



# Relationship of airborne fungal spores to epidemiological data on respiratory disease: a systematic review

Dámaris A. Jiménez-Uribe ·  
Rosa Acevedo-Barrios ·  
Carolina Rubiano-Labrador · Paloma Cariñanos

Received: 28 April 2025 / Accepted: 6 November 2025  
© The Author(s) 2026

**Abstract** Exposure to fungal spores is associated with various types of respiratory health problems, and volumetric suction particle samplers have been used to estimate their concentrations in the atmosphere. This systematic review analyzes the sampling of fungal spores in outdoor air worldwide and its relationship to epidemiological data on respiratory disease. Ninety-four studies were identified that met the following inclusion criteria: They were original studies published in English or Spanish between 2010 and 2024, used active volumetric impact samplers, and identified the type of fungal spores in air. Most of the studies were conducted in Europe, with a duration of 1 to 2 years. The fungal taxa with the highest records were *Alternaria* sp. and *Cladosporium* sp. Only 13% of the studies correlated fungal spore concentrations with epidemiological variables; however,

77% of these studies concluded that there is a clear relationship between airborne fungal spore concentration and the occurrence of respiratory symptoms in the sensitized population. Therefore, this study provides an elaborate review of recent airborne fungal spore surveillance issues worldwide, attempting to include different perspectives of recent research on outdoor volumetric sampling, including epidemiological analysis.

**Keywords** Aerobiology · Bioaerosols · Fungal spores · Health effects · Meteorological variables · Respiratory allergies · Outdoor air

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10453-025-09890-w>.

D. A. Jiménez-Uribe (✉) · R. Acevedo-Barrios ·  
C. Rubiano-Labrador  
Grupo de Estudios Químicos y Biológicos, Dirección de  
Ciencias Básicas, Universidad Tecnológica de Bolívar,  
Cartagena de Indias D. T. y C., POB 130001, Colombia  
e-mail: duribe@utb.edu.co

P. Cariñanos  
Department of Botany, Faculty of Pharmacy, Andalusian  
Institute for Earth System Research, IISTA-CEAMA,  
University of Granada, 18071 Granada, Spain

## 1 Introduction

Bioaerosols are present in all environments and have the capacity to transport toxic, allergenic, or pathogenic substances that have the potential to affect human health, agricultural productivity, and ecosystem stability (Bisen et al., 2012; Woo et al., 2013). It is estimated that approximately 25% of atmospheric pollution consists of these biological particles (Cao et al., 2014). A notable subset of bioaerosols comprises fungal spores, which are characterized by their high reproductive capacity, year-round viability, small size, and ease of dispersion by wind (Castro, 2009; Egan et al., 2014; Pashley et al., 2012).

The global diversity of fungal species is estimated to be between 2.2 and 3.8 million, of which over 112

have been identified as potentially allergenic due to their capacity to trigger immune responses in sensitized individuals (Hawksworth & Lücking, 2017; Levetin et al., 2016). A series of studies conducted in various regions worldwide have demonstrated that exposure to these fungi can elicit allergic diseases, including atopic dermatitis, allergic rhinitis, and asthma. These studies have found that between 19 and 45% of individuals with allergies and up to 80% of asthmatic patients are affected, contingent on the specific country and population group examined. Furthermore, the duration of symptoms has been reported to be significantly prolonged in exposed individuals, (Baxi et al., 2019; Cao et al., 2014; Mari et al., 2003; Pongracic et al., 2010; Roy et al., 2017; Tham et al., 2017). A substantial body of research has indicated an association between elevated levels of airborne fungal spores and an increase in hospital admissions and asthma-related mortality (Lin et al., 2016; Newson et al., 2000; Tham et al., 2014).

Allergic diseases currently affect approximately 30% of the global population, with a growing prevalence attributed to elevated concentrations of airborne fungal spores and rising global temperatures (Lundbäck et al., 2016; Pawankar et al., 2011; Sánchez et al., 2022). These diseases represent a significant public health burden, both economically and in terms of reduced labor productivity and quality of life (Cervantes-De La Torre et al., 2018; Charalampopoulos et al., 2022).

The onset of allergy-related diseases associated with bioaerosols can be predicted by identifying the fungal genera present in the atmosphere, along with their particle size, concentration, and allergenic potential. These variables can be assessed through aerobiological monitoring (Blais-Lecours et al., 2015; Uk Lee et al., 2016). To date, the majority of monitoring efforts have been concentrated in temperate and seasonal regions, where pollen-related allergies are commonly diagnosed and reported. However, in tropical regions, characterized by high temperatures, relative humidity, solar radiation, and salinity, all of which influence fungal spore concentration and diversity, aerobiological monitoring remains limited (Huertas et al., 2018; Rodriguez-Gomez et al., 2020).

Furthermore, clinical threshold values, defined as the minimum airborne concentrations required to trigger allergic symptoms, vary by spore type and have only been established for the most commonly studied

genera: *Alternaria*, *Cladosporium*, *Aspergillus*, and *Penicillium* (O’Gorman & Fuller, 2008; Olsen et al., 2020; Pashley et al., 2012). This limitation arises from the difficulty clinicians face in correlating spore concentrations with sensitization symptoms, primarily due to the lack of comprehensive data on atmospheric spore abundance (Anees-Hill et al., 2021; Cecchi et al., 2010; Sadyś et al., 2016). Consequently, continuous bioaerosol monitoring and assessment are imperative to evaluate exposure risks and to establish reliable clinical thresholds.

In this context, the present review provides a comprehensive analysis of recent advances in volumetric sampling of fungal spores in outdoor environments, with particular emphasis on the articulation of these aerobiological data with epidemiological studies using health indicators—such as hospitalizations, skin tests, and respiratory questionnaires—for correlation. It has been demonstrated that a comprehensive approach, integrating spore quantification with clinical-population analysis, is essential for establishing reliable exposure thresholds and formulating effective preventive strategies against allergic diseases.

## 2 Materials and methods

This systematic review was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Yepes-Nuñez et al., 2021). A search of the Scopus database was conducted from May to October 2024 using a search string related to outdoor airborne fungal spores (“outdoor” AND “airborne” AND “spore” OR “spores” AND “fungal” OR “fungi” EXCLUDES “Indoor Air Pollution”). Studies were initially selected based on title and abstract and subsequently by full-text evaluation. The exclusive use of Scopus was justified by its broad multidisciplinary coverage, which includes high-impact journals in environmental sciences, aerobiology, and mycology.

Eligibility criteria were: original study published English or Spanish, or between 2010 and 2024, use of active volumetric impact samplers, and identification of airborne fungal spores. Exclusion criteria were: conference proceedings, reviews or editorials, sampling other than volumetric, identification of fungal taxa only by viable methods, sampling conducted indoors or conducted in the vicinity of areas that

could produce biases in fungal spore counts (waste-water treatment plants, landfills, composting sites, crop fields, forest plantations, etc.).

From the systematic review conducted, 2418 studies were initially identified in the database, 193 were selected for their title and abstract, 3 were eliminated because they covered the same sampling period and location, and finally, 94 met the inclusion criteria (Fig. 1 and Online Resource 1).

To extract the relevant information from each of the selected articles, a pre-designed template was used that included the following parameters: authors, year of publication, country where the sampling was carried out, continent, start and end dates of the sampling, duration of the sampling, methodology used, objective of the study, and fungal taxa identified. In addition, the fungal taxa most frequently identified in the articles were analyzed. To this end, specific data were extracted, such as the seasonal/annual spore integral (spores-day/m<sup>3</sup>), relative dominance (as a percentage of the total), annual total spores (spores/m<sup>3</sup>), peak daily spore concentrations (spores/m<sup>3</sup>), days with concentrations above the clinical threshold (if applicable), and the number of sampling sites. Data were also collected on the statistical correlation between spore concentrations and various meteorological factors, such as temperature, precipitation, relative humidity, wind speed, atmospheric pressure, and radiation (Online Resource 2).

When articles presented data corresponding to different years or monitoring locations, these were averaged to obtain an overall value that would facilitate analysis at the country level. Subsequently, using the

data obtained, a meta-analysis was performed to evaluate the overall behavior of the samples taken over the last 15 years, highlighting the most relevant trends and patterns in relation to meteorological variables and spore concentrations.

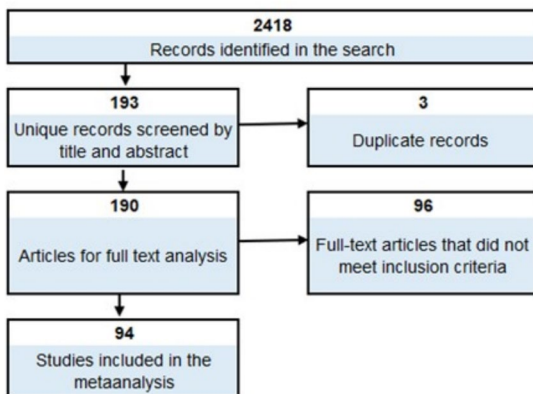
### 3 Results and discussion

#### 3.1 Geographical and temporal distribution of studies

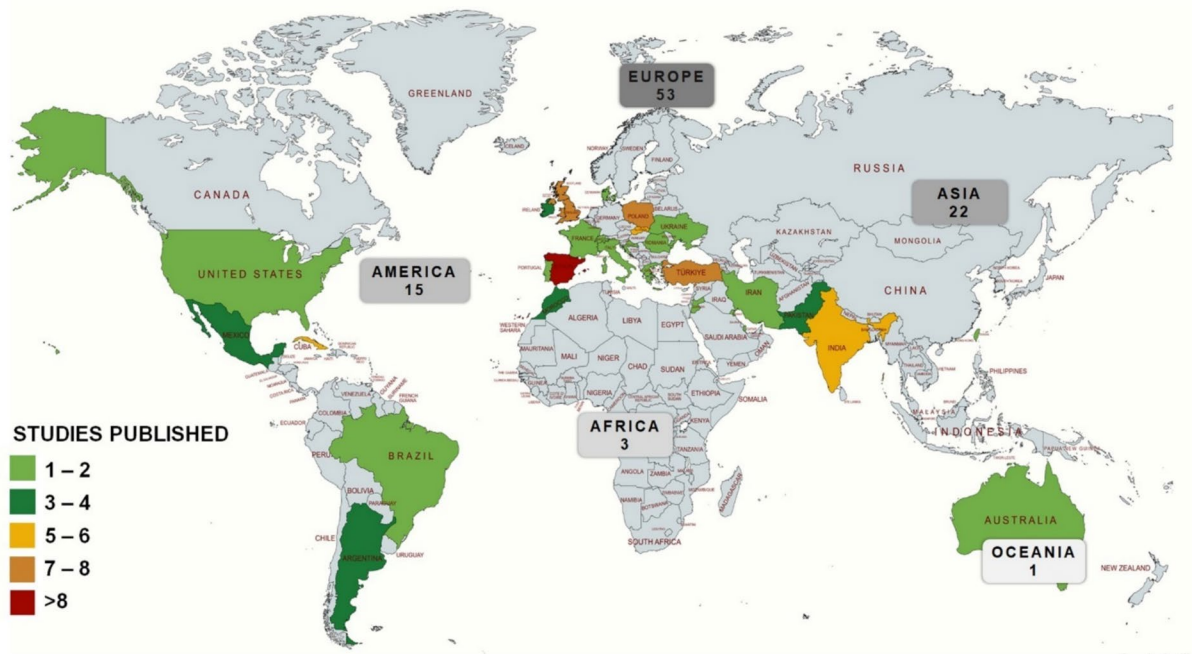
Fungal spores can be found worldwide; however, in the systematic review conducted, studies were only found in 30 countries (Bisen et al., 2012). Europe leads the research on fungal bioaerosol, with 53 published studies, followed by Asia and America. In contrast, Oceania is the least represented in this field. Spain has the highest number of studies ( $n=16$ ), followed by the UK ( $n=8$ ), Poland, and Turkey ( $n=7$ ) (Fig. 2). Despite the significant representation in Europe, many studies are concentrated in only four countries, limiting the overall understanding of bioaerosol behavior across the continent. A similar pattern is observed in other continents, where only a few countries report fungal spore counts.

Within the systematic review, the oldest sampling began in 1978 and, in the 1990s, there was an increase in sampling in Europe and America. In the 2000s, it reached its peak with thirty-seven studies distributed across five continents. Since 1996, non-European countries began to conduct studies; however, Africa and Oceania have not continued to publish results to date, demonstrating a large information gap on this topic in these continents (Fig. 3).

