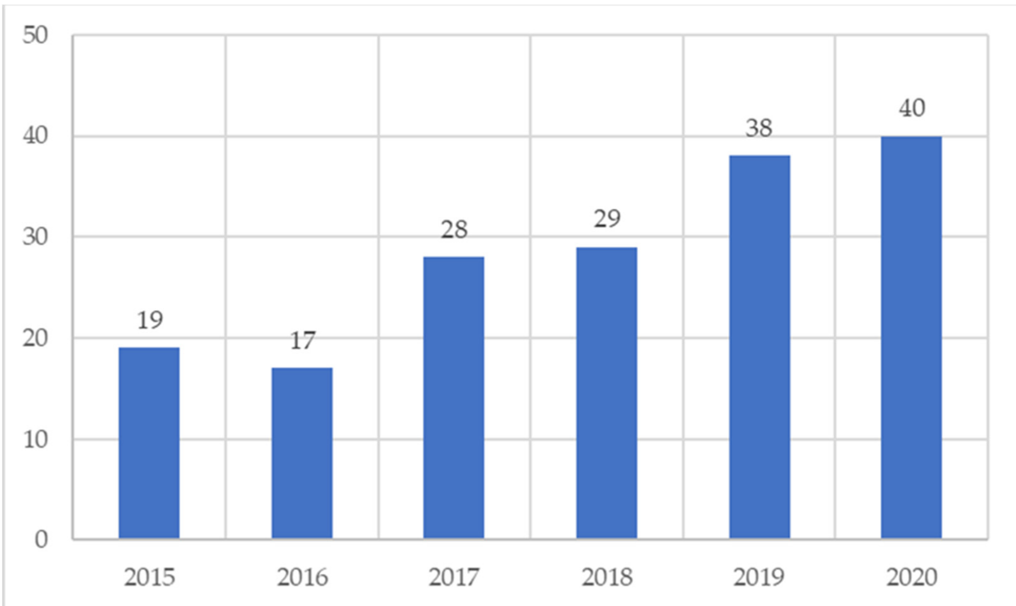

Figure 2. Distribution of the selected articles over time (2015–2020).

The 171 articles analyzed in this study are published in 101 different journals. The most represented journals encompass 18% of the sampled articles: *Building and the Environment* (15 papers), *Environmental Monitoring and Assessment* (8 papers) and *International Journal of Environmental Research and Public Health* (8 papers). These figures highlight the dispersion in the interest for this thematic issue.

To assess the scientific quality of the sampled papers, two indicators were used: the quartile and the H-index of the publishing journals, obtained from the SJR database. From the 101 journals found in the present sample, 84 journals (publishing 82% of the sampled papers) are ranked in the SJR database. Figure 3 presents the distribution of the papers by journals' quartiles, showing that 67% were published in journals within the first and second quartile. Nonetheless, 20 papers (12%) were published in journals without an assigned H-index in SJR. For the other 151 papers, journals' H-index varied from 6 to 397, with a median value of 81. Sixty eight papers (40% of the sample) were published in journals with an H-index above 100.

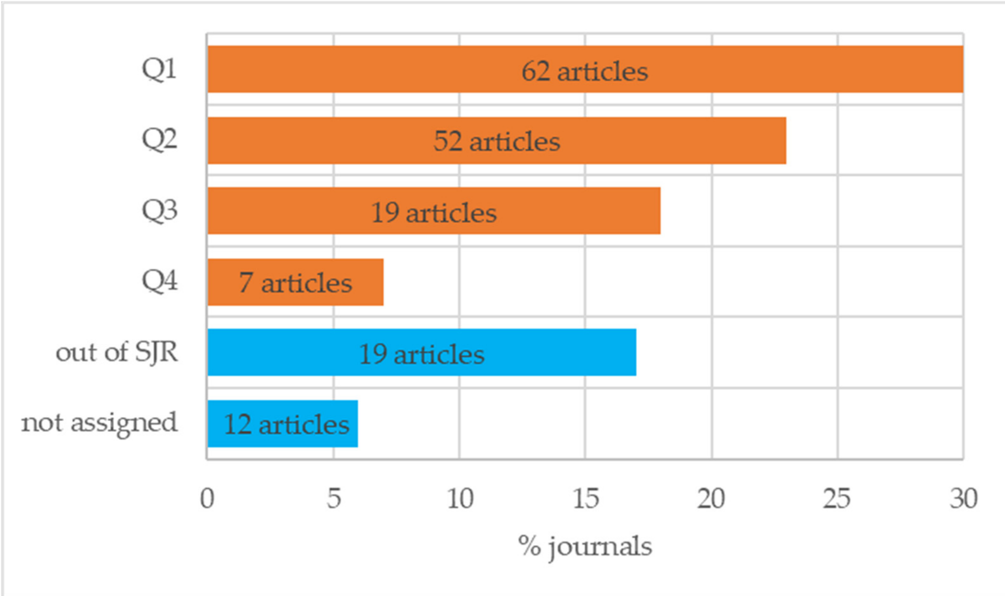

Figure 3. Percentage distribution by quartile of journals and articles (number inside the bar) in which the selected papers were published.

