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Original article

The story line of the studies on airborne contamination in museums and historical libraries related to biodeterioration and health of operators and visitors

Roberto Albertini[1,2], *Mostafa Mohieldin Mahgoub Ibrahim*[1], *Alessia Coluccia*[1], *Maria Eugenia Colucci*[1], *Paola Affanni*[1], *Roberta Zoni*[1], *Licia Veronesi*[1], *Giovanna Pasquariello*[3], *Cesira Pasquarella*[1]

[1]Department of Medicine and Surgery, University of Parma, Parma, Italy; [2]U.O. Medicina interna di Continuità, Azienda Ospedaliero-Universitaria di Parma, Parma, Italy; [3]Former Director of the Biology and Environmental Controls Laboratory Central Institute for Graphic Arts, Ministry of Cultural Heritage and Activities, Rome, Italy

Abstract. *Background and aim:* In cultural-heritage-related indoor environments, biological particles represent a hazard not only for cultural property, but also for operators and visitors. The effectiveness of conservation for indoor cultural heritage and the health of operators and visitors derives from appropriate control and management. This study aimed to analyse the scientific community's activity on airborne contamination in indoor cultural heritage related to biological risks for artifacts, staff, and users to sensibilize insiders and decision makers about the importance of knowledge on this topic. *Methods:* We searched in Scopus for articles reporting the words "libraries or museums and air/airborne contamination" in the article title or abstract or keywords. Articles written in all languages were considered and crosschecked with related issues. *Results:* A total of 206 documents concerning the biodeterioration of libraries or museums were found since 1977 until July 26, 2023 of which 155 were original articles. United States, Italy, Poland, China and United Kingdom were the countries most involved in this research. A total of 47 documents investigated microbial air/airborne contamination in libraries, or museums, and Italy appeared on the first five countries, with the publication of some papers proposing multidisciplinary approaches for sampling and analysis of data. *Conclusions:* Our study can represent a contribution towards the studies on biological air quality of indoor cultural heritage for libraries, and museums. It is necessary to promote and support the research on this topic with a One Health approach, considering that a healthy environment for humans is equally healthy for artworks and artefacts. (www.actabiomedica.it)

Key words: cultural heritage, biodeterioration, health, airborne microbial contamination, sampling, preventive conservation

Introduction

Many visitors frequent museums and historical libraries, many scholars deepen their research in these environments and many employees spend many hours every day for control, preservation and archiving activities. A large part of indoor cultural heritage is present in Italy where an inestimable value of cultural heritage is preserved. Museums and historical libraries, due to the age of the preservation buildings, their characteristics and contents, are as precious as vulnerable. In these environments, airborne biological particles can represent a hazard both for artefacts due to their deteriorative action, and for the health of operators and visitors due to their potential infectious, allergenic, and toxic effects. Over the past decades, scientific research has made considerable progress in the knowledge of the vulnerability of materials to environmental conditions

and the awareness of the need for preventive conservation has increased involving measures and actions aimed at avoiding and minimising deterioration (1-3).

The effectiveness of conservation for indoor cultural heritage and the health of operators and visitors derives from appropriate control and management (4-5). The atmosphere normally contains various biological and not biological particulates. The analysis of airborne biological components (bioaerosol) can contribute to the defining the risk of degradation and health injuries for people. Airborne biological components are characterized by fungal spores, bacteria, viruses, animal, and plant origin fragments, and also pollen grains. In unfavourable environmental conditions, being mainly constituted by organic materials, the artefacts, can represent a nutritional source and a physical support for airborne fungi and bacteria, with the consequent irreversible biodeterioration (6). Inadequate biological quality of indoor air can also be very hazardous for the occupants of the building, leading to chronic diseases associated with the sick building syndrome (SBS) (7-10). Among SBS causative factors, outdoor sources have been recognized as inadequate ventilation, intake of chemical contaminants from indoor and outdoor sources (VOCs, volatile organic compounds, e.g.), but also persistence of biological contaminants bioaerosol (bacteria, fungi, pollen, viruses, etc) with dispersion of MVOCs (microbial volatile organic compounds) that derive from fungal and bacterial colonization of substrates (11-12). Moreover, microorganisms outdoor can easily enter indoor spaces, such as museums and historical libraries, in direct ways, through doors and windows, or indirectly with visitors' footwear and clothes, which often carry trapped microbial spores and vegetative cells. Fungal spores can also be dispersed by insects and mites since insects' infestation of materials and fungi proliferation are often associated; metabolic water, fragmented debris, and droppings produced by insects represent, in fact, a perfect medium for fungal growth and, at the same time, some insects and mites can directly feed on fungal structures (13).