Most fungal sampling lasted 1 year ( $n=35$ ) or 2 years ( $n=20$ ), and only a subset reported follow-ups of  $\geq 10$  years ( $n=9$ ). Although an annual cycle allows for the description of intra-annual seasonality at a site, it is insufficient to establish stable and generalizable seasonality (Sánchez Espinosa et al., 2024). Furthermore, long-term analyses show that climatic conditions can modify the duration of seasons and generate upward trends in concentrations (Millington & Corden, 2005; Reznik et al., 2023). Consequently, multi-year series are required to understand local climatology, separate atypical years from real trends, and infer robust long-term behaviors. In this context, studies on fungal bioaerosols have pursued



**Fig. 1** Flowchart of the systematic review selection process



**Fig. 2** Worldwide sampling locations of the studies included in the review. The color of the countries indicates the number of studies published. The gray rectangles represent the number of published studies per continent

**Fig. 3** Temporal and geographical distribution of the studies included in the review, according to the year in which their sampling campaigns began



various objectives: 78% identified and quantified spores, 42% compared counts with meteorological variables, 33% analyzed spatiotemporal variability, 13% compared sampling/analysis methodologies, and 6% implemented predictive models. This heterogeneity of approaches reinforces the need for multi-year series and comparable protocols that integrate these

objectives and allow for more robust and transferable conclusions.

### 3.2 Taxa of airborne fungal spores

In the systematic review, allergenic spores were mainly associated with the Ascomycota (82%) and

Basidiomycota (18%) phyla. The most identified spores within each phylum are presented in Fig. 4.

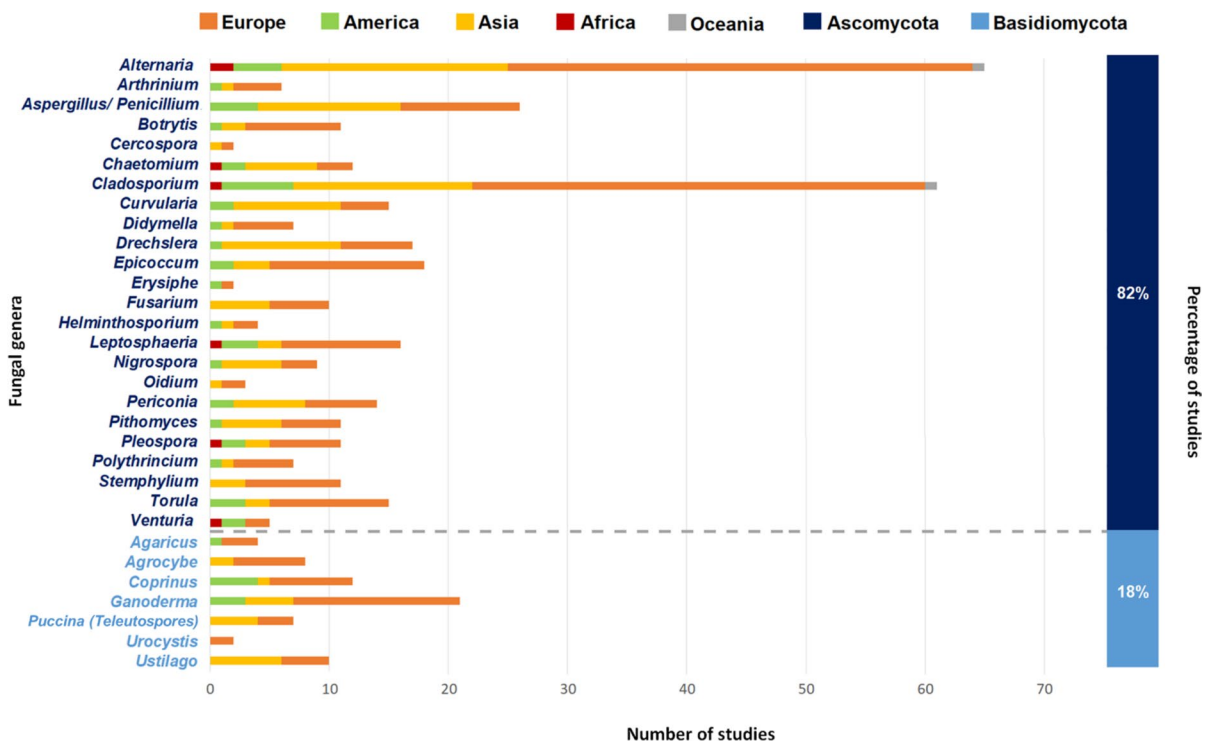
### 3.2.1 Phylum Ascomycota

The phylum Ascomycota, reported on five continents and in 82% of the articles reviewed, reproduces sexually through ascospores formed in asci or asexually through conidia produced in conidiophores. Not all species generate both types of spores; their occurrence varies between taxa (Deacon, 2005; Liu, 2024). While ascospores are usually released after wet or rainy periods, conidia are dispersed more continuously and include numerous clinically important allergenic taxa (Levetin et al., 2016).

Among the allergenic taxa, *Alternaria* spp. is one of the most frequently mentioned in studies on its allergenic potential, because most exposures occur in outdoor environments (Kasprzyk & Worek, 2006; Williams et al., 2016). Although *Alternaria* concentrations in the environment are lower than those of other allergenic spores, a significant sensitization rate

of 13–17% has been observed among atopic patients, representing up to 60% of positive cases (Amado et al., 2014; Arbes et al., 2005; Lehmann et al., 2017). Patients sensitized to this genus also have a greater propensity to develop allergic reactions to other taxa (Amado et al., 2014). Several scientific studies have established a correlation between asthma and allergic rhinitis with skin tests for *Alternaria* spp., which show sensitization generally at an early age and result in the development of childhood asthma (Moral et al., 2008; Salo et al., 2006).

The studies examined show that airborne concentrations of *Alternaria* exhibit marked spatial and temporal variability. Globally, the relative contribution of this genus is predominantly in the range of 2% to 15% of total fungal spores, with outliers reported in Qatar (19%) and in certain contexts in Spain and Pakistan (> 10%)(Gharbi et al., 2022; Hasnain et al., 2012; Vélez-Pereira et al., 2016). Annual concentrations vary considerably, ranging from a few hundred spores/m<sup>3</sup> in regions with low occurrence, such as Cuba or certain areas of India, to more than 100,000



**Fig. 4** Fungal genera reported by continent and phylum. Genus labels in dark blue = Ascomycota; genus labels in light blue = Basidiomycota. The vertical bar at right summarizes the share of studies by phylum (Ascomycota = dark blue; Basidiomycota = light blue)

spores/m<sup>3</sup> in Jordan and Kuwait, indicating significant regional contrasts (Abu-Dieyeh & Barham, 2014; Al-Ahmad et al., 2019; Almaguer-Chávez et al., 2018; Chakrabarti et al., 2012). In terms of seasonal dynamics, a consistent pattern is evident in Europe, Western Asia, and the Americas, characterized by peaks during the warm, dry months, particularly between July and September, with an onset in spring (March–May) and a decline toward autumn (September–November). However, there are notable exceptions: In India, concentrations are associated with the monsoon period, while in Mexico, peaks are concentrated during the summer (Dey et al., 2019; Ortega Rosas et al., 2020). Overall, the available evidence confirms that *Alternaria* is a ubiquitous and clinically relevant genus, with a defined seasonality in temperate and subtropical regions, although its abundance is highly dependent on local climatic and geographical factors.

*Cladosporium* was identified in 67% of the studies and is also the most frequent and the most abundant genus in propagule samples. This is because its spores are easily dispersed by wind (Oliveira et al., 2009; Pyrri & Kapsanaki-Gotsi, 2015; Soleimani et al., 2013). Its conidia are pigmented and measure 5–40 × 3–13 µm, forming simple or branched chains. This genus has a strong allergenic potential that severely affects people with allergic rhinitis and asthma (Gabriel et al., 2016; Ogórek et al., 2012; Pomés et al., 2016; Raphoz et al., 2010).

The data collected for *Cladosporium* show that this genus is one of the most dominant components of the atmospheric microbiota, reaching relative abundance percentages that often exceed 50% and, in some cases, reaching values above 80% of the total spores recorded (Pace et al., 2019). The annual concentrations reported are remarkably high, with figures ranging from tens of thousands to several million spores/m<sup>3</sup>, as observed in studies conducted in Poland, Slovakia, and the UK (Ščevková et al., 2023; Weryszko-Chmielewska et al., 2018; Žilka et al., 2024). Likewise, daily peaks range widely, from hundreds to more than 10,000 spores/m<sup>3</sup>, evidence of high spatial and temporal variability (Ianovici, 2016; Rad et al., 2023). In terms of seasonality, records in Europe, Asia, and America agree that peaks occur during the warm months, mainly between July and August, with a general onset in spring (March–May) and a decline in autumn (September–November) (Grinn-Gofroń et al., 2020; Kilic et al., 2020; Patel et al., 2018). In

tropical regions, such as the Caribbean, a marked abundance is also reported in summer, closely related to local weather conditions (Almaguer-Chávez et al., 2018; Díaz Vázquez et al., 2024). In summary, the findings indicate that *Cladosporium* has a wide geographical distribution, marked summer seasonality, and a predominant share of the total spore load, underscoring its epidemiological importance and its status as a leading fungal allergen on a global scale.

*Aspergillus* spp. and *Penicillium* spp. are two of the most prevalent airborne allergens, mainly associated with asthma exacerbations and proliferation in high-humidity environments. A review of the existing literature reveals that they are mentioned in 31% of the studies reviewed (Scott et al., 2004; Tournas, 2005). *Aspergillus* and *Penicillium* spores exhibit a globose or subglobose morphology, with smooth or rough walls and a diameter ranging from 2 to 7 µm. This characteristic makes it difficult to detect and differentiate spores using volumetric traps and optical microscopy, complicating the taxonomic identification process. Consequently, these spores are collectively classified as “*Aspergillus/Penicillium* type” (de Ana et al., 2006; De Linares et al., 2023; Piontelli, 2008). These genera have also been linked to persistent asthma and have been characterized as multiple specific allergens (Cramer et al., 2011; Deacon, 2005; Kousha et al., 2011; Williams et al., 2016).

*Aspergillus/Penicillium* records indicate widespread presence, although in relative terms, generally minor compared to other genera: Typical dominance ranges from approximately 1–8%, with occasional increases to around 20–21%, for example in Taiwan and Cuba (Espinosa et al., 2019; Kallawicha et al., 2017). The reported magnitudes show marked heterogeneity, with daily peaks ranging from tens to more than 4000 spores/m<sup>3</sup>, while annual totals fluctuate between hundreds and approximately 40,000 spores/m<sup>3</sup> at various points in Spain (Vélez-Pereira et al., 2016). The phenology is characterized by its perennality, manifesting itself in continuous detection throughout the year in various locations (Kallawicha et al., 2017; Naseer et al., 2024; Roy & Gupta Bhattacharya, 2020). Seasonal peaks are observed, which in the northern hemisphere are concentrated between June and October, declining toward the end of autumn; in the southern hemisphere, peaks are recorded in the southern spring (October–November), with seasons that can extend into autumn (Nitiu

& Mallo, 2011). Overall, the available evidence indicates that *Aspergillus/Penicillium* is ubiquitous and clinically relevant, although its contribution to the total spore load tends to be moderate and its variation is highly dependent on location and season. Based on the data provided, no additional causal mechanisms or patterns other than seasonality are observed.

For *Drechslera* spp., most species of the genus are saprobes and plant pathogens. Their conidia are pigmented, pseudoseptate and can germinate from single cells (Goh et al., 1998). Some species can cause opportunistic infections, fungal sinusitis and bronchopulmonary mycosis (Menezes et al., 1998). In addition, some species have been reported to be allergen producers and were reported in 19% of the studies (Chew et al., 2000).

The records available for *Drechslera* are scarce and heterogeneous, but they converge on a low relative contribution to the total spore load of between 0.2 and 4.1%, as well as modest annual magnitudes of between 100 and 10,000 spores/m<sup>3</sup>. In Europe (Spain, Serbia, Portugal) and Asia (India), seasonality is concentrated in the warm months of the northern hemisphere, with the season beginning around May–June, peaking in July–August, and ending in August–September (Das & Gupta-Bhattacharya, 2012; Simović et al., 2023; Sousa et al., 2016; Vélez-Pereira et al., 2016). Cuba shows peaks in December (Espinosa et al., 2019). Daily peaks vary widely between 4 and 175 spores/m<sup>3</sup>, suggesting marked spatial variability. Given the limited number of series and the absence of complete information in several studies, it is not possible to draw additional conclusions beyond this seasonality and its generally minor nature.