There was an increasing trend in articles published in journals in the first and second quartile (Figure 4) from 2015 to 2020. The yearly percentage of articles in the first and second quartile increased from 21% in 2015 to 60% in 2020, emphasizing the increase in research quality over time.

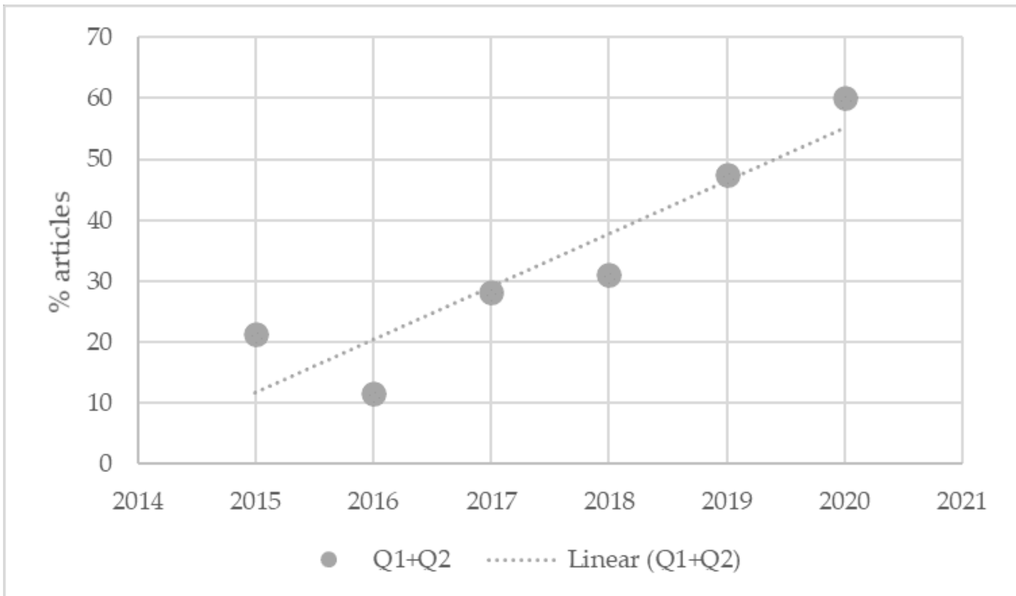

Figure 4. Trend of percentage distribution of articles in journals within the Q1 and Q2 quartiles.

3.2. Textometric Analysis

The textometric analysis of the keywords in the sampled papers reveals a total of 24 keywords with a minimum occurrence of five times. The word 'hospital' was the one most frequent keyword—42 times. The words were organized graphically in a word cloud, obtained with the IRaMuTeQ software, according to their frequency (Figure 5)—the size of each word is associated with its frequency of appearance. A high diversity of keywords was found, and some of them do not represent the key concepts of the articles—some guidelines or criteria for keyword use should be available to improve searches.

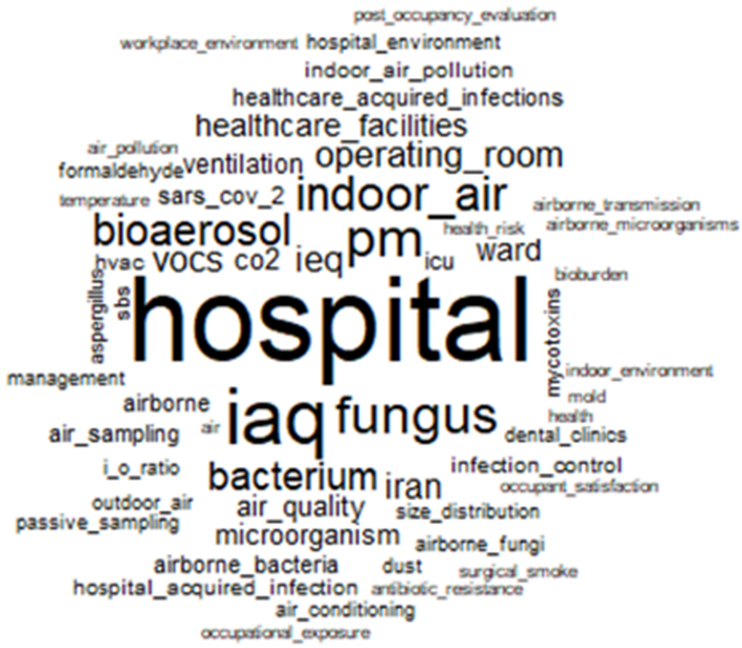

Figure 5. Word cloud of the keywords in the selected papers.