Fungal spores are the most frequent and harmful microorganisms associated with the biodeterioration of organic and inorganic materials indoor. Their high metabolic versatility allows them to colonize various types of substrates (wood, paper, stone, e.g.) with damage to both the aesthetic and destructive kinds of deterioration (14). The deterioration of the materials is a complex phenomenon usually attributable to various factors, including air pollution and microclimate conditions. The role of the microclimate is not marginal (15-17) and can have consequences on the degree of preservation and health (16-17). This is particularly true in ancient historical buildings mainly affected by the sudden fluctuations of hygrothermal values which were found to widely exceed recommended levels for good air quality for both artworks and human beings (20-21). A high humidity of over 70% and reduced ventilation are related to the growth of fungi (22). Low humidity leads to drying of nasal mucosa, skin irritations and allergies. Too high temperatures can cause physical and mental exhaustion of symptoms and considerably increase the risk of allergies and bronchial asthma, fatigue, lack of concentration and headaches (23).

The purpose of aerobiological research applied to the conservation of cultural heritage is to evaluate and prevent the risk of alteration by airborne microorganisms of artefacts of historical, artistic and archaeological interest and the health impact on visitors and operators.

The preservation of conditions of artefacts needs to be continuously monitored to avoid degradation effects caused by time and public exploitation. The knowledge of how atmospheric pollutants affect the processes of deterioration of artworks is essential for their protection and the choice of appropriate materials to be used to construct new architectural containers (24).

Considering that aerobiology has marked characteristics of interdisciplinarity, through aerobiological monitoring, it is also possible to provide essential data for interventions of prevention, conservation, and restoration of indoor cultural heritage (1,25).

Conservation needs to be directed not only to the artwork, but also to their "container", the environment that interacts with it. The "preventive conservation" must consider the dynamic relationship that links the artwork to its context, and the biological characterization of the air is essential to make corrective interventions where situations of potential risk occur. Priority must be given to prevention interventions for analysing the environmental conditions (e.g. temperature and relative humidity) of the sites where the artworks and artefacts are exposed and air quality from a biological point of view, too.

The relationship between cultural heritage and the environment continues to represent a topic of great interest to scientific community. At the European level, in the past few years, research projects have been run aimed at assessing and quantifying the damage to which some of the materials that are generally used in the cultural heritage sector are subject. The objective of these studies was to analyse the deterioration mechanisms of each material examined, arriving at defining for each of them specific mathematical relationships (dose-response functions) capable of quantitatively estimating, where it is not possible to measure it directly, the damage attributable to air pollutants and climatic parameters (26-27). Moreover, the health is an interesting and important aspect to evaluate when the problem of the perception of indoor air quality is raised (28-31).

Another critical issue is how to measure contamination. Different methodologies and measuring techniques for biological monitoring have been adopted, but often without standardised approach. Recently, a working model for evaluating contamination in cultural heritage environments has been defined and applied with a multidisciplinary approach (32-37).

Considering the very high number of artefacts conserved worldwide in indoor cultural heritage and that the great majority is conserved in Italy, with inestimable value, the present study aimed at analysing the interest among the scientific community in these issues to spread knowledge on this topic and sensibilize insiders and decision makers. It could be crucial to deepen the importance of knowledge on cultural heritage environments related to the impact of airborne biological pollutants (e.g. fungi and bacteria) on biodeterioration materials, and on human health.