The genus *Epicoccum* spp. is frequently found in soil as a saprophyte and plant pathogen (Grinn-Gofroń, 2008). *Epicoccum* spp. were documented in 20% of the studies. Its conidia are characterized by brown color, rough walls, globular shape, and multicellular structure, measuring between 15 and 20 µm (Levetin et al., 2016). *Epicoccum* presents a spore distribution pattern similar to that of *Alternaria*. In particular, it belongs to allergenic genera associated with conditions such as hypersensitivity pneumonitis and allergic fungal sinusitis (Bisht et al., 2002; Rizzi-Longo et al., 2009).

*Epicoccum* spp. showed moderate and seasonal presence, with daily peaks that in most studies did not exceed 500 spores/m<sup>3</sup> and annual totals generally

below 3,500 spores-day/m<sup>3</sup>. Its relative dominance rarely exceeded 2%, placing it as a secondary genus in terms of atmospheric abundance. In Europe, it reached its most representative values, with summer peaks of up to 870 spores/m<sup>3</sup> and annual totals of 200–3,000 spores-day/m<sup>3</sup>, showing well-defined seasons between June and September (King et al., 2011; Simović et al., 2023). In America, the records were lower, with maximums of 100 spores/m<sup>3</sup>, present in the dry season (Espinosa et al., 2019). In Asia, values were intermediate, with peaks of around 400 spores/m<sup>3</sup> (Akgül et al., 2016). *Epicoccum* spp. behaves as a secondary genus in abundance, but with clear seasonality, whose contribution to the atmospheric mycobiota is particularly relevant in temperate and Mediterranean climates.

Regarding *Curvularia* spp., although rarely abundant, the conidia are frequently found in air samples, characterized by thick walls, transverse septa and a curved appearance (Levetin et al., 2016). They were identified in 15% of the studies and have been associated with susceptibility to asthma and respiratory allergies (Sio et al., 2021). Daily peaks rarely exceeded 250 spores/m<sup>3</sup>, while annual totals were around 1,000 spores-day/m<sup>3</sup>. Its relative dominance was less than 2% in most of the contexts analyzed. The seasonality of *Curvularia* was mainly related to periods of heat and humidity, reflecting its dependence on favorable conditions for sporulation (Almaguer-Chávez et al., 2018).

In Asia, especially in Pakistan, *Curvularia* had the highest values, with annual totals of more than 2,000 spores-day/m<sup>3</sup> (Abbas et al., 2012). In America, maximums of 200 spores/m<sup>3</sup> were recorded, with a relative dominance of 6%, higher than on other continents (Espinosa et al., 2019). In Europe, concentrations were low and sporadic, with average totals of 62 spores/m<sup>3</sup>, remaining a genus of secondary presence (Fernández-Rodríguez et al., 2014; Sousa et al., 2016). *Curvularia* spp. behaves as a genus that is not very abundant, but with a marked association with warm climates, being more relevant in tropical regions, where it reaches its maximum concentration values.

### 3.2.2 Phylum basidiomycota

Phylum Basidiomycota exhibits a vast macromorphological producing its sexual spores, basidiospores

externally on basidia (Reznik et al., 2023; Rivera-Mariani et al., 2020). In non-viable light-microscopy counts from Hirst-type samplers, these basidiospores are typically small and morphologically undistinctive ( $\approx 3\text{--}12\ \mu\text{m}$ ), which precludes reliable genus-level resolution; accordingly, they are reported in aggregate as “basidiospores.” Only a few genera with pronounced diagnostic traits—such as *Ganoderma* or *Coprinus*—can occasionally be recognized under these conditions (Elbert et al., 2007; Hernández Trejo et al., 2012; Kasprzyk, 2008).

Despite being frequently recorded as a pooled category, basidiospores are clinically relevant: They are known to produce allergens, and higher concentrations have been associated with increased emergency visits for asthma (Chane-Si-Ken et al., 2022). In this review, 18% of the studies analyzed reported Basidiomycota, with records spanning fifteen countries across Europe, the Americas, and Asia, underscoring their broad distribution and relevance for aerobiological surveillance.

*Ganoderma* spp., identified in 24% of the studies, is commonly known as a wood decay fungus and a prevalent genus of airborne fungal spores worldwide (Craig & Levetin, 2000; Singh & Mathur, 2021). Its spores are recognizable by their orange inner wall and spines penetrating a hyaline outer wall, ranging in size from  $6.5\text{--}13 \times 5\text{--}9\ \mu\text{m}$ . Recent studies have identified that this genus may be the third most prevalent allergenic genus after *Alternaria* and *Cladosporium* (Grinn-Gofroń & Strzelczak, 2011).

*Ganoderma* spores show a well-defined seasonal pattern, with daily peaks between 156 and 720 spores/ $\text{m}^3$  and annual totals generally below 30,000 spores/ $\text{m}^3$ , reaching their maximum in the summer and early fall months, especially in July and August. In Europe, the genus shows a regular but not dominant presence, with averages of 600 spores/ $\text{m}^3$  and annual totals of around 14,000 spores/ $\text{m}^3$  (Fernández-Rodríguez et al., 2018; Ščevková et al., 2020). In America, regional differences are observed: In the Caribbean, levels reach up to 2600 spores/ $\text{m}^3$ , with prolonged seasons lasting until autumn, while in South America the values are low (Almaguer-Chávez et al., 2018; Cid-Martínez et al., 2019; Díaz Vázquez et al., 2024; Emygdio et al., 2018). In Asia, in continental and semi-arid climates, *Ganoderma* has shorter seasons, with peaks of 300–400 spores/ $\text{m}^3$  (Abu-Dieyeh & Barham, 2014; Akgül et al., 2016). In

general, *Ganoderma* maintains moderate abundances, but with significant peaks in tropical and Mediterranean areas, establishing itself as a summer genus.

The genus *Coprinus* releases abundant basidiospores when humidity levels are high (Almaguer et al., 2014; Webster & Weber, 2007). Studies have found that due to their small size, *Coprinus* spores can penetrate deeply into the respiratory tract, worsening the respiratory conditions of patients (Levetin et al., 2016; Rivera-Mariani & Bolaños-Rosero, 2012). It was reported in 15% of the articles reviewed, as being associated with respiratory allergies (Cailaud et al., 2022).

Its distribution is seasonal, with peaks between spring and fall, and its concentrations vary widely, from 82 spores/ $\text{m}^3$  to peaks of 2,549 spores/ $\text{m}^3$ , with a seasonal average ranging between 700 and 26,000 spores/ $\text{m}^3$ . In the Americas, *Coprinus* showed high dominance in Cuba (15.8%), with seasons between May and October, while in Mexico and Brazil the values were much lower, with dominances below 3% (Díaz Vázquez et al., 2024; Emygdio et al., 2018; Rocha Estrada et al., 2013). In Europe, the highest annual totals were reported in Spain and Serbia, with well-defined summer peaks, while in Asia the values were considerably lower, with annual concentrations of only 340 spores/ $\text{m}^3$  (Das & Gupta-Bhattacharya, 2012; Simović et al., 2023; Vélez-Pereira et al., 2016). In summary, *Coprinus* is not a marginal genus, as in some regions it can reach high concentration and dominance, while in others its presence is almost nil, highlighting its dependence on local factors.

The genus *Agrocybe* was reported in 10% of the studies in the review, as an allergenic spore (Ščevková et al., 2019, 2020; Sevindik et al., 2022; Vélez-Pereira et al., 2016). It has been classified as a wet spore, like *Coprinus*, *Ganoderma*, and *Leptosphaeria*. These spores show higher concentrations during the night or early morning hours, and a negative correlation with air temperature has been observed. (Carlile et al., 2001; Ščevková et al., 2019). On the other hand, an increase in *Agrocybe* concentration in the air has also been reported with an increase in atmospheric  $\text{NO}_2$  levels (Damialis et al., 2015).

The data available for *Agrocybe* shows limited distribution and low dominance in atmospheric spore concentrations. In studies conducted in Turkey and Ukraine, median daily peaks range from 124 to 1,017 spores/ $\text{m}^3$ , with a relatively low annual total of 1,021

spores/m<sup>3</sup> in Ukraine and 1,017 spores/m<sup>3</sup> in Turkey. The dominance of this genus is also low, with values reaching only 1.2% in Turkey and 0.2% in Ukraine, reinforcing its minor role in the total atmospheric spore load. In terms of seasonality, *Agrocybe* shows a defined pattern, with higher concentrations between April and August, with July and September being the peak months in the different locations (Reznik et al., 2023; Sevindik et al., 2022). Overall, these data suggest that *Agrocybe* is a genus with moderate and seasonal presence in certain regions, but with a minimal contribution to the total spore load in the air.

### 3.3 Sampling and quantification methodologies

The seven-day volumetric spore trap based on the initial design of Hirst (1952) employs the non-viable particle impaction method, which is widely used by various organizations for pollen and spore monitoring. The volumetric spore sampler is usually placed on the roofs of buildings to collect a representative sample of the air that has been mixed, bringing with it particles released from diverse sources (Lacey & West, 2006). In the studies analyzed, the average installation height of the volumetric sampler was 17 m above ground level.

Viable and non-viable bioaerosols are identified and quantified by optical microscopy, which also allows detailed observation of their structures. Their efficiency is improved by using stains such as methylene blue, which allow them to be classified morphologically. This method, called direct counting, is nowadays one of the most widespread analytical techniques. To obtain better visibility of the particles, phase contrast microscopes are used to observe nearly invisible particles, fluorescence microscopy, which uses ultraviolet or near-ultraviolet illumination that causes fluorescent particulate compounds to emit light, or scanning electron microscopy (SEM), in which the surface of the bioaerosol is scanned with an electron beam (Després et al., 2012; Pöhlker et al., 2012).

This systematic review found that 17% of the studies used light microscopy for taxon identification and counting, while 6% used culture techniques, fluorescence microscopy or DNA analysis to compare results between analytical methods. Despite uniformity in sampling methodologies and the units in which concentrations are expressed (spores/m<sup>3</sup>) (Galán et al.,

2007), studies vary in the way they are reported. Some provide daily averages, others monthly averages, others the annual integral, and some present data in total spore counts while others provide them by fungal taxon. This makes quantitative comparisons between the studies analyzed very difficult (Janssen et al., 2021; Symon et al., 2025).

### 3.4 Relationship with meteorological factors

Meteorological parameters such as temperature, relative humidity, solar radiation, and atmospheric pressure influence the production, release, dispersion, deposition, diversity, and concentration of bioaerosols (Bertolini et al., 2013; Polymenakou & Mandalakis, 2013; Şakiyan & Inceoğlu, 2003). In 49% of the reviewed studies, the relationship between fungal spore concentrations and meteorological variables was analyzed by statistical correlation coefficients.

#### 3.4.1 Temperature

Temperature is one of the most influential factors that, depending on the season and time of day, affects the metabolism, reproduction, and viability of fungal spores, correlating directly with atmospheric concentrations (Mantoani et al., 2025; Millington & Corden, 2005; Pasanen et al., 2000). In the case of dry spores, *Alternaria* and *Cladosporium* showed consistent positive correlations with minimum, average, and maximum temperatures in Mediterranean regions such as Morocco and Spain, reaching peaks of more than 600 spores/m<sup>3</sup> on the warmest days and increasing the number of days above the clinical threshold during the summer (Bardei et al., 2017; Sabariego et al., 2012; Sánchez Espinosa et al., 2024). Less abundant genera such as *Drechslera* and *Curvularia* also followed this pattern, with summer increases in countries such as India and Mexico, reflecting their close link to the growth and aging cycles of grasses in hot conditions (Das & Gupta-Bhattacharya, 2012; Rocha Estrada et al., 2013). Similarly, *Aspergillus/Penicillium* was more prevalent in warm climates, with positive associations with average temperature and daily maximums above 400 spores/m<sup>3</sup> in Asian studies (Kallawicha et al., 2017; Naseer et al., 2024).

Other less abundant genera, such as *Drechslera* and *Curvularia*, recorded their highest concentrations in the summer months in Cuba and Spain, coinciding

with rising temperatures, which reinforces their thermophilic nature (Almaguer-Chávez et al., 2018; Fernández-Rodríguez et al., 2014). *Coprinus* showed variable behavior: In Cuba and Ukraine, it reached high annual totals with peaks during the warm months of July and August, while in Mexico and Brazil, its presence was marginal, probably limited by local conditions (Almaguer-Chávez et al., 2018; Emygdio et al., 2018; Reznik et al., 2023; Rocha Estrada et al., 2013). Overall, the evidence confirms that temperature acts as a facilitating factor for dry spores (*Alternaria*, *Cladosporium*, *Aspergillus/Penicillium*, *Drechslera*, *Curvularia*), while in genera such as *Coprinus* its effect depends more on the interaction with substrate availability and local conditions.