The lexicographic analysis of the textual corpus for the abstracts produced 40,381 occurrences, with 4075 active forms in a total of 4822 lexical forms (words). The most frequent active forms were air (547), hospital (465), indoor (437), concentration (302), and study (274), and 3438 of the active forms had a frequency higher than or equal to 3.

The dendrogram of the clusters obtained with IRaMuTeQ (Figure 6) shows four clusters created from branch divisions of studies from the sampled papers. One branch includes Clusters 1 to 3, whereas Cluster 4 belongs to a single branch. The numbers in each bar correspond to the percentage of words in the abstracts associated with each cluster. Cluster 1 is the largest one with 35.2% of the 4075 active forms. The color scheme aims to facilitate visualization.

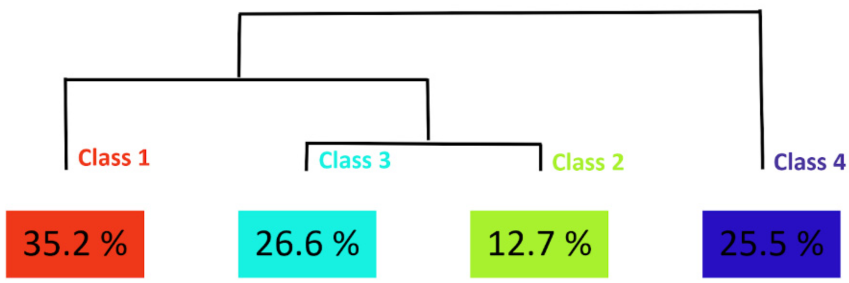

Figure 6. Dendrogram of the clusters from the abstracts, with the corresponding percentage of the forms.

Factorial representation (Figure 7) allows us to show the interconnection of these four clusters in the form of a factorial plan. Clusters 2 and 3 are clearly interconnected, while cluster 4 stands out for being less interconnected with the others (Figures 6 and 7). The size of the words in Figure 7 is related to the associated Chi-square value.