Methods

Based on the methodologies applied in our recent studies (35,38,39), we searched in Scopus for articles published until July 26, 2023, reporting the words libraries or museums, air/airborne contamination in article title or abstract or keywords. Articles written in all languages were included and we have crosschecked with "biodeterioration", "health of workers/visitors", "microbial", "fungi", "bacterial", "sampling", "active sampling", "passive sampling", "microclimate", "cfd" (computational fluid dynamics).

According to the study design, the following variables were considered: years and related number of articles, subject areas, type of document published, type of journal, nationalities of the authors and affiliations.

Results

A total of 206 documents deals with searching for air/airborne contamination in libraries or museums. An increase in the number of documents from 1977 to 2020 was observed (Figure 1).

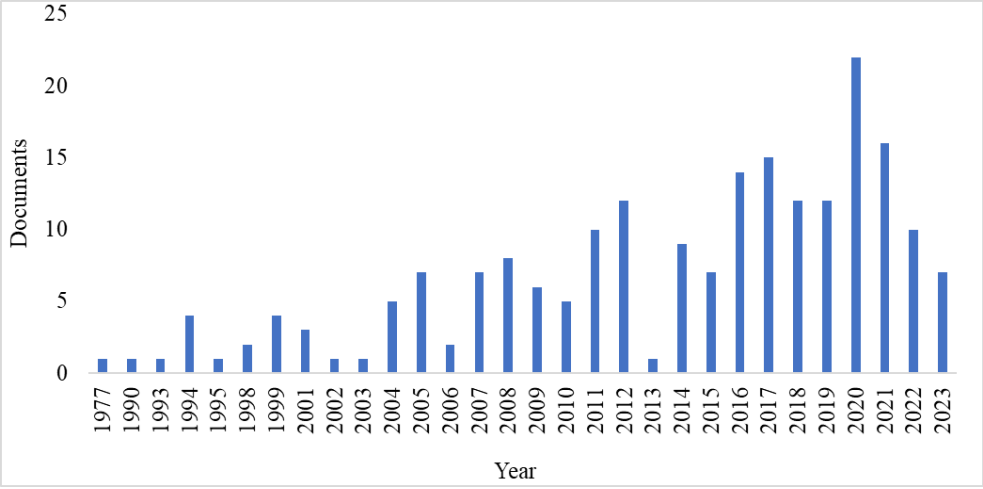

Figure 1. Papers, for years, on air/airborne contamination in libraries or museums.

Out of 206 documents, 155 were original articles, 24 reviews, 21 conference papers, 3 book chapters, 2 books (Figure 2).

The first five countries with at least one author facing this issue were the United States (11%), Italy (9%), Poland (7%), China (5%) and United Kingdom (5%) (Figure 3).

The interest for the biodeterioration of artworks started in 2005; a total of 18 documents were found, with a continued and increasing interest from 2015 to 2021 (Figure 4).

Figures 5 and 6 show the journal where papers were published and their subject areas, respectively.

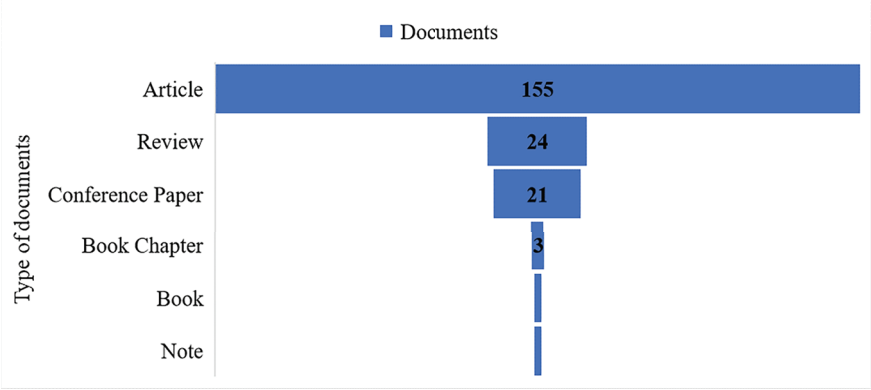

Figure 2. Type of papers published on air/airborne contamination in libraries or museums.