### 3.4.2 Relative humidity

Relative humidity showed different effects depending on the type of spore. In the group of dry spores, such as *Alternaria* and *Cladosporium*, negative correlations with humidity were observed in several studies in Europe and North Africa (Filali Ben Sidel et al., 2015; Sarda-Estève et al., 2019). In Granada and Seville, *Cladosporium* concentrations decreased significantly on days with humidity above 70%, while *Alternaria* reduced its presence in saturated environments, maintaining its maximum levels under dry summer conditions (Aira et al., 2013). This pattern also extended to less abundant genera such as *Drechslera* and *Curvularia*, whose summer peaks were associated with dry periods following grass senescence. *Aspergillus/Penicillium* showed similar behavior: Their concentrations decreased in very humid environments, confirming their preference for relatively dry and hot periods (Espinosa et al., 2019).

In contrast, moist spores responded in the opposite manner. In Spain and Greece, *Ganoderma* recorded marked increases on days with humidity above 75%, reflecting its dependence on moisture for the maturation of fruiting bodies and active spore release (Charalampopoulos et al., 2022; Elvira-Rendueles et al., 2013). *Coprinus* showed a comparable pattern: In Cuba and Serbia, its highest loads coincided with humid periods in summer and fall, while in drier regions such as Mexico, its presence was marginal (Almaguer-Chávez et al., 2018; Rocha Estrada et al., 2013; Simović et al., 2023).

In summary, relative humidity is a critical determinant of the composition of atmospheric mycobiota: Dry spores (*Alternaria*, *Cladosporium*, *Aspergillus/Penicillium*, *Drechslera*, *Curvularia*) proliferate under dry conditions and decline under high humidity, while moist spores (*Ganoderma*, *Coprinus*) reach their maximum levels in moisture-saturated environments, defining opposite patterns that explain much of the regional variability observed.

### 3.4.3 Other meteorological factors

Among secondary meteorological variables, wind played a significant role in the dispersion and transport of spores. Studies conducted in Europe observed that moderate wind speeds favored the upward and horizontal movement of light genera such as *Cladosporium* and *Aspergillus/Penicillium*, while intense gusts reduced local concentrations through dilution (Antón et al., 2019). Atmospheric pressure, although less studied, showed significant associations in certain regions: Pressure drops preceded increases in *Leptosphaeria* concentrations, possibly due to meteorological instability favoring spore release and suspension (Sadyś et al., 2015).

Solar radiation has a dual effect: High levels tend to increase concentrations of *Cladosporium* and *Ganoderma*, while in genera such as *Leptosphaeria* they decrease on very sunny days (Grinn-Gofroń et al., 2020; Ščevková et al., 2019). Beyond climate, certain spore traits favor their persistence in the air: A resistant cell wall gives them tolerance to dryness, and dark pigments such as melanin protect them from ultraviolet radiation and oxidative damage (Hopke et al., 2018; Suthar et al., 2023). Together, these factors help explain why pigmented dry spores tend to predominate in warm, dry, and windy environments, in addition to the effect of weather conditions.

In summary, meteorological factors such as temperature, humidity, wind, pressure, and radiation interact synergistically, modulating the daily and seasonal dynamics of the atmospheric mycobiota, favoring dominant genera and limiting those most sensitive to extreme conditions (Zhai et al., 2018).

## 3.5 Clinical thresholds

In order to diagnose allergic diseases, it is essential to identify the concentration of allergens in the

atmosphere and to establish the relationship between exposure to these concentrations and the onset of symptoms. This enables the definition of appropriate clinical threshold values (Ghosh et al., 2022). Various governmental agencies and private organizations have proposed exposure limits for fungal spores; however, many of these thresholds are expressed in colony-forming units (CFU), which are based on viable sampling techniques that present significant limitations. This is primarily because, although some bioaerosols are viable, they are not always cultivable and may fail to form colonies under standard laboratory conditions, resulting in underestimated concentrations (Becher et al., 2000; Chi & Li, 2007; de Aquino Neto & de Góes Siqueira., 2000; Jo & Seo, 2005; Kim et al., 2018; Pegas et al., 2010; Wainwright et al., 2004; Yang & Heinsohn, 2007).

Other studies have established threshold values based on non-viable sampling methods; however, these efforts are generally limited to the most extensively studied fungal genera and show significant variability across countries. For instance, the proposed threshold for *Alternaria* is 50 spores/m<sup>3</sup> in the United Kingdom, 80 spores/m<sup>3</sup> in Poland, and 100 spores/m<sup>3</sup> in Finland (Frankland & Davies, 1965; Ranta & Pessi, 2006; Rapiejko et al., 2007). For *Cladosporium*, the clinical threshold is 3,000 spores/m<sup>3</sup> in the United Kingdom and Croatia, 2800 in Poland, and 4000 in Finland (Frankland & Davies, 1965; Peternel et al., 2004; Ranta & Pessi, 2006; Rapiejko et al., 2007). Conversely, studies conducted in Germany on *Aspergillus* spp. suggest that allergic symptoms may emerge at concentrations as low as 50 spores/m<sup>3</sup> (Holmberg, 1987).

Given the heterogeneity of clinical thresholds reported across countries, one of the most useful epidemiological indicators identified in the reviewed literature is the number of days per season that exceed the clinical threshold. This parameter not only reflects the duration of exposure risk for sensitized individuals but also provides a more direct link between atmospheric concentrations and potential health outcomes (Ortega-Rosas et al., 2025; Vélez-Pereira et al., 2023).

Based on the articles analyzed in this review, consistent data on days above threshold were found mainly for *Alternaria* and *Cladosporium*. For *Alternaria* (threshold  $\geq 100$  spores/m<sup>3</sup>; 25 site-seasons analyzed), the median number of days above threshold

was 37 (IQR 28–58), with a range of 4–125 and a mean of 47. Notably, 80% of sites exceeded 15 days, 72% exceeded 30 days, while 20 and 16% surpassed 60 and 90 days, respectively. At the continental level, the median exposure was highest in Africa (89 days), followed by Europe (42.5 days) and Asia (28 days), indicating that populations in semi-arid and Mediterranean climates face the longest risk windows.

For *Cladosporium* (threshold  $\geq 3000$  spores/m<sup>3</sup>; 17 site-seasons), the median was 65 days (IQR 40–90), with a range of 12–147 and a mean of 64.4. Here, 88.2% of sites had  $\geq 15$  days, 76.5%  $\geq 30$  days, and 64.7%  $\geq 60$  days, while nearly 30% experienced  $\geq 90$  days above threshold. The highest values were reported in Asia (median 95 days) and Europe (median 64 days), with more moderate exposure in Africa (22 days). For *Aspergillus/Penicillium*, data availability was limited ( $n=1$ , 2 days above threshold), underscoring the need for further epidemiological studies before meaningful comparisons can be made. Taken together, these findings highlight that *Alternaria* and *Cladosporium* can sustain extended seasonal exposures above clinical thresholds, often for several consecutive weeks, with significant regional variability.

### 3.6 Relationship with epidemiological studies

Numerous researchers have postulated that the health implications associated with airborne fungal spores are contingent on three primary factors: (a) the fungal genera present in the atmosphere, (b) their allergenic potential, and (c) their environmental concentration (Ghosh et al., 2022; Roponen et al., 2002). While these three factors are critical for estimating health risks, most studies have addressed only one or, at most, a combination of two, without integrating all three factors simultaneously.

This tendency is exemplified in the present systematic review, which revealed that a mere 13% of the analyzed studies correlated fungal genera and airborne spore concentrations with epidemiological data. The evaluated populations in these studies were primarily composed of patients treated at healthcare facilities for respiratory conditions, including coughing, recurrent colds, dyspnea, sneezing, wheezing, asthma, and allergic rhinitis. A notable aspect of the analysis is the absence of age

stratification in 8 studies, with 5 of them focusing exclusively on pediatric and adolescent populations.

To assess the relationship between respiratory diseases and airborne spore concentrations, six studies applied skin prick tests using fungal allergen extracts and compared positive results with bioaerosol counts (Abbas et al., 2012; Al-Ahmad et al., 2019; Chakraborty et al., 2014; Dey et al., 2019; Katotomichelakis et al., 2016; Kilic et al., 2020). Three studies employed statistical correlation methods to evaluate the association between the number of respiratory disease cases and allergenic spore concentrations (Batra et al., 2022; Chakrabarti et al., 2012; Ortega Rosas et al., 2020). Two additional studies employed respiratory health questionnaires to assess clinical conditions and subsequently compared those results with aerobiological sampling data (Al-Nesf et al., 2022; Chen et al., 2011). However, only one study directly compared daily spore concentrations with clinical threshold values reported in the literature (Weryszko-Chmielewska et al., 2018). The collective findings of these studies indicate a clear relationship between the concentration of airborne fungal spores and the onset of respiratory symptoms in sensitized individuals.

Despite the pervasive recognition of the detrimental health implications associated with fungal spores, a comprehensive, universally accepted dose–response relationship that delineates acceptable exposure limits remains elusive. This dearth of knowledge stems from three interrelated factors. Firstly, there is an absence of consistent dose–response data. Secondly, the availability of real-time bioaerosol identification and quantification is insufficient. Thirdly, methodological variability among existing studies hinders cross-comparability. Consequently, there is an imperative for the development of robust longitudinal research conducted across multiple environments and geographic regions, employing standardized and validated sampling methodologies. Such studies should not only identify and quantify airborne fungal taxa but also correlate these findings with clinical indicators of respiratory health. It is only through this comprehensive approach that we can generate applicable scientific evidence that will directly benefit sensitized populations and contribute to improving their quality of life.

## 4 Conclusion

Despite the ubiquity of fungal bioaerosols, the extant evidence is concentrated in a limited number of contexts. Specifically, outdoor volumetric sampling was carried out in 30 countries, mostly with 1–2 year campaigns. The geographical and temporal coverage of the data is restricted, which limits global inference and the capture of interannual variability. This results in notable gaps in regions such as Africa and Oceania, as well as in tropical and semi-arid climates. In order to enhance existing knowledge and mitigate regional biases, there is a necessity for the establishment of coordinated observation networks and the implementation of extended time series. These measures are instrumental in characterizing regional patterns and trends with greater resolution.

The clinical link is the primary factor hindering the attainment of accurate results in the studies conducted. A mere 13% of the research has established a correlation between concentrations and genders with epidemiological indicators, such as skin tests, medical consultations, or hospitalizations, as well as questionnaires. The issue of scarcity, when considered in conjunction with the heterogeneity of clinical thresholds, poses a significant challenge in determining applicable dose–response relationships and comparing exposure thresholds between regions.

The results of the study identify prolonged exposure intervals for genera of high health relevance. *Alternaria* ( $\geq 100$  spores/m<sup>3</sup>) demonstrated a median of 37 days across 25 site-seasons, while *Cladosporium* ( $\geq 3000$  spores/m<sup>3</sup>) exhibited a median of 65 days in 17 site-seasons, exhibiting significant regional variability. This evidence thus provides a scientific basis for the implementation of specific seasonal alerts and the prioritization of both genera in surveillance. Conversely, the observed taxonomic landscape (Ascomycota 82% and Basidiomycota 18%) provides a framework for the standardization of allergen panels and the allocation of monitoring resources.

In summary, the current evidence base facilitates progress in surveillance; however, further research with an epidemiological focus is necessary to translate this into clinical and public health decisions. This should include longitudinal and multicenter studies that integrate clinical and environmental variables

from their design, the adoption of comparable metrics explicitly linked to health outcomes, geographical expansion to underrepresented regions, and more extensive campaigns that capture interannual variability. It is only in this manner that aerobiological monitoring will be capable of providing support for the formulation of preventive recommendations, the generation of seasonal alerts, and the establishment of a prioritization of allergens based on the actual risk to the population.

**Author contributions** All authors contributed to the conception and design of the study. The literature search, data analysis, and writing were carried out by Dámaris A. Jiménez-Uribe. Rosa Acevedo-Barrios, Carolina Rubiano-Labrador, and Paloma Cariñanos critically reviewed the paper and commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

**Funding** Open Access funding provided by Colombia Consortium. This work was supported by Department of Science, Technology and Innovation-COLCIENCIAS (Colombia) through the doctoral fellowship to D.A. J.-U.