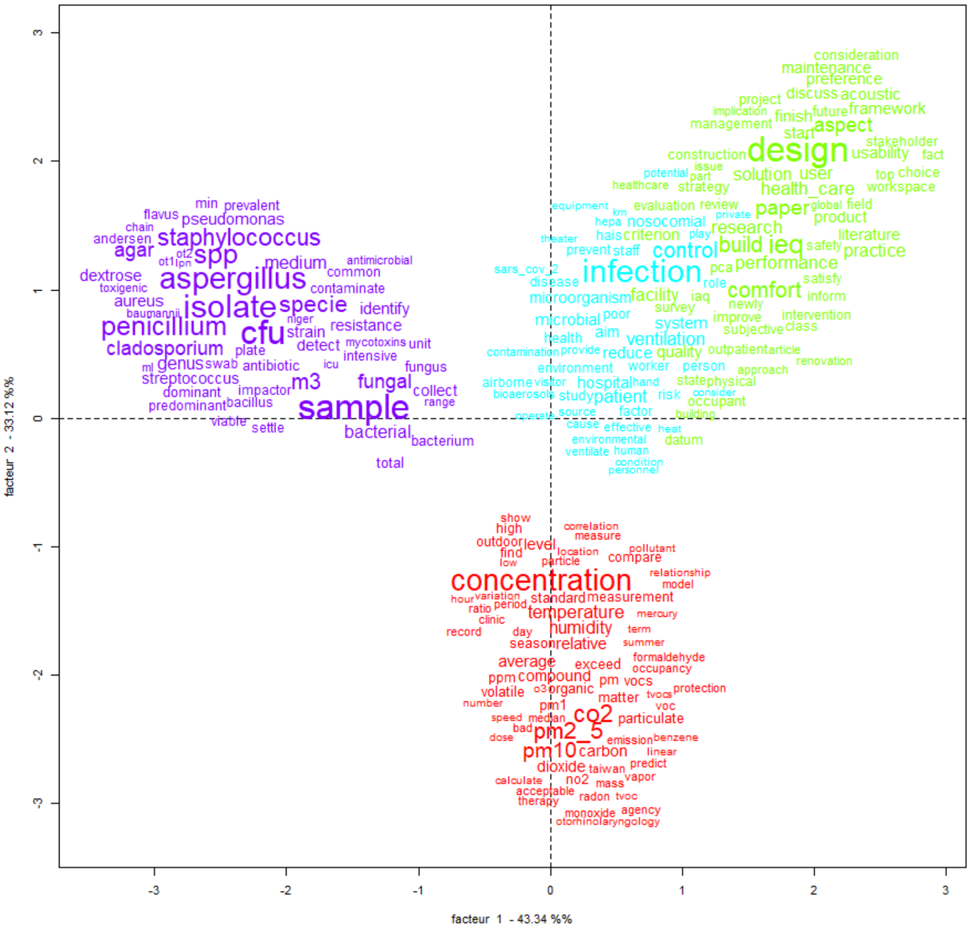

Figure 7. Representation of the factorial analysis.

The analysis of the semantic fields in each cluster identified in the dendrogram suggests the following categorization of the studies developed in the sample papers:

- Cluster 1 is related to studies focusing on physicochemical parameters. The most impacted words (higher Chi-squared values) are: concentration (120.2), CO_2 (89.6), PM2.5 (79.6), PM10 (64.7), temperature (53.2) and humidity (49.7). The analysis of the studies categorized in this cluster highlights the following issues: outdoor pollution sources should be addressed when evaluating indoor air quality [20,31,32], as should meteorological conditions [33–35]; isolated parameters—Radon gas [33] and CO_2 [19,36,37]—could be used to assess health risks in healthcare facilities; mercury vapors and VOCs in dental clinics are important issues which are still underexplored [38–40]; particles and VOCs released through surgical smoke in operating rooms are a concern for IAQ [41–44]; anatomopathological activities are associated with the significant release of organic contaminants to indoor air [45,46].
- Cluster 2 is related to the design and management of infrastructures. The most impacted words (higher Chi-squared values) are: design (153.9), *IEQ* (100.8), comfort (75.1) and build (73.2). The importance of design characteristics for adequate IAQ assurance is well established [24,47,48]. Nevertheless, there are still improvement opportunities regarding the choices of products and construction materials [10,26,49,50], as well as of daily activities' products [5,48,51,52]; special attention needs to be given to engineering procedures and maintenance activities [5,25,36,53–55].

- Cluster 3 is related to the environmental control of healthcare facilities. The most impacted words (higher Chi-squared values) are: infection (130.6), control (73.7), patient (53.2), ventilation (51.5), system (42.3) and hospital (42.2). These studies reveal great concern regarding air quality in operating rooms' air flow environment [56–58]. The importance of adequate particle filtration systems is also highlighted in several studies [43,59–62]. The influence of ventilation on the prevalence of hospital infections has also been studied [54,62,63], including studies on SARS-CoV-2 infection [27,53,55,64,65]. Cleaning procedures also have an important role in the control of microbiological loads [14,53,66,67]. Regular monitoring of indoor environmental conditions is essential to assess the efficiency of environmental control practices [9,48,59,68].
- Cluster 4 is related to studies focusing on microbiological contamination. The most impacted words (higher Chi-squared values) are: sample (151.8), CFU (146.1), isolate (131.2), aspergillus (126.3), penicillium (101.1) and staphylococcus (87.2). Relevance is given to the identification of microorganisms with antibiotic resistance [69–72], and to the detected presence of mycotoxins in HVAC filters [73]. The importance of controlling airborne particles in intensive care units is highlighted, due to the patient's compromised immune system [70,74,75]. The influence of the outdoor environment on indoor microbiological contamination is established [49,76–79], as well as the importance of adequate indoor temperature and relative humidity control to reduce microbiological loads [17,19,68].

Studies were found with no significant association with only one cluster. Articles frequently focus on environmental control measures considering both physicochemical and microbiological contaminants [12,80–84]. Ventilation management and control is of the utmost importance to reduce microbiological and physicochemical contamination in healthcare facilities [19,53,58,62,80,85,86].

3.3. Contributions per Country

In the period under analysis (2015–2020), 37 different countries conducted studies focusing on IAQ in healthcare facilities. The lead in these research studies was taken by Iran and China, with 35 (20%) and 27 (16%) of the 171 sampled papers, respectively (Figure 8).