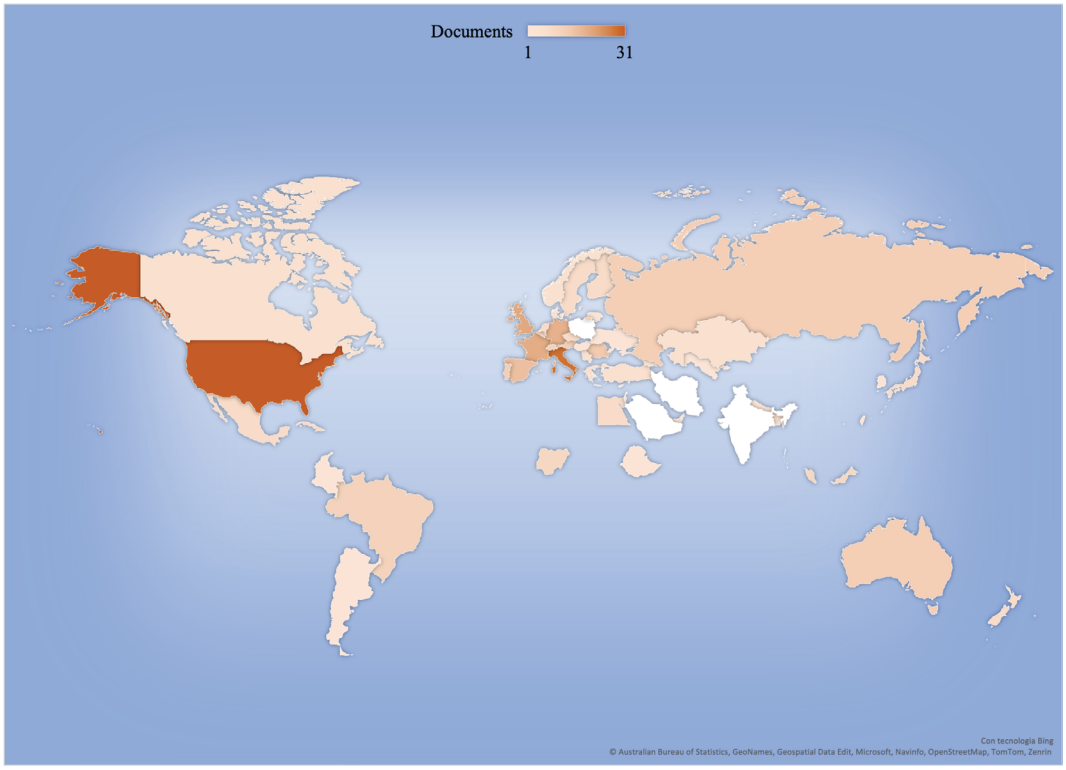

Figure 3. The map of countries with at least one author involved in paper about air/airborne contamination in libraries or museums.

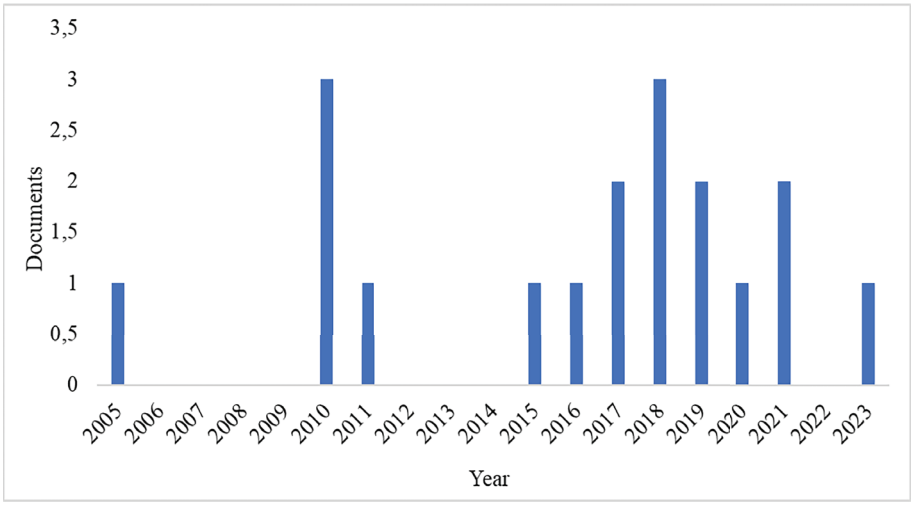

Figure 4. Papers, for years, about airborne biodeterioration of artworks in libraries or museums.