**Data Availability** No datasets were generated or analyzed during the current study.

#### Declarations

**Conflicts of interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

#### References

- Abbas, S., Katelaris, C. H., Singh, A. B., Raza, S. M., Khan, M. A., Rashid, M., Abbas, M., & Ismail, M. (2012). World Allergy Organization study on aerobiology for creating first pollen and mold calendar with clinical significance in Islamabad, Pakistan; A project of World Allergy Organization and Pakistan Allergy, Asthma & Clinical Immunology Centre of Islamabad. *World Allergy Organization Journal*, 5(9), Article 9. <https://doi.org/10.1097/WOX.0b013e31826421c8>
- Abu-Dieyeh, M. H., & Barham, R. (2014). Concentrations and dynamics of fungal spore populations in the air of Zarqa, Jordan, using the volumetric method. *Grana*, 53(2), Article 2. <https://doi.org/10.1080/00173134.2014.896413>
- Aira, M.-J., Rodríguez-Rajo, F.-J., Fernández-González, M., Seijo, C., Elvira-Rendueles, B., Abreu, I., Gutiérrez-Bustillo, M., Pérez-Sánchez, E., Oliveira, M., Recio, M., Tormo, R., & Morales, J. (2013). Spatial and temporal distribution of *Alternaria* spores in the Iberian Peninsula atmosphere, and meteorological relationships: 1993–2009. *International Journal of Biometeorology*, 57(2), Article 2. <https://doi.org/10.1007/s00484-012-0550-x>
- Akgül, H., Yılmazkaya, D., Akata, I., Tosunoğlu, A., & Bıçakçı, A. (2016). Determination of airborne fungal spores of Gaziantep (SE Turkey). *Aerobiologia*, 32(3), Article 3. <https://doi.org/10.1007/s10453-015-9417-z>
- Al-Ahmad, M., Jusufovic, E., Arifhodzic, N., Rodriguez, T., & Nurkic, J. (2019). Association of molds and meteorological parameters to frequency of severe asthma exacerbation. *Allergy, Asthma & Clinical Immunology*, 15(1), Article 1. <https://doi.org/10.1186/s13223-019-0323-8>
- Almaguer, M., Rojas-Flores, T. I., Rodríguez-Rajo, F. J., & Aira, M.-J. (2014). Airborne basidiospores of *Coprinus* and *Ganoderma* in a Caribbean region. *Aerobiologia*, 30(2), 197–204. <https://doi.org/10.1007/s10453-013-9318-y>
- Almaguer-Chávez, M., Aira, M., Rojas, T.-I., Fernández-González, M., & Rodríguez-Rajo, F.-J. (2018). New findings of airborne fungal spores in the atmosphere of Havana, Cuba, using aerobiological non-viable methodology. *Annals of Agricultural and Environmental Medicine*, 25(2), Article 2. <https://doi.org/10.26444/aaem/89738>
- Al-Nesf, M. A., Gharbi, D., Mobayed, H. M., Mohammed Ali, R., Dason, B. R., Adeli, M., Tuffaha, A., Sattar, H. A., & Trigo, MdelM. (2022). The correlation between middle schoolchildren allergic symptoms and airborne particle season: A cross-sectional study. *Medicine*, 101(17), Article 17. <https://doi.org/10.1097/MD.00000000000029210>
- Amado, M. C., Portnoy, J. M., & Barnes, C. (2014). Fungal cross-allergenicity in specific Ige testing. *Journal of Allergy and Clinical Immunology*, 133(2, Supplement), Article AB92. <https://doi.org/10.1016/j.jaci.2013.12.344>
- Anees-Hill, S., Douglas, P., Pashley, C. H., Hansell, A., & Marczylo, E. L. (2021). A systematic review of outdoor airborne fungal spore seasonality across Europe and the implications for health. *Science of The Total Environment*, 151716. <https://doi.org/10.1016/j.scitotenv.2021.151716>
- Antón, S. F., de la Cruz, D. R., Sánchez, J. S., & Sánchez Reyes, E. (2019). Analysis of the airborne fungal spores present in the atmosphere of Salamanca (MW Spain): A preliminary survey. *Aerobiologia*, 35(3), Article 3. <https://doi.org/10.1007/s10453-019-09569-z>
- Arbes, S. J., Gergen, P. J., Elliott, L., & Zeldin, D. C. (2005). Prevalences of positive skin test responses to 10 common allergens in the US population: Results from the Third National Health and Nutrition Examination Survey. *Journal of Allergy and Clinical Immunology*, 116(2), 377–383. <https://doi.org/10.1016/j.jaci.2005.05.017>

- Bardei, F., Bouziane, H., Trigo, MdelM., Ajouray, N., El Haskouri, F., & Kadiri, M. (2017). Atmospheric concentrations and intradiurnal pattern of *Alternaria* and *Cladosporium* conidia in Tétouan (NW of Morocco). *Aerobiologia*. <https://doi.org/10.1007/s10453-016-9465-z>
- Batra, M., Vicendese, D., Newbiggin, E., Lambert, Ka., Tang, M., Abramson, M. J., Dharmage, S. C., & Erbas, B. (2022). The association between outdoor allergens – pollen, fungal spore season and high asthma admission days in children and adolescents. *International Journal of Environmental Health Research*. <https://doi.org/10.1080/09603123.2021.1885633>
- Baxi, S. N., Sheehan, W. J., Sordillo, J. E., Muilenberg, M. L., Rogers, C. A., Gaffin, J. M., Permaul, P., Lai, P. S., Louissias, M., Petty, C. R., Fu, C., Gold, D. R., & Phipatanakul, W. (2019). Association between fungal spore exposure in inner-city schools and asthma morbidity. *Annals of Allergy, Asthma & Immunology*, 122(6), 610–615.e1. <https://doi.org/10.1016/j.anai.2019.03.011>
- Becher, R., Hongslo, J. K., & Dybing, E. (2000). Guidelines for indoor air in Norway - a practical approach. *Pollution Atmosphérique Climat Santé Société*, 166, 245–246. <https://doi.org/10.4267/pollution-atmosphérique.3772>
- Bertolini, V., Gandolfi, I., Ambrosini, R., Bestetti, G., Innocente, E., Rampazzo, G., & Franzetti, A. (2013). Temporal variability and effect of environmental variables on airborne bacterial communities in an urban area of Northern Italy. *Applied Microbiology and Biotechnology*, 97(14), 6561–6570. <https://doi.org/10.1007/s00253-012-4450-0>
- Bisen, P. S., Debnath, M., & Prasad, G. B. (2012). *Microbes: Concepts and Applications*. John Wiley & Sons.
- Bisht, V., Singh, B. P., Arora, N., Gaur, S. N., & Sridhara, S. (2002). Antigenic and allergenic cross-reactivity of *Epicoccum nigrum* with other fungi. *Annals of Allergy, Asthma & Immunology*, 89(3), 285–291. [https://doi.org/10.1016/S1081-1206\(10\)61956-4](https://doi.org/10.1016/S1081-1206(10)61956-4)
- Blais-Lecours, P., Perrott, P., & Duchaine, C. (2015). Non-culturable bioaerosols in indoor settings: Impact on health and molecular approaches for detection. *Atmospheric Environment*, 110, 45–53. <https://doi.org/10.1016/j.atmosenv.2015.03.039>
- Caillaud, D., Keirsbulck, M., Leger, C., Leynaert, B., Outdoor Mould ANSES Working Group. (2022). Outdoor mold and respiratory health: State of science of epidemiological studies. *The Journal of Allergy and Clinical Immunology. In Practice*, 10(3), 768–784.e3. <https://doi.org/10.1016/j.jaip.2021.09.042>
- Cao, C., Jiang, W., Wang, B., Fang, J., Lang, J., Tian, G., Jiang, J., & Zhu, T. F. (2014). Inhalable microorganisms in Beijing's PM2.5 and PM10 pollutants during a severe smog event. *Environmental Science & Technology*. <https://doi.org/10.1021/es4048472>
- Carlile, M. J., Watkinson, S. C., & Gooday, G. W. (2001). *The Fungi*. Gulf Professional Publishing.
- Castro, C. (2009). *Evaluación aeromicológica en la calidad del aire de la zona aledaña al relleno sanitario Portillo Grande en el otoño del 2009*. UNALM.
- Cecchi, L., D'Amato, G., Ayres, J. G., Galan, C., Forastiere, F., Forsberg, B., Gerritsen, J., Nunes, C., Behrendt, H., Akdis, C., Dahl, R., & Annesi-Maesano, I. (2010). Projections of the effects of climate change on allergic asthma: The contribution of aerobiology. *Allergy*, 65(9), 1073–1081. <https://doi.org/10.1111/j.1398-9995.2010.02423.x>
- Cervantes-De La Torre, K., Guillen-Grima, F., Aguinaga-Ontoso, I., & Mendoza-Mendoza, A. (2018). Presencia de alergias en menores por consumo temprano de alimentos en Barranquilla, Colombia. *Revista De Salud Pública*, 20, 177–181. <https://doi.org/10.15446/rsap.v20n2.62997>
- Chakrabarti, H. S., Das, S., & Gupta-Bhattacharya, S. (2012). Outdoor airborne fungal spora load in a suburb of Kolkata, India: Its variation, meteorological determinants and health impact. *International Journal of Environmental Health Research*. <https://doi.org/10.1080/09603123.2011.588323>
- Chakraborty, P., Chakraborty, A., Ghosh, D., Mandal, J., Biswas, S., Mukhopadhyay, U. K., & Gupta Bhattacharya, S. (2014). Effect of airborne *Alternaria* conidia, ozone exposure, PM10 and weather on emergency visits for asthma in school-age children in Kolkata city, India. *Aerobiologia*. <https://doi.org/10.1007/s10453-013-9312-4>
- Chane-Si-Ken, N., Allou, N., Bénétteau, S., Verduyn, M., Gazaille, V., Raheison, C., & André, M. (2022). Asthma exacerbations in Reunion Island: Environmental factors. *Respiratory Medicine and Research*, 81, Article 100779. <https://doi.org/10.1016/j.resmer.2020.100779>
- Charalampopoulos, A., Damialis, A., & Vokou, D. (2022). Spatiotemporal assessment of aeromycoflora under differing urban green space, sampling height, and meteorological regimes: The atmospheric fungiscape of Thessaloniki, Greece. *International Journal of Biometeorology*. <https://doi.org/10.1007/s00484-022-02247-9>
- Chen, B.-Y., Chao, H. J., Chan, C.-C., Lee, C.-T., Wu, H.-P., Cheng, T.-J., Chen, C.-C., & Guo, Y. L. (2011). Effects of ambient particulate matter and fungal spores on lung function in schoolchildren. *Pediatrics*. <https://doi.org/10.1542/peds.2010-1038>
- Chew, F. T., Lim, S. H., Shang, H. S., Siti Dahlia, M. D., Goh, D. Y. T., Lee, B. W., Tan, H. T. W., & Tan, T. K. (2000). Evaluation of the allergenicity of tropical pollen and airborne spores in Singapore. *Allergy*, 55(4), 340–347. <https://doi.org/10.1034/j.1398-9995.2000.00308.x>
- Chi, M.-C., & Li, C.-S. (2007). Fluorochrome in monitoring atmospheric bioaerosols and correlations with meteorological factors and air pollutants. *Aerosol Science and Technology*, 41(7), 672–678. <https://doi.org/10.1080/02786820701383181>
- Cid-Martínez, M. A., Gallardo-Velázquez, K., Rosique-Gil, J. E., Domínguez-Rodríguez, V. I., & Focil-Monterrubio, R. L. (2019). CUANTIFICACIÓN DE LAS ESPO-RAS DE <EM>GANODERMA</EM> DEL AIRE EXTERIOR EN LA CIUDAD DE VILLAHERMOSA, TABASCO, MÉXICO. *Revista Internacional de Contaminación Ambiental*, 35(2), Article 2. <https://doi.org/10.20937/RICA.2019.35.02.20>
- Craig, R. L., & Levetin, E. (2000). Multi-year study of *Ganoderma* aerobiology. *Aerobiologia*, 16(1), 75–81. <https://doi.org/10.1023/A:1007682600175>
- Cramer, R. A., Rivera, A., & Hohl, T. M. (2011). Immune responses against *Aspergillus fumigatus*: What have we