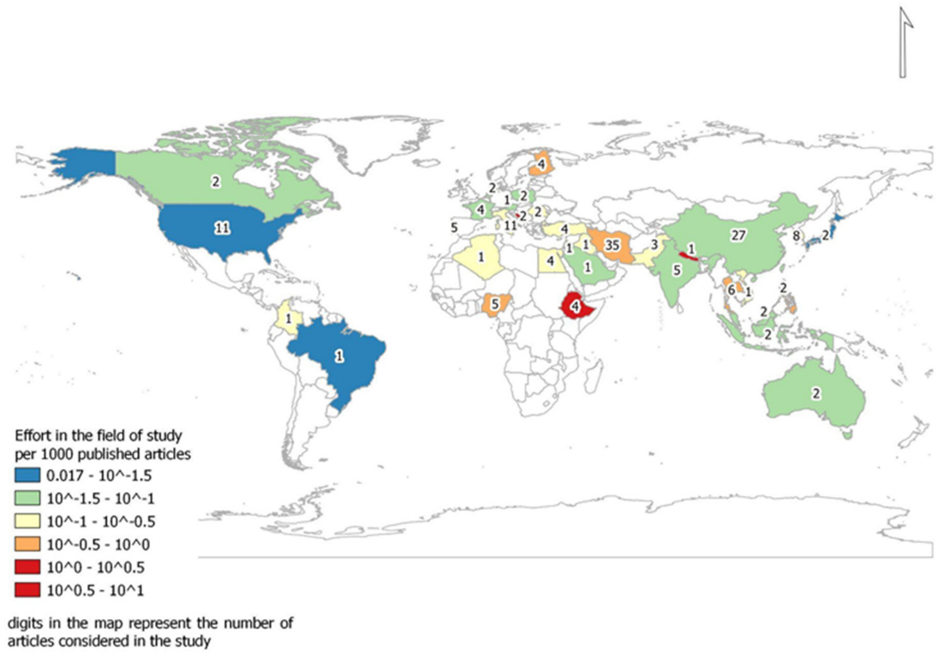

Figure 8. Number of selected papers per country and research effort in this field of studies.

The relative effort of each country in publishing scientific papers in this area of expertise was evaluated by calculating the ratio between the number of sampled papers in this study and the total number of technical journal papers published by each country, reported by the World Bank [87].

Surprisingly, a higher GDP does not mean research interest in the subject—the countries with higher GDP showed little publication effort in this field during the period of study (Figure 8). On the other hand, countries like Bosnia and Herzegovina, Ethiopia, and Nepal show the highest publication effort in the topic (number of published articles per 1000 publications).

3.4. Healthcare Facilities under Study

Hospitals were the healthcare unit of major interest for the IAQ studies, being studied in 91% of the sampled papers (Figure 9). Other healthcare units, specifically focused in 17 papers, highlight the IAQ concern in primary care centers (53%) and dental clinics (29%) (Figure 10). The most frequently analyzed locations are operating rooms, wards and intensive care units.

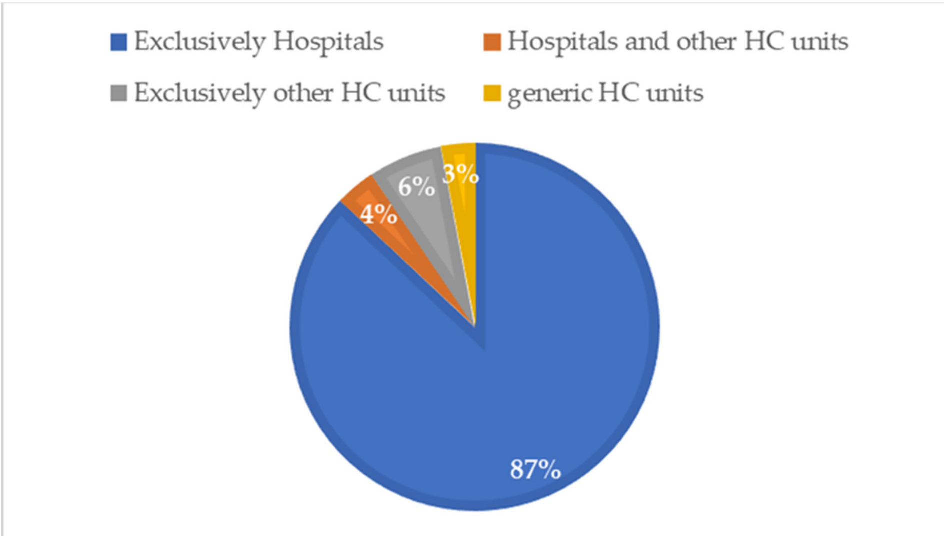

Figure 9. Type of healthcare facilities studied in the selected papers.