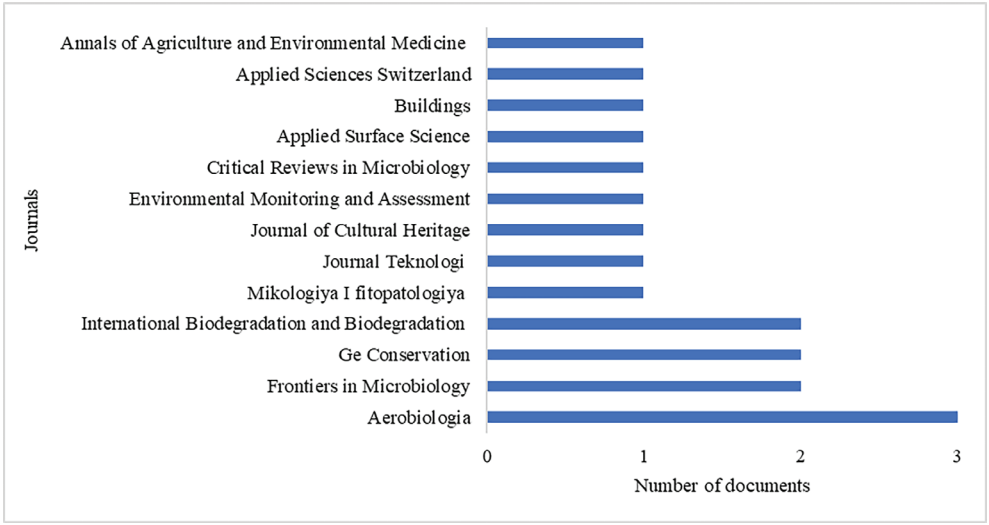

Figure 5. The journals publishing papers about biodeterioration and air/airborne contamination in libraries or museums.

Another issue we considered was related to health, which started in 1977 with a total of 45 papers. However, only 20 papers dealt with health of workers or visitors. The highest frequency countries for papers with at least one author per country were Italy (4), Poland (4), Romania (4), Australia (2), Kazakhstan (2) (Figure 7).

Searching the air/airborne contamination in museums or libraries with the keywords microbial, fungi and bacteria/bacterial we found a total of 47 documents investigating microbial air/airborne contamination (data not shown), 74 documents investigating fungi air/airborne contamination (Figure 8). The first study was published in 1998. Only since 2007 this issue has been addressed regularly every year. Italy appeared in the first five countries with 11 papers with at least one author (data not shown). Furthermore, 70 documents investigated bacteria/bacterial and air/airborne contamination from 1998 (data not shown).