- learned? *Current Opinion in Infectious Diseases*, 24(4), 315–322. <https://doi.org/10.1097/QCO.0b013e328348b159>
- Damialis, A., Vokou, D., Gioulekas, D., & Halley, J. M. (2015). Long-term trends in airborne fungal-spore concentrations: A comparison with pollen. *Fungal Ecology*, 13, 150–156. <https://doi.org/10.1016/j.funeco.2014.09.010>
- Das, S., & Gupta-Bhattacharya, S. (2012). Monitoring and assessment of airborne fungi in Kolkata, India, by viable and non-viable air sampling methods. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-011-2294-1>
- de Aquino Neto, F. R., & de Góes Siqueira, L. F. (2000). Guidelines for indoor air quality in offices in Brazil. *Proceedings of Healthy Buildings*, 4, 549–554.
- de Ana, S. G., Rodríguez, J., & T., & Ramírez, E. A. (2006). Seasonal Distribution of Alternaria, Aspergillus, Cladosporium and Penicillium Species Isolated in Homes of Fungal Allergic Patients. *J Investig Allergol Clin Immunol*, 16, 357.
- De Linares, C., Navarro, D., Puigdemunt, R., & Belmonte, J. (2023). *Aspergillus* conidia and allergens in outdoor environment: A health hazard? *Journal of Fungi*, 9(6), Article 6. <https://doi.org/10.3390/jof9060624>
- Deacon, J. W. (2005). *Fungal Biology*. John Wiley & Sons.
- Després, V. R., Huffman, J. A., Burrows, S. M., Hoose, C., Safatov, A. S., Buryak, G., Fröhlich-Nowoisky, J., Elbert, W., Andreae, M. O., Pöschl, U., & Jaenicke, R. (2012). Primary biological aerosol particles in the atmosphere: A review. *Tellus b: Chemical and Physical Meteorology*. <https://doi.org/10.3402/tellusb.v64i0.15598>
- Dey, D., Ghosal, K., & Bhattacharya, S. G. (2019). Aerial fungal spectrum of Kolkata, India, along with their allergenic impact on the public health: A quantitative and qualitative evaluation. *Aerobiologia*. <https://doi.org/10.1007/s10453-018-9534-6>
- Díaz Vázquez, L., Almaguer Chávez, M., Fernández-González, M., & Sánchez Espinosa, K. C. (2024). New airborne fungal spores in the atmosphere of Havana, Cuba. *Aerobiologia*. <https://doi.org/10.1007/s10453-024-09816-y>
- Egan, C., Li, D.-W., & Klironomos, J. (2014). Detection of arbuscular mycorrhizal fungal spores in the air across different biomes and ecoregions. *Fungal Ecology*, 12, 26–31. <https://doi.org/10.1016/j.funeco.2014.06.004>
- Elbert, W., Taylor, P.E., Andreae, M.O., & Pöschl, U. (2007). Contribution of fungi to primary biogenic aerosols in the atmosphere: wet and dry discharged spores carbohydrates and inorganic ions. *Atmospheric Chemistry and Physics*, 7(17), 4569–4588. <https://doi.org/10.5194/acp-7-4569-2007>
- Elvira-Rendueles, B., Moreno, J., Garcia-Sanchez, A., Vergara, N., Martinez-Garcia, M. J., & Moreno-Grau, S. (2013). Air-spore in Cartagena, Spain: Viable and non-viable sampling methods. *Annals of Agricultural and Environmental Medicine*, 20(4). <http://agro.icm.edu.pl/agro/element/bwmeta1.element.agro-ddea1f11-b6ed-4c18-8c44-0da5afa5c78a>
- Emygdio, A. P. M., Degobbi, C., Gonçalves, F. L. T., & Andrade, MdeF. (2018). One year of temporal characterization of fungal spore concentration in São Paulo metropolitan area, Brazil. *Journal of Aerosol Science*, 115, 121–132. <https://doi.org/10.1016/j.jaerosci.2017.07.003>
- Espinosa, K. C. S., Chávez, M. A., Ramírez, I. P., Flores, T. I. R., & Rodríguez, M. J. A. (2019). DIVERSIDAD FÚNGICA EN LA ATMÓSFERA DE LA HABANA (CUBA) DURANTE TRES PERÍODOS POCO LLUVIOSOS. *Revista Internacional De Contaminación Ambiental*. <https://doi.org/10.20937/RICA.2019.35.01.10>
- Fernández-Rodríguez, S., Tormo-Molina, R., Maya-Manzano, J. M., Silva-Palacios, I., & Gonzalo-Garijo, Á. (2014). Outdoor airborne fungi captured by viable and non-viable methods. *Fungal Ecology*, 7, 16–26. <https://doi.org/10.1016/j.funeco.2013.11.004>
- Fernández-Rodríguez, S., Tormo-Molina, R., Lemonis, N., Clot, B., O'Connor, D. J., & Sodeau, J. R. (2018). Comparison of fungal spores concentrations measured with wideband integrated bioaerosol sensor and Hirst methodology. *Atmospheric Environment*, 175, 1–14. <https://doi.org/10.1016/j.atmosenv.2017.11.038>
- Filali Ben Sidel, F., Bouziane, H., del Mar Trigo, M., El Haskouri, F., Bardei, F., Redouane, A., Kadiri, M., Riadi, H., & Kazzaz, M. (2015). Airborne fungal spores of Alternaria, meteorological parameters and predicting variables. *International Journal of Biometeorology*. <https://doi.org/10.1007/s00484-014-0845-1>
- Frankland, A. W., & Davies, R. R. (1965). Allergie aux spores de moisissures en Angleterre. *Le Poumon Et Le Cœur*, 21, 11–23.
- Gabriel, M. F., Postigo, I., Tomaz, C. T., & Martínez, J. (2016). *Alternaria alternata* allergens: Markers of exposure, phylogeny and risk of fungi-induced respiratory allergy. *Environment International*, 89, 71–80. <https://doi.org/10.1016/j.envint.2016.01.003>
- Galán, C., Cariñanos, P., Alcázar, P., & Domínguez, E. (2007). *Manual de Calidad y Gestión de la Red Española de Aerobiología*. Servicio De Publicaciones De La Universidad De Córdoba.
- Gharbi, D., Mobayed, H. M., Ali, R. M., Tuffaha, A., Dason, B. R., Ibrahim, T., Adeli, M., Sattar, H. A., Trigo, MdelM., & Al-Nesf, M. A. (2022). First volumetric records of airborne Cladosporium and Alternaria spores in the atmosphere of Al Khor (northern Qatar): A preliminary survey. *Aerobiologia*. <https://doi.org/10.1007/s10453-022-09746-7>
- Ghosh, B., Das, A., & Lal, H. (2022). Bioaerosol and Its Impact on Human Health. In S. Sonwani & A. Shukla (Eds.), *Airborne Particulate Matter: Source, Chemistry and Health* (pp. 167–193). Springer Nature. [https://doi.org/10.1007/978-981-16-5387-2\\_8](https://doi.org/10.1007/978-981-16-5387-2_8)
- Goh, T.-K., Hyde, K. D., & Lee, D. K. L. (1998). Generic distinction in the Helminthosporium-complex based on restriction analysis of the nuclear ribosomal RNA gene. *Fungal Diversity*, 1, 85–107.
- Grinn-Gofroń, A. (2008). The variation in spore concentrations of selected fungal taxa associated with weather conditions in Szczecin, Poland, 2004–2006. *Grana*, 47(2), 139–146. <https://doi.org/10.1080/00173130802091385>
- Grinn-Gofroń, A., & Strzelczak, A. (2011). The effects of meteorological factors on the occurrence of Ganoderma

- sp. spores in the air. *International Journal of Biometeorology*. <https://doi.org/10.1007/s00484-010-0329-x>
- Grinn-Gofroń, A., Çeter, T., Pinar, N. M., Bosiacka, B., Çeter, S., Keçeli, T., Myśliwy, M., Şahin, A. A., & Bogawski, P. (2020). Airborne fungal spore load and season timing in the Central and Eastern Black Sea region of Turkey explained by climate conditions and land use. *Agricultural and Forest Meteorology*, 295, Article 108191. <https://doi.org/10.1016/j.agrformet.2020.108191>
- Hasnain, S. M., Akhter, T., & Waqar, M. A. (2012). Airborne and allergenic fungal spores of the Karachi environment and their correlation with meteorological factors. *Journal of Environmental Monitoring*. <https://doi.org/10.1039/C2EM10545D>
- Hawksworth, D. L., & Lücking, R. (2017). Fungal diversity revisited: 2.2 to 3.8 million species. *Microbiology Spectrum*. <https://doi.org/10.1128/microbiolspec.funk-0052-2016>
- Hernández Trejo, F., Muñoz Rodríguez, A.F., Tormo Molina, R. et al. (2012). Airborne ascospores in Mérida (SW Spain) and the effect of rain and other meteorological parameters on their concentration. *Aerobiologia*, 28, 13–26. <https://doi.org/10.1007/s10453-011-9207-1>
- Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology*. <https://doi.org/10.1111/j.1744-7348.1952.tb00904.x>
- Holmberg, K. (1987). Indoor mold exposure to health effects. *Indoor Air: Volatile Organic Compounds, Combustion Gases, Particles and Fibers, Microbiological Agents.*, 1, 637–642.
- Hopke, A., Brown, A. J. P., Hall, R. A., & Wheeler, R. T. (2018). Dynamic fungal cell wall architecture in stress adaptation and immune evasion. *Trends in Microbiology*, 26(4), 284–295. <https://doi.org/10.1016/j.tim.2018.01.007>
- Huertas, M. E., Acevedo-Barrios, R. L., Rodríguez, M., Gaviria, J., Arana, R., & Arciniegas, C. (2018). Identification and quantification of bioaerosols in a tropical coastal region: Cartagena de Indias, Colombia. *Aerosol Science and Engineering*. <https://doi.org/10.1007/s41810-018-0037-1>
- Ianovici, N. (2016). Atmospheric concentrations of selected allergenic fungal spores in relation to some meteorological factors, in Timișoara (Romania). *Aerobiologia*. <https://doi.org/10.1007/s10453-016-9427-5>
- Janssen, R. H. H., Heald, C. L., Steiner, A. L., Perring, A. E., Huffman, J. A., Robinson, E. S., Twohy, C. H., & Ziemba, L. D. (2021). Drivers of the fungal spore bioaerosol budget: Observational analysis and global modeling. *Atmospheric Chemistry and Physics*, 21(6), 4381–4401. <https://doi.org/10.5194/acp-21-4381-2021>
- Jo, W.-K., & Seo, Y.-J. (2005). Indoor and outdoor bioaerosol levels at recreation facilities, elementary schools, and homes. *Chemosphere*, 61(11), 1570–1579. <https://doi.org/10.1016/j.chemosphere.2005.04.103>
- Kallawicha, K., Chen, Y.-C., Chao, H. J., Shen, W.-C., Chen, B.-Y., Chuan, Y.-C., & Guo, Y. L. (2017). Ambient fungal spore concentration in a subtropical metropolis: Temporal distributions and meteorological determinants. *Aerosol and Air Quality Research*. <https://doi.org/10.4209/aaqr.2016.10.0450>
- Kasprzyk, I. (2008). Aeromycology—Main research fields of interest during the last 25 years. *Annals of Agricultural and Environmental Medicine: AAEM*, 15(1), 1–7.
- Kasprzyk, I., & Worek, M. (2006). Airborne fungal spores in urban and rural environments in Poland. *Aerobiologia*. <https://doi.org/10.1007/s10453-006-9029-8>
- Katotomichelakis, M., Nikolaidis, C., Makris, M., Proimos, E., Aggelides, X., Constantinidis, T. C., Papadakis, C. E., & Danielides, V. (2016). *Alternaria* and *Cladosporium* calendar of western thrace: Relationship with allergic rhinitis symptoms. *The Laryngoscope*. <https://doi.org/10.1002/lary.25594>
- Kilic, M., Altunoglu, M. K., Akdogan, G. E., Akpınar, S., Taskın, E., & Erkal, A. H. (2020). Airborne fungal spore relationships with meteorological parameters and skin prick test results in Elazığ, Turkey. *Journal of Environmental Health Science and Engineering*. <https://doi.org/10.1007/s40201-020-00545-1>
- Kim, K.-H., Kabir, E., & Jahan, S. A. (2018). Airborne bioaerosols and their impact on human health. *Journal of Environmental Sciences*, 67, 23–35. <https://doi.org/10.1016/j.jes.2017.08.027>
- King, E. A., Murphy, E., & Rice, H. J. (2011). Evaluating the impact on noise levels of a ban on private cars in Dublin city centre, Ireland. *Transportation Research Part d: Transport and Environment*. <https://doi.org/10.1016/j.trd.2011.05.002>
- Kousha, M., Tadi, R., & Soubani, A. O. (2011). Pulmonary aspergillosis: A clinical review. *European Respiratory Review*, 20(121), 156–174. <https://doi.org/10.1183/09059180.00001011>
- Lacey, M., & West, J. (2006). *The air spora: A manual for catching and identifying airborne biological particles*. Springer.
- Lehmann, S., Sprünken, A., Wagner, N., Tenbrock, K., & Ott, H. (2017). Clinical relevance of IgE-mediated sensitization against the mould *Alternaria alternata* in children with asthma. *Therapeutic advances in respiratory disease*. <https://doi.org/10.1177/1753465816680786>
- Levetin, E., Horner, W. E., Scott, J. A., Barnes, C., Baxi, S., Chew, G. L., Grimes, C., Horner, W. E., Kennedy, K., Larenas-Linnemann, D., Levetin, E., Miller, J. D., Phipatanakul, W., Portnoy, J. M., Scott, J. A., & Williams, P. B. (2016). Taxonomy of allergenic fungi. *The Journal of Allergy and Clinical Immunology: In Practice*. <https://doi.org/10.1016/j.jaip.2015.10.012>
- Lin, W.-R., Chen, Y.-H., Lee, M.-F., Hsu, L.-Y., Tien, C.-J., Shih, F.-M., Hsiao, S.-C., & Wang, P.-H. (2016). Does spore count matter in fungal allergy?: The role of allergenic fungal species. *Allergy, Asthma & Immunology Research*, 8(5), 404–411. <https://doi.org/10.4168/aa.2016.8.5.404>
- Liu, D. (2024). Classification of medically important fungi. In Y.-W. Tang, M. Y. Hindiyeh, D. Liu, A. Sails, P. Spearman, & J.-R. Zhang (Eds.), *Molecular Medical Microbiology* (3rd ed., pp. 2763–2777). Academic Press. <https://doi.org/10.1016/B978-0-12-818619-0.00034-4>
- Lundbäck, B., Backman, H., Lötvall, J., & Rönmark, E. (2016). Is asthma prevalence still increasing? *Expert Review of Respiratory Medicine*, 10(1), 39–51. <https://doi.org/10.1586/17476348.2016.1114417>