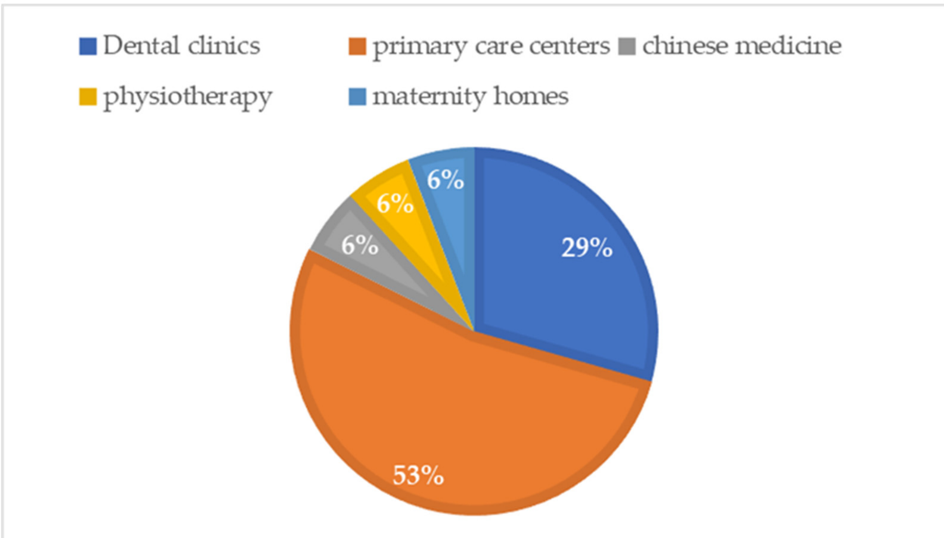

Figure 10. Non-hospital healthcare facilities studied in the selected papers.

3.5. Parameters under Study

A total of 145 articles (84.8%) disclose results of experimental measurements in situ. The published experimental data revealed that most papers (61%) focus on one to three indoor air quality parameters (Figure 11), although the sample included three papers that report results on 10 parameters or more [12,88,89]. Nine papers focused on the SARS-CoV-2 infection and one paper on the Legionella bacteria [90]. Twelve papers report the results of surveys applied to patients and / or healthcare professionals, and 14 papers report results of literature reviews.

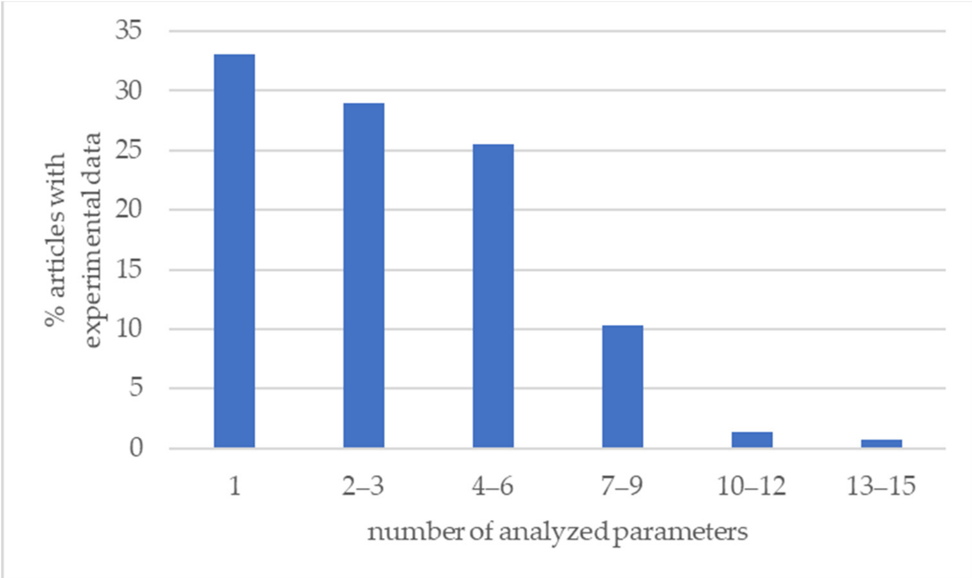

Figure 11. Number of analyzed parameters in the sampled papers with experimental data.