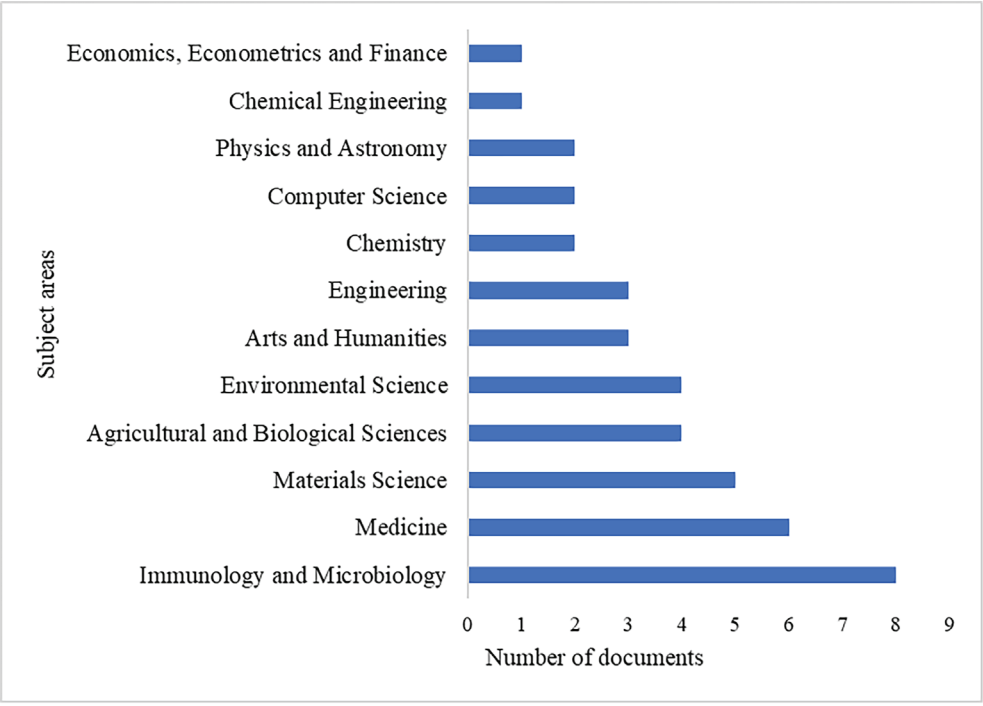

Figure 6. Number of papers for each subject area about biodeterioration and air/airborne contamination in libraries or museums.

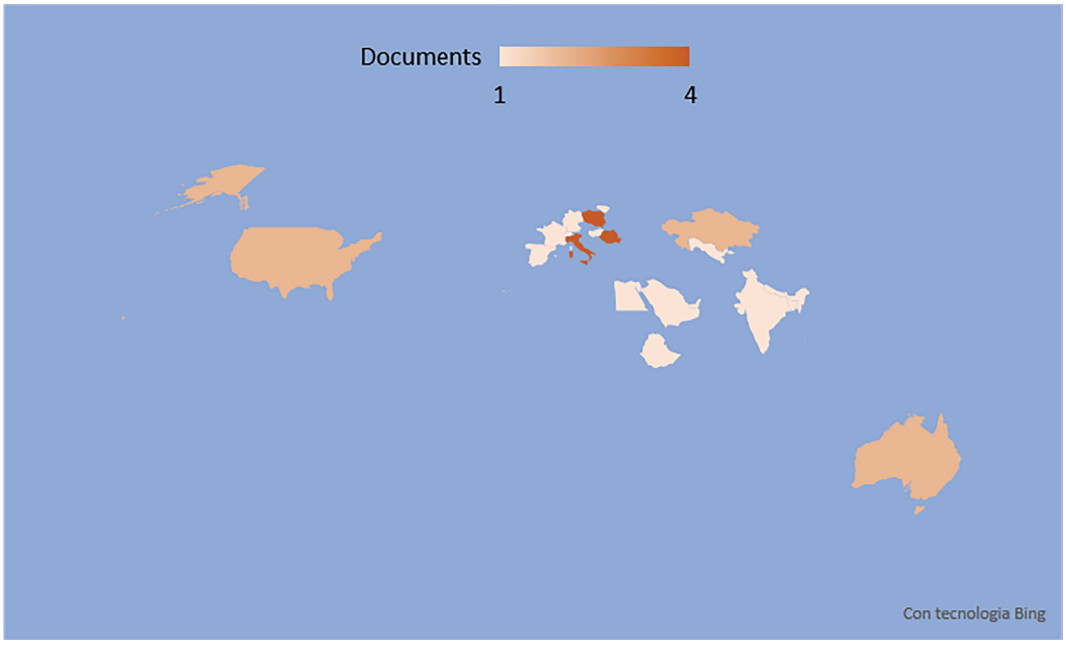

Figure 7. The frequency distribution of countries for papers with at least one author per country addressed the health of workers or visitors in libraries or museums.