- Mantoani, M. C., Sapucci, C. R., Guerra, L. C. C., Andrade, M. F., Dias, M. A. F. S., Dias, P. L. S., Albrecht, R. I., Silva, E. P., Rodrigues, F., Araujo, G. G., Galante, D., Silva, D. M. C., Martins, J. A., Martins, L. D., Boschilia, S. M., Phillips, V. T. J., Carotenuto, F., Šantl-Temkiv, T., Morris, C. E., & Gonçalves, F. L. T. (2025). Airborne fungal spore concentrations double but diversity decreases with warmer winter temperatures in the Brazilian Atlantic Forest biodiversity hotspot. *The Microbe*, 7, Article 100300. <https://doi.org/10.1016/j.microb.2025.100300>
- Mari, A., Schneider, P., Wally, V., Breitenbach, M., & Simon-Nobbe, B. (2003). Sensitization to fungi: Epidemiology, comparative skin tests, and IgE reactivity of fungal extracts. *Clinical & Experimental Allergy*, 33(10), 1429–1438. <https://doi.org/10.1046/j.1365-2222.2003.01783.x>
- Menezes, E. A., Gambale, W., Macedo, M. S., Castro, F., Paula, C. R., & Croce, J. (1998). Characterization of allergenic fractions from *Drechslera monoceras*. *Journal of Investigational Allergology and Clinical Immunology*, 8(4), 214–218.
- Millington, W. M., & Corden, J. M. (2005). Long term trends in outdoor Aspergillus/Penicillium spore concentrations in Derby, UK from 1970 to 2003 and a comparative study in 1994 and 1996 with the indoor air of two local houses. *Aerobiologia*, 21(2), 105–113. <https://doi.org/10.1007/s10453-005-4180-1>
- Moral, L., Roig, M., Garde, J., Alós, A., Toral, T., & Fuentes, M. J. (2008). Allergen sensitization in children with asthma and rhinitis: Marked variations related to age and microgeographical factors. *Allergologia Et Immunopathologia*, 36(3), 128–133. [https://doi.org/10.1016/S0301-0546\(08\)72536-9](https://doi.org/10.1016/S0301-0546(08)72536-9)
- Naseer, S., Noor, M. J., & Iftikhar, S. (2024). Airborne pollen and spore monitoring for seasonal trends and dynamic interconnection with meteorological parameters in Rawalpindi city, Pakistan. *Atmospheric Environment*, 336, Article 120755. <https://doi.org/10.1016/j.atmosenv.2024.120755>
- Newson, R., Strachan, D., Corden, J., & Millington, W. (2000). Fungal and other spore counts as predictors of admissions for asthma in the Trent region. *Occupational and Environmental Medicine*, 57(11), 786–792. <https://doi.org/10.1136/oem.57.11.786>
- Nitiu, D. S., & Mallo, A. C. (2011). Seasonal variation of pollen and fungal spores in the atmosphere of Plata city (Argentina). *Boletín De La Sociedad Argentina De Botánica*, 46(3–4), 297–304.
- O’Gorman, C. M., & Fuller, H. T. (2008). Prevalence of culturable airborne spores of selected allergenic and pathogenic fungi in outdoor air. *Atmospheric Environment*. <https://doi.org/10.1016/j.atmosenv.2008.01.009>
- Ogóreck, R., Lejman, A., Pusz, W., Miłuch, A., & Miodyńska, P. (2012). Characteristics and taxonomy of *Cladosporium* fungi. *Mikologia Lekarska*, 19(2), 80–85.
- Oliveira, M., Ribeiro, H., Delgado, J. L., & Abreu, I. (2009). Aeromycological profile of indoor and outdoor environments. *Journal of Environmental Monitoring*. <https://doi.org/10.1039/B820736D>
- Olsen, Y., Skjøth, C. A., Hertel, O., Rasmussen, K., Sigsgaard, T., & Gosewinkel, U. (2020). Airborne *Cladosporium* and *Alternaria* spore concentrations through 26 years in Copenhagen, Denmark. *Aerobiologia*. <https://doi.org/10.1007/s10453-019-09618-7>
- Ortega Rosas, C. I., Calderón-Ezquerro, M. D. C., & Gutiérrez-Ruacho, O. G. (2020). Fungal spores and pollen are correlated with meteorological variables: Effects in human health at Hermosillo, Sonora, Mexico. *International Journal of Environmental Health Research*, 30(6), Article 6. <https://doi.org/10.1080/09603123.2019.1625031>
- Ortega-Rosas, C. I., Medina-Félix, D., Macías-Duarte, A., & Gamez, T. (2025). A six-year airborne fungal spore calendar for a city in the Sonoran Desert, Mexico: Implications for human health. *Journal of Fungi*, 11(3), 183. <https://doi.org/10.3390/jof11030183>
- Pace, L., Boccacci, L., Casilli, M., & Fattorini, S. (2019). Temporal variations in the diversity of airborne fungal spores in a Mediterranean high altitude site. *Atmospheric Environment*, 210, 166–170. <https://doi.org/10.1016/j.atmosenv.2019.04.059>
- Pasanen, A.-L., Rautiala, S., Kasanen, J.-P., Raunio, P., Rantamäki, J., & Kalliokoski, P. (2000). The relationship between measured moisture conditions and fungal concentrations in water-damaged building materials. *Indoor Air*, 10(2), 111–120. <https://doi.org/10.1034/j.1600-0668.2000.010002111.x>
- Pashley, C. H., Fairs, A., Free, R. C., & Wardlaw, A. J. (2012). DNA analysis of outdoor air reveals a high degree of fungal diversity, temporal variability, and genera not seen by spore morphology. *Fungal Biology*, 116(2), 214–224. <https://doi.org/10.1016/j.funbio.2011.11.004>
- Patel, T. Y., Buttner, M., Rivas, D., Cross, C., Bazylinski, D. A., & Seggev, J. (2018). Variation in airborne fungal spore concentrations among five monitoring locations in a desert urban environment. *Environmental Monitoring and Assessment*, 190(11), Article 11. <https://doi.org/10.1007/s10661-018-7008-5>
- Pawankar, R., Canonica, G. W., Holgate, S. T., & Lockey, R. F. (2011). *Libro Blanco sobre Alergia de la WAO*. 26.
- Pegas, P. N., Evtuygina, M. G., Alves, C. A., Nunes, T., Cerqueira, M., Franchi, M., Pio, C., Almeida, S. M., & Freitas, MdoC. (2010). Outdoor/indoor air quality in primary schools in Lisbon: A preliminary study. *Química Nova*, 33, 1145–1149. <https://doi.org/10.1590/S0100-4022010000500027>
- Peternel, R., Culig, J., & Hrga, I. (2004). Atmospheric concentrations of *Cladosporium* spp. and *Alternaria* spp. Spores in Zagreb Croatia and effects of some meteorological factors. *Annals of Agricultural and Environmental Medicine*, 11(2), 303.
- Piontelli, E. (2008). aportes morfotaxonomicos en el genero aspergillus link: claves para las especies ambientales y clinicas mas comunes. *Boletín Micológico*, 28, 49–66.
- Pöhlker, C., Huffman, J. A., & Pöschl, U. (2012). Autofluorescence of atmospheric bioaerosols – fluorescent biomolecules and potential interferences. *Atmospheric Measurement Techniques*, 5(1), 37–71. <https://doi.org/10.5194/amt-5-37-2012>
- Polymenakou, P. N., & Mandalakis, M. (2013). Assessing the short-term variability of bacterial composition in background aerosols of the Eastern Mediterranean during a rapid change of meteorological conditions.