The parameters that were measured in the papers with experimental data are shown in Figure 12. The most frequently reported parameters are related to environmental quality—temperature (T) and relative humidity (RH)—and with microbiologic contamination—bacteria and fungi load. Measurements of the concentration of carbon dioxide (CO_2) and particulate matter (PM) were also frequently reported. In what concerns chemical contaminations, the most frequently monitored compounds were total volatile organic compounds (TVOCs), carbon monoxide (CO), benzene, toluene, ethylbenzene and xylene (BTEX), and formaldehyde. Other parameters that were measured in at least one of the sampled papers were ammonia and nitrogen oxide [91], anesthetic gases [92,93], limonene [12], mercury vapor [38], n-hexane and styrene [89], polycyclic aromatic compounds (PAH) [94], trichloroethylene and tetrachloroethylene [88], and phthalates [95]. Ultra-fine particles and black carbon, which have recently been considered a priority research target by the World Health Organization (WHO) [1], were focused on in only three of the sampled articles [43,96,97].

The experimental measurements reported in the sampled papers were analyzed to assess the range of results obtained for the most represented parameters (Table 1).

The results show a wide range of experimental values obtained for most parameters used to characterize IAQ in healthcare facilities, frequently not complying with the recommended limits of the WHO regarding ambient air (according to the WHO (2021), ambient air pollution is understood as air pollution in the outdoor environment, but which can enter or be present in indoor environments [1]). However, these results should be used with care—the different nature of the published data sets, such as seasonality of campaigns, region where the study was conducted, sampling points within the healthcare unit, experimental procedures, etc., hinders further comparative or statistical analysis. For example, studies aiming to quantify particulate matter concentrations in indoor air may use optometric techniques (e.g., [43]), or gravimetric methodologies (e.g., [12]).

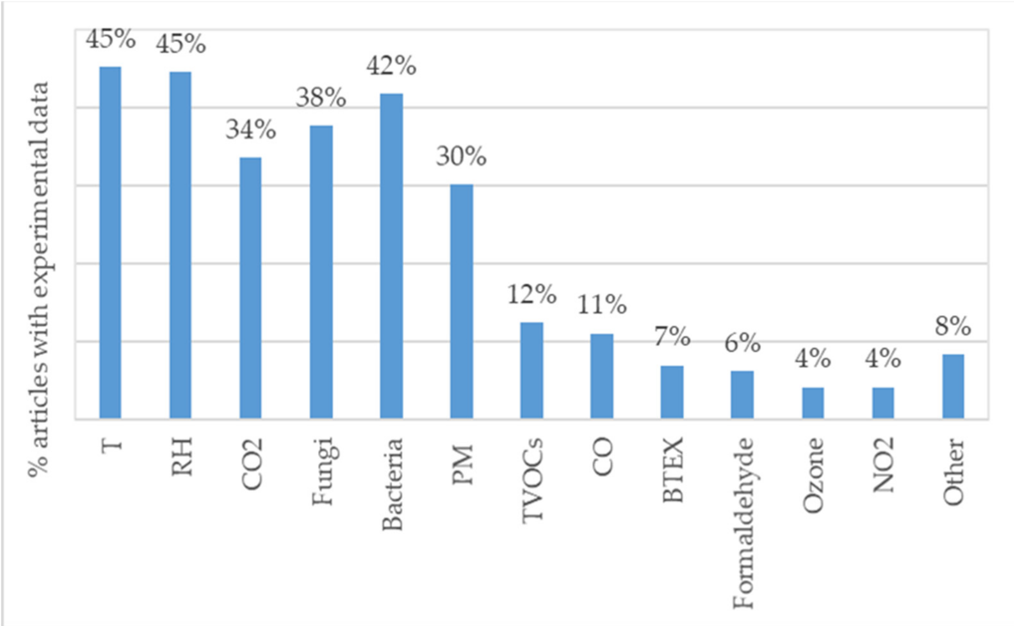

Figure 12. Parameters with reported results in the sampled papers with experimental data.

Table 1. Range of reported results for the measured IAQ parameters compared with WHO guidelines.