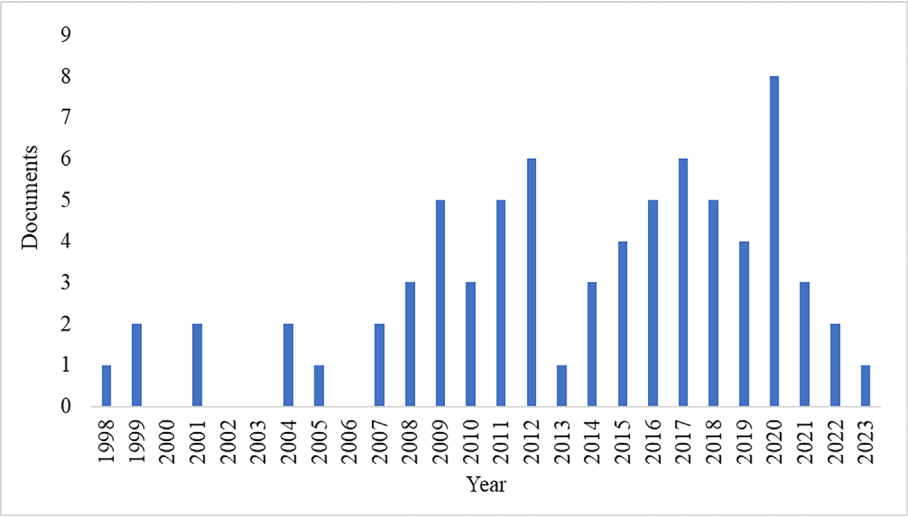

Figure 8. Papers, for years, involved in fungi air/airborne contamination in libraries or museums.

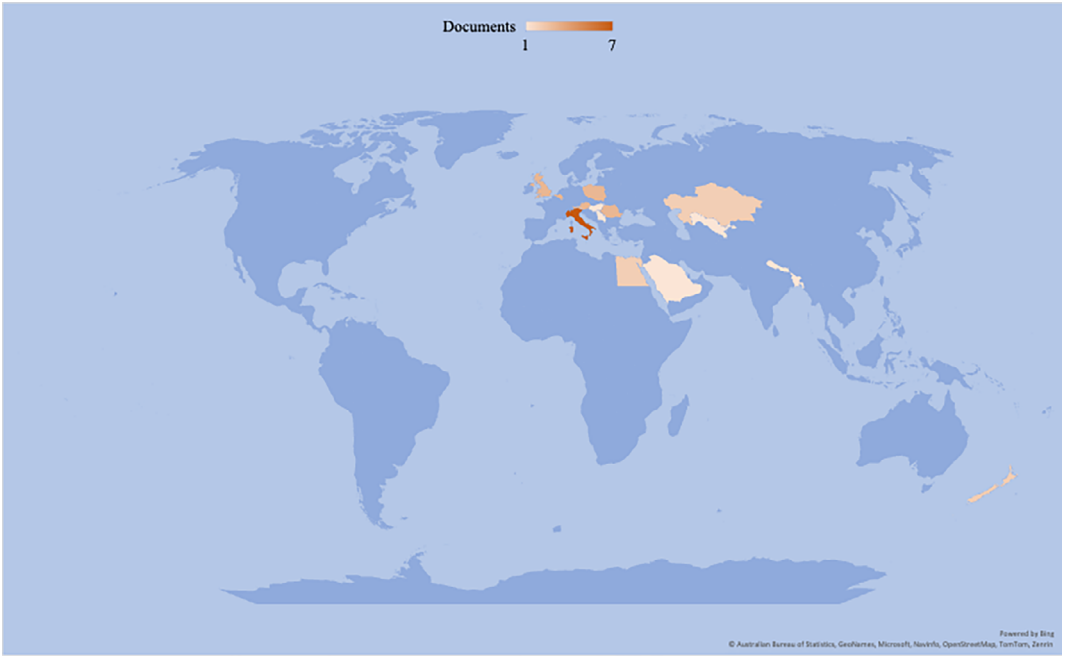

Figure 9. The frequency distribution of authors' countries that discussed the relationship between air/airborne contamination and microclimate in libraries or museums.