- Aerobiologia*, 29(3), 429–441. <https://doi.org/10.1007/s10453-013-9295-1>
- Pomés, A., Chapman, M. D., & Wünschmann, S. (2016). Indoor allergens and allergic respiratory disease. *Current Allergy and Asthma Reports*, 16(6), Article 43. <https://doi.org/10.1007/s11882-016-0622-9>
- Pongracic, J. A., O'Connor, G. T., Muilenberg, M. L., Vaughn, B., Gold, D. R., Kattan, M., Morgan, W. J., Gruchalla, R. S., Smartt, E., & Mitchell, H. E. (2010). Differential effects of outdoor versus indoor fungal spores on asthma morbidity in inner-city children. *Journal of Allergy and Clinical Immunology*, 125(3), 593–599. <https://doi.org/10.1016/j.jaci.2009.10.036>
- Pyrri, I., & Kapsanaki-Gotsi, E. (2015). Evaluation of the fungal aerosol in Athens, Greece, based on spore analysis. *Aerobiologia*, 31(2), Article 2. <https://doi.org/10.1007/s10453-014-9355-1>
- Rad, H. D., Maleki, H., Goudarzi, G., Assarehzadegan, M.-A., Idani, I., Babaei, A. A., Neisi, A., Jahantab, S., Parishani, M. R., Dinarvand, M., Sorooshian, A., Namjoo, F., & Pour, M. N. (2023). Investigating airborne pollen grains and fungal spores that might be related to thunderstorm asthma attacks. *International Journal of Environmental Research*, 17(2), 28. <https://doi.org/10.1007/s41742-023-00515-z>
- Ranta, H., & Pessi, A. M. (2006). Pollen bulletin summary 2005. *Finnish Pollen Bulletin*, 30, 1–12.
- Raphoz, M., Goldberg, M. S., Garneau, M., Héguay, L., Valois, M.-F., & Guay, F. (2010). Associations between atmospheric concentrations of spores and emergency department visits for asthma among children living in Montreal. *Archives of Environmental & Occupational Health*, 65(4), 201–210. <https://doi.org/10.1080/19338241003730937>
- Rapiejko, P., Stankiewicz, W., Szczygielski, K., & Jurkiewicz, D. (2007). Progowe stężenie pyłku roślin niezbędne do wywołania objawów alergicznych. *Otolaryngologia Polska*, 61(4), 591–594. [https://doi.org/10.1016/S0030-6657\(07\)70491-2](https://doi.org/10.1016/S0030-6657(07)70491-2)
- Reznik, Y. V., Yermishev, O. V., Palamarchuk, O. V., Bobrovska, O. A., & Rodinkova, V. V. (2023). Features of the seasonal dynamics of airborne fungal spore concentrations in Ukraine. *Biosystems Diversity*, 31(1), Article 1. <https://doi.org/10.15421/012308>
- Rivera-Mariani, F. E., & Bolaños-Rosero, B. (2012). Allergenicity of airborne basidiospores and ascospores: Need for further studies. *Aerobiologia*, 28(2), 83–97. <https://doi.org/10.1007/s10453-011-9234-y>
- Rivera-Mariani, F. E., Almaguer, M., Aira, M. J., & Bolaños-Rosero, B. (2020). Comparison of atmospheric fungal spore concentrations between two main cities in the caribbean basin. *Puerto Rico Health Sciences Journal*, 39(3), 235.
- Rizzi-Longo, L., Pizzulin-Sauli, M., & Ganis, P. (2009). Seasonal occurrence of *Alternaria* (1993–2004) and *Epicoccum* (1994–2004) spores in Trieste (NE Italy). *Annals of Agricultural and Environmental Medicine*, 16(1), 63–70.
- Rocha Estrada, A., Alvarado Vázquez, M. A., Gutiérrez Reyes, R., Salcedo Martínez, S. M., & Moreno Limón, S. (2013). Temporary change of spores *Alternaria*, *Cladosporium*, *Coprinus*, *Curvularia* and *Venturia* in air Monterrey metropolitan area, Nuevo Leon, Mexico. *Revista Internacional De Contaminación Ambiental*, 29(2), 155–165.
- Rodríguez-Gomez, C., Ramirez-Romero, C., Cordoba, F., Raga, G. B., Salinas, E., Martinez, L., Rosas, I., Quintana, E. T., Maldonado, L. A., Rosas, D., Amador, T., Alvarez, H., & Ladino, L. A. (2020). Characterization of culturable airborne microorganisms in the Yucatan Peninsula. *Atmospheric Environment*, 223, Article 117183. <https://doi.org/10.1016/j.atmosenv.2019.117183>
- Roponen, M., Seuri, M., Nevalainen, A., & Hirvonen, M.-R. (2002). Fungal spores as such do not cause nasal inflammation in mold exposure. *Inhalation Toxicology*, 14(5), 541–549. <https://doi.org/10.1080/089583701753678616>
- Roy, S., & Gupta Bhattacharya, S. (2020). Airborne fungal spore concentration in an industrial township: Distribution and relation with meteorological parameters. *Aerobiologia*. <https://doi.org/10.1007/s10453-020-09653-9>
- Roy, S., Chakraborty, A., Maitra, S., & Bhattacharya, K. (2017). Monitoring of airborne fungal spore load in relation to meteorological factors, air pollutants and allergic symptoms in Farakka, an unexplored biozone of eastern India. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-017-6044-x>
- Sabariego, S., Bouso, V., & Perez-Badia, R. (2012). Comparative study of airborne *Alternaria* conidia levels in two cities in Castilla-La Mancha (central Spain), and correlations with weather-related variables. *Annals of Agricultural and Environmental Medicine*, 19(2), Article 2. <https://bibliotekanauki.pl/articles/49997>
- Sadyś, M., Strzelczak, A., Grinn-Gofroń, A., & Kennedy, R. (2015). Application of redundancy analysis for aerobiological data. *International Journal of Biometeorology*. <https://doi.org/10.1007/s00484-014-0818-4>
- Sadyś, M., Adams-Groom, B., Herbert, R. J., & Kennedy, R. (2016). Comparisons of fungal spore distributions using air sampling at Worcester, England (2006–2010). *Aerobiologia*. <https://doi.org/10.1007/s10453-016-9436-4>
- Şakiyan, N., & Inceoğlu, Ö. (2003). Atmospheric concentrations of *Cladosporium* Link and *Alternaria* Nées spores in Ankara and the effects of meteorological factors. *Turkish Journal of Botany*, 27(2), 77–81.
- Salo, P. M., Arbes, S. J., Sever, M., Jaramillo, R., Cohn, R. D., London, S. J., & Zeldin, D. C. (2006). Exposure to *Alternaria alternata* in US homes is associated with asthma symptoms. *Journal of Allergy and Clinical Immunology*, 118(4), 892–898. <https://doi.org/10.1016/j.jaci.2006.07.037>
- Sánchez, P., Vélez-del-Burgo, A., Suñén, E., Martínez, J., & Postigo, I. (2022). Fungal allergen and mold allergy diagnosis: Role and relevance of *Alternaria alternata* Alt a 1 protein family. *Journal of Fungi*. <https://doi.org/10.3390/jof8030277>
- Sánchez Espinosa, K. C., Aira, M. J., Fernández-González, M., & Rodríguez-Rajo, F. J. (2024). Airborne *Alternaria* spores: 70 annual records in Northwestern Spain. *Journal of Fungi*. <https://doi.org/10.3390/jof10100681>
- Sarda-Estève, R., Baisnée, D., Guinot, B., Sodeau, J., O'Connor, D., Belmonte, J., Besancenot, J.-P., Petit, J.-E., Thibaudon, M., Oliver, G., Sindt, C., & Gros, V.

- (2019). Variability and geographical origin of five years airborne fungal spore concentrations measured at Saclay, France from 2014 to 2018. *Remote Sensing*. <https://doi.org/10.3390/rs11141671>
- Ščevková, J., Hrabovský, M., Kováč, J., & Rosa, S. (2019). Intradaily variation of predominant airborne fungal spore biopollutants in the Central European urban environment. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-019-06616-7>
- Ščevková, J., Dušička, J., Tropeková, M., & Kováč, J. (2020). Summer storms and their effects on the spectrum and quantity of airborne bioparticles in Bratislava, Central Europe. *Environmental Monitoring and Assessment*, 192(8), Article 537. <https://doi.org/10.1007/s10661-020-08497-7>
- Ščevková, J., Vašková, Z., Dušička, J., Žilka, M., & Zvaríková, M. (2023). Co-occurrence of airborne biological and anthropogenic pollutants in the central European urban ecosystem. *Environmental Science and Pollution Research*, 30(10), 26523–26534. <https://doi.org/10.1007/s11356-022-24048-8>
- Scott, J., Untereiner, W. A., Wong, B., Straus, N. A., & Malloch, D. (2004). Genotypic variation in *Penicillium chrysogenum* from indoor environments. *Mycologia*, 96(5), 1095–1105. <https://doi.org/10.1080/15572536.2005.11832908>
- Sevindik, M., Akgül, H., & Tosunoglu, A. (2022). Temporal variations in fungal spores in Mardin city atmosphere, upper Mesopotamia, SE-Turkey. *Grana*. <https://doi.org/10.1080/00173134.2021.1976825>
- Simović, I., Matavulj, P., & Šikoparija, B. (2023). Manual and automatic quantification of airborne fungal spores during wheat harvest period. *Aerobiologia*, 39(2), 227–239. <https://doi.org/10.1007/s10453-023-09788-5>
- Singh, A. B., & Mathur, C. (2021). Fungal Aerobiology and Allergies in India: An Overview. In T. Satyanarayana, S. K. Deshmukh, & M. V. Deshpande (Eds.), *Progress in Mycology: An Indian Perspective* (pp. 397–417). Springer. [https://doi.org/10.1007/978-981-16-2350-9\\_14](https://doi.org/10.1007/978-981-16-2350-9_14)
- Sio, Y. Y., Pang, S. L., Say, Y.-H., Teh, K. F., Wong, Y. R., Shah, S. M. R., Reginald, K., & Chew, F. T. (2021). Sensitization to airborne fungal allergens associates with asthma and allergic rhinitis presentation and severity in the Singaporean/Malaysian population. *Mycopathologia*. <https://doi.org/10.1007/s11046-021-00532-6>
- Soleimani, Z., Goudarzi, G., Naddafi, K., Sadeghinejad, B., Latifi, S. M., Parhizgari, N., Alavi, N., Babaei, A. A., Akhoond, M. R., Khaefi, M., Rad, H. D., Mohammadi, M. J., & Shahsavani, A. (2013). Determination of culturable indoor airborne fungi during normal and dust event days in Ahvaz, Iran. *Aerobiologia*, 29(2), 279–290. <https://doi.org/10.1007/s10453-012-9279-6>
- Sousa, L., Camacho, I. C., Grinn-Gofroń, A., & Camacho, R. (2016). Monitoring of anamorphic fungal spores in Madeira region (Portugal), 2003–2008. *Aerobiologia*. <https://doi.org/10.1007/s10453-015-9400-8>
- Suthar, M., Dufossé, L., & Singh, S. K. (2023). The enigmatic world of fungal melanin: A comprehensive review. *Journal of Fungi*, 9(9), 891. <https://doi.org/10.3390/jof9090891>
- Symon, F. A., Anees-Hill, S., Satchwell, J., Fairs, A., Edwards, R., Wardlaw, A. J., Cuthbertson, L., Hansell, A. L., & Pashley, C. H. (2025). A fungal spore calendar for England: Analysis of 13 years of daily concentrations. *Allergy*, 80(2), 617–620. <https://doi.org/10.1111/all.16356>
- Tham, R., Dharmage, S. C., Taylor, P. E., Katelaris, C. H., Vicendese, D., Abramson, M. J., & Erbas, B. (2014). Outdoor fungi and child asthma health service attendances. *Pediatric Allergy and Immunology*. <https://doi.org/10.1111/pai.12257>
- Tham, R., Katelaris, C. H., Vicendese, D., Dharmage, S. C., Lowe, A. J., Bowatte, G., Taylor, P., Burton, P., Abramson, M. J., & Erbas, B. (2017). The role of outdoor fungi on asthma hospital admissions in children and adolescents: A 5-year time stratified case-crossover analysis. *Environmental Research*, 154, 42–49. <https://doi.org/10.1016/j.envres.2016.12.016>
- Tournas, V. H. (2005). Spoilage of vegetable crops by bacteria and fungi and related health hazards. *Critical Reviews in Microbiology*, 31(1), 33–44. <https://doi.org/10.1080/10408410590886024>
- Uk Lee, B., Lee, G., & Joon Heo, K. (2016). Concentration of culturable bioaerosols during winter. *Journal of Aerosol Science*, 94, 1–8. <https://doi.org/10.1016/j.jaerosci.2015.12.002>
- Vélez-Pereira, A. M., De Linares, C., Delgado, R., & Belmonte, J. (2016). Temporal trends of the airborne fungal spores in Catalonia (NE Spain), 1995–2013. *Aerobiologia*. <https://doi.org/10.1007/s10453-015-9410-6>
- Vélez-Pereira, A. M., De Linares, C., Canela, M. A., & Belmonte, J. (2023). A comparison of models for the forecast of daily concentration thresholds of airborne fungal spores. *Atmosphere*, 14(6), Article 1016. <https://doi.org/10.3390/atmos14061016>
- Wainwright, M., Wickramasinghe, N. C., Narlikar, J. V., Rajaratnam, P., & Perkins, J. (2004). Confirmation of the presence of viable but non-culturable bacteria in the stratosphere. *International Journal of Astrobiology*, 3(1), 13–15. <https://doi.org/10.1017/S1473550404001739>
- Webster, J., & Weber, R. (2007). *Introduction to Fungi*. Cambridge University Press.
- Weryszko-Chmielewska, E., Kasprzyk, I., Nowak, M., Sulborska, A., Kaczmarek, J., Szymanska, A., Haratym, W., Gilski, M., & Jedryczka, M. (2018). Health hazards related to conidia of *Cladosporium*—Biological air pollutants in Poland, central Europe. *Journal of Environmental Sciences*, 65, 271–281. <https://doi.org/10.1016/j.jes.2017.02.018>
- Williams, P. B., Barnes, C. S., Portnoy, J. M., Barnes, C., Baxi, S., Grimes, C., Horner, W. E., Kennedy, K., Larenas-Linnemann, D., Levetin, E., Miller, J. D., Phipatanakul, W., Portnoy, J. M., Scott, J., & Williams, P. B. (2016). Innate and adaptive immune response to fungal products and allergens. *The Journal of Allergy and Clinical Immunology: In Practice*, 4(3), 386–395. <https://doi.org/10.1016/j.jaip.2015.11.016>
- Woo, A. C., Brar, M. S., Chan, Y., Lau, M. C. Y., Leung, F. C. C., Scott, J. A., Vrijmoed, L. L. P., Zawar-Reza, P., & Pointing, S. B. (2013). Temporal variation in airborne microbial populations and microbially-derived allergens

- in a tropical urban landscape. *Atmospheric Environment*, 74, 291–300. <https://doi.org/10.1016/j.atmosenv.2013.03.047>
- Yang, C. S., & Heinsohn, P. A. (2007). *Sampling and Analysis of Indoor Microorganisms*. John Wiley & Sons.
- Yepes-Nuñez, J. J., Urrútia, G., Romero-García, M., & Alonso-Fernández, S. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews Declaración PRISMA 2020: Una guía actualizada para la publicación de revisiones sistemáticas. *Revista Española De Cardiología*, 74(9), 790–799. <https://doi.org/10.1016/j.recesp.2021.06.016>
- Zhai, Y., Li, X., Wang, T., Wang, B., Li, C., & Zeng, G. (2018). A review on airborne microorganisms in particulate matters: Composition, characteristics and influence factors. *Environment International*, 113, 74–90. <https://doi.org/10.1016/j.envint.2018.01.007>
- Žilka, M., Hrabovský, M., Dušička, J., Zahradníková, E., Gahurová, D., & Ščevková, J. (2024). Comparative analysis of airborne fungal spore distribution in urban and rural environments of Slovakia. *Environmental Science and Pollution Research*, 31(54), 63145–63160. <https://doi.org/10.1007/s11356-024-35470-5>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.