IAQ Parameter	Minimum Reported Value	Maximum Reported Value	WHO Recommended Guidelines [1,98–100]
Temperature (*n* = 64)	12 °C [18]	35 °C [101]	–
Relative Humidity (*n* = 63)	14% [37]	90% [81]	–
CO_2 (*n* = 48)	28 ppm [7]	5826 ppm [9]	–
Fungi (*n* = 54)	0 [14,78,79,102–105]	5147 CFU/m^3 [106]	–
Bacteria (*n* = 60)	0 [103,104,107]	9733 CFU/m^3 [108]	–
PM (generic, *n* = 6)	6 µg/m^3 [18]	967 µg/m^3 [109]	–
PM 1 (*n* = 7)	0.15 µg/m^3 [85]	757 µg/m^3 [109]	–
PM 2.5 (*n* = 33)	0.35 µg/m^3 [85]	810 µg/m^3 [109]	15 µg/m^3 (24 h) [a]
PM 10 (*n* = 27)	0.5 µg/m^3 [78]	2396 µg/m^3 [110]	45 µg/m^3 (24 h) [a]
TVOCs (*n* = 18)	0 [9]	7190 ppb [40]	–
CO (*n* = 16)	0 [42,111]	10.25 ppm [112] (11.94 mg/m^3) [b]	100 mg/m^3 (15 min) 35 mg/m^3 (1 h) 10 mg/m^3 (8 h) 4 mg/m^3 (24 h) [a]
Benzene (*n* = 9)	<0.1 µg/m^3 [31]	13 ppb [40] (130 µg/m^3) [b]	no safe level of exposure can be recommended
Toluene (*n* = 8)	0.1 µg/m^3 [12]	34 ppb [40] (130 µg/m^3) [b]	–
Ethylbenzene (*n* = 6)	0.1 µg/m^3 [12]	850 µg/m^3 [10]	–
Xylene (*n* = 7)	0 [42]	3397 µg/m^3 [10]	–
Formaldehyde (*n* = 4)	0.9 µg/m^3 [12]	810 ppb [40] (1.01 mg/m^3) [b]	0.1 mg/m^3 (30 min)
Ozone (*n* = 6)	2 ppb [113] (4.0 µg/m^3) [b]	42 ppb [113] (84 µg/m^3) [b]	100 µg/m^3 (8 h) [a]
NO_2 (*n* = 6)	0 [91]	371 ppb [114] (710 µg/m^3) [b]	200 µg/m^3 (1 h) 25 µg/m^3 (24 h) [a]

[a] 99th percentile (i.e., 3–4 exceedance days per year); [b] Conversion of ppb to µg/m^3 was made assuming gas conditions of 20 °C and 1013 hPa.

Nonetheless, the analysis in Table 1 provides useful information, as it demonstrates that there are still serious issues with IAQ monitoring in healthcare facilities, highlighting the importance of following experimental methodologies according to international standards or guidelines, to enable comparative results.

Another problem that stands out from Table 1 is the high levels of indoor air contamination (physicochemical and/or microbiological) that are still found in healthcare units. This highlights the urgent need to develop more research and define robust strategies to improve IAQ in healthcare facilities.

4. Conclusions

The analysis of the 171 articles obtained through a structured literature review focusing on IAQ in healthcare facilities reveals that there is a worldwide growing research interest in this subject.

There is a wide range of journals that publish articles on this topic, and the trend in scientific quality of the analysed, published studies has been increasing. Nevertheless, a smaller number of journals would be more effective in disseminating scientific information on the subject.

Regarding the contribution of each country on the topic under analysis, surprisingly, countries with higher GDP show little publication effort compared to countries with lower GDP, which have a higher number of articles published on this topic per 1000 publications. The lead in research studies was taken by Iran and China, with 20% and 16% of the 171 sampled papers, respectively.

The research focuses mainly on hospitals (91% of the sampled papers). Other healthcare facilities, which are important and representative of the healthcare activity, are understudied.

The textometric analysis of the abstracts revealed that the sampled papers focus mainly on four topics—physicochemical parameters, design and maintenance of infrastructures, environmental control measures, and microbiological contamination. The analysis of the sampled papers shows that the studies tend to be repetitive on the objectives, locations within the healthcare units and parameters under analysis.

The majority of the analyzed articles (85%) report experimental data, with the most frequently measured parameters being related to environmental quality (temperature and relative humidity were analyzed in 45% of the studies), microbiological load (fungi and bacteria data were reported in 38% and 42% of the papers, respectively), CO_2 (was the focus of 32% of the studies) and particulate matter (30% of the papers reported experimental data on this parameter). When planning experimental campaigns regarding IAQ parameters, care should be taken upon delineation of the research designs to make it possible to compare the results with international reference guidelines and/or standards.

Situations of non-compliance with the WHO guidelines for indoor air quality are frequently reported, evidencing the need for further research investments leading to improvements in this area.

There are research opportunities for studies focusing on other important pollutants (e.g., ultra-fine particles and PAH compounds). Moreover, research gaps exist regarding the formation of secondary pollutants from interactions between chemical contaminants, and risk assessments on the synergistic interactions between chemical contaminants and microbiological loads.

It is well established that the design of facilities, the choice of adequate materials for construction and renovation, and the adequacy of management procedures towards IAQ improvement should be based on scientific research and data analysis. Therefore, these topics are promising lines of research that may lead to improvements in the indoor air quality in healthcare facilities, with potentially relevant impacts on patient safety and occupational health.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14020967/s1, complete list of references included in the structured literature review.

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Conflicts of Interest: The authors declare no conflict of interest.

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