As for air/airborne contamination sampling (44 papers) were found, but 9 of them didn't deal with biological contamination. We found a total of 23 articles that addressed the active sampling method, 5 articles addressed the passive method, and 7 papers did not indicate the method used.

About microclimate, we found 298 papers dealing with this issue, but only 14 documents from 1999 focused this issue on relationship with air/airborne contamination.

Furthermore, Italy is the first country with 7 papers with at least one author involved, followed by Austria (3), Belgium (3), Poland (3) and Romania (3) (Figure 9).

Table 1. Countries with authors involved in studies about libraries or museums air/airborne contamination per continent and percentages on total countries by continent.

Continents	Number of Countries with at least one author	Number of Countries/Continents	Percentage
Europe	22	48	46%
Asia	20	49	41%
America	8	50	16%
Africa	3	54	6%
Oceania	3	14	21%

We found only 1 article discussing passive and active sampling methods in relationship with computational fluid dynamics (CFD) (34).

Table 1 shows the number of countries with at least one author included in studies about libraries and museums air/airborne contamination per continent and the percentage calculated from the total countries by single continent.

Discussion

The conservation of historic-artistic assets is a complicated process due to the diversity of methods, styles, cultures, traditions and above all materials that have characterized the production of cultural heritage over time and space. Each material interacts with the surrounding environment depending on its chemical-physical properties and is therefore subject to different deterioration mechanisms.

Our study represents a summary of the progress of the studies on air quality in indoor heritage environments (libraries and museums) revealing the interest among the scientific community in biological airborne contamination and monitoring to address the risk assessment for proper management both for biodeterioration of artefacts and artworks and the health of visitors and operators.

A large kind of approaches and biological, chemical, and physical parameters have been deepened by the scientific community to understand the tracks to manage airborne biological contamination. Cultural heritage preventive conservation plays a fundamental role as it allows the continuous control of the state of the artwork. It is necessary to promote and support the constant analysis and monitoring over time of all those environmental parameters that can give rise to various types of degradation of a biological origin.

It is evident how the interest in airborne biological contamination linked to biodeterioration and health of operators and visitors has been maturing, only in the last few decades. It is interesting to note that only a few authors have addressed the aspect of sampling, and its standardization and these authors belong to relatively few countries. Among these, only Italian authors have tried to address this issue with a multidisciplinary approach proposing standardized methods of sampling and analysis aimed at various parameters, both microclimate and microbiological contamination, also applying computational fluid dynamics analyses. Many authors have evaluated the microclimate in libraries and museums, but only a few of them have evaluated how physical parameters were related to air contamination.

It seems evident that evaluations of individual case studies with limited observation through the application of very different methods cannot provide comparable results in the different situations that are observed in very diversified contexts also from a climatic and not just a microclimatic point of view. Moreover, climate change will also have repercussions, even indoor, on the conservation of cultural heritage and on health of the people who frequent those environments for tourism or work. In effect, climate change poses many threats. While the main focus has been on the potential impact on the environment and the economy, there has been limited investigation into its effects on cultural heritage. Climate change can potentially cause irreparable damage to historic buildings and artefacts (37-41). It is possible to adapt buildings so they can

mitigate effects, but with climate uncertainty, it becomes complex to predict what measures are required to maintain, for example, temperature, humidity, and biological particles between thresholds that can limit the risk of damage to property and people (42).

It is important to be aware that air sampling should be included in a global evaluation of the environmental quality including surface sampling and microclimate parameters in a global approach (33, 34, 36, 43, 44).

It is necessary to promote and support the research on this topic with a One Health approach, considering that a healthy environment for humans is equally healthy for artwork.

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Conflict of Interest: Each author declares that he or she has no commercial associations (e.g. consultancies, stock ownership, equity interest, patent/licensing arrangement etc.) that might pose a conflict of interest in connection with the submitted article.

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Correspondence:
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Roberto Albertini, PhD, MSc
Department of Medicine and Surgery, University of Parma
Via Gramsci 14, Parma, 43126 Italy
Phone: +390521702966
E-mail: roberto.albertini@unipr.it