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Aeromycological studies in the crops of the main cereals: A systematic review

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ABSTRACT

Aeromycological studies on cereal crops allow to determine the temporal variation of plant pathogens affecting the crop and to determine the appropriate time to apply fungicides. However, this topic has not been systematically reviewed. The aim of this work was to systematically analyze all aeromycological studies carried out on corn, wheat, rice, oats, barley, rye, sorghum, and millet. A systematic search was carried out in Scopus from the start of the database until 1 August 2022. Inclusion criteria were that they were aeromycological studies on wheat or rice or corn or oats or sorghum or rye or barley or millet and studies published in peer-reviewed journals indexed in Journal Citation Reports and written in English or Spanish. Forty-three studies (21 in wheat, 15 in rice, 5 in corn, 1 in sorghum, and 2 in barley) that met all eligibility criteria were included (one of the studies in corn was also conducted in wheat). No aeromycological studies were found in oats, rye, and millet. It was noted that most aeromycological research has been conducted on wheat crops and predominantly in countries in the Americas. Also, fungal propagules are mainly collected by non-viable methods, using various types of collectors. Generally, the studies were aimed at identifying a specific pathogen and not at the diversity of pathogens that can be found. The relationship of the fungi identified with meteorological parameters was variable in the different studies. This systematic review helps to summarize aeromycological studies that have been conducted on wheat, rice, corn, sorghum, and barley crops. It also suggests where future studies in this area should be directed, based on the limitations encountered.

1. Introduction

Cereals are staple food crops in both developed and developing countries, providing an important source of energy and nutrients. These are approximately 75% carbohydrate and 6–15% protein, providing more than 50% of the overall energy supply [1]. These cereals mainly include corn, wheat, rice, oats, barley, rye, sorghum, and millet [2]. Wheat and rice are the most widely consumed cereals in the world, and the rest are considered coarse grains [3]. In the year 2021, according to the records of the Food and Agriculture Organization of the United Nations (FAO), the most produced cereal in the world was corn, followed in decreasing order by rice, wheat, barley, sorghum, millet, oats, and rye. In the same year in Europe the highest production was wheat, followed by corn, barley, oats, rye, rice, sorghum, and millet. Specifically, in Spain, the most produced cereal was barley, followed by wheat, corn, oats, rice, rye, and sorghum. Millet is not produced in this country [4].

These crops are affected by several phytopathogenic fungi dispersed through the air during their phenological development, which causes a decrease in the harvest and its quality [5]. The magnitude of economic losses is determined by the susceptibility levels of the varieties planted and by the type of agronomic management they receive [6–8]. *Alternaria*, *Bipolaris*, *Blumeria*, *Curvularia*, *Fusarium*, *Puccinia*, *Pyricularia*, and *Zymoseptoria* are the fungal pathogens usually reported worldwide [9–12]. The damage that these fungi cause to cereal crops can be prevented through aeromycological studies of the areas dedicated to their sowing. Knowledge of the atmospheric concentration of spores and their correlation with meteorological factors can be used to infer sources of inoculum for local epidemics and to develop risk models for the management of these diseases [13,14].

Various types of volumetric samplers have been used in Europa, Asia, America, and Africa, to collect fungal propagules as well as exposure of Petri plate [5,8,15,16]. Most of these studies have focused on detecting a

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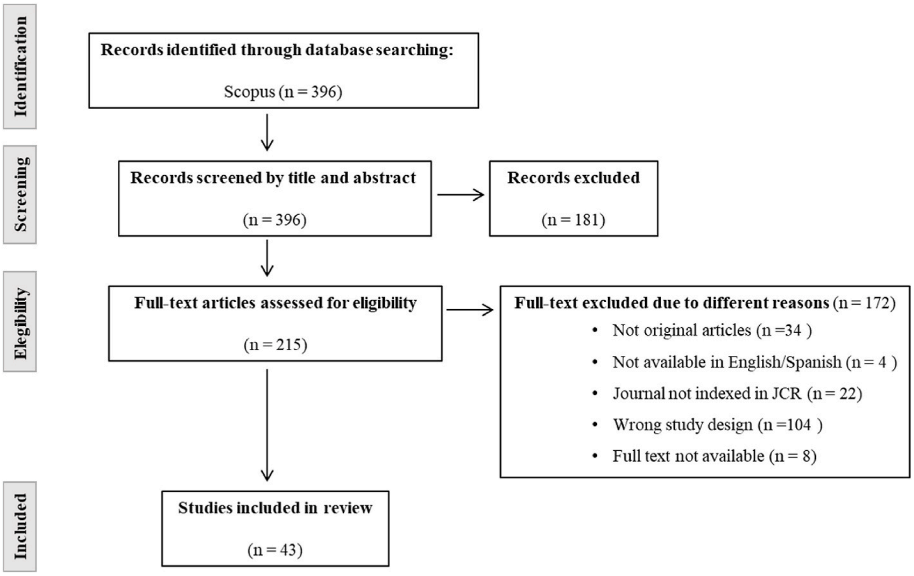

Fig. 1. Studies included through the review process according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [19].

specific genus or species rather than on diversity. The main meteorological variables that have been related to the presence of these fungi are Relative Humidity, Temperature, Rainfall, Solar radiation, Dew point, Wind direct, and Wind velocity [6,17,18].

However, this research is not carried out continuously in all cereal-producing countries or by the same methodologies. In addition, there is no review that synthesizes the findings on this topic. Therefore, the objective of this work was to systematically analyze all aeromycological studies carried out on wheat, rice, corn, oats, sorghum, rye, barley, and millet crops.

2. Methods

2.1. Protocol

This review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [19].

2.2. Data sources and search strategy

We searched studies in the electronic database Scopus from database inception to 1 August 2022. The search strategy used for was TITLE-ABS-KEY (wheat OR rice OR corn OR oat OR sorghum OR rye OR barley OR millet) AND (aerobiology OR aeromycology OR aeromycological OR aerobiological OR {aerobiological dynamics} OR {airborne fungal} OR {airborne spores}) AND (fungi OR spores OR {fungal bioaerosol} OR {fungal propagule}).

2.3. Eligibility criteria

Two researchers (KCSE and LDV) independently assessed the eligibility of studies. Inclusion criteria were defined as aeromycological studies in crops of wheat or rice or corn or oat or sorghum or rye or barley or millet and studies published in peer-refereed journals indexed in Journal Citation Reports and written in English or Spanish. Exclusion criteria were defined as conference proceedings, theses, editorials, letters to editor, narrative reviews, systematic reviews and meta-analyses.

2.4. Study selection

The study selection process was conducted in different stages. Firstly, records were identified through the Scopus database. Later, titles and abstracts of the search results were examined to identify those that were likely to be included. Subsequently, those articles appearing eligible were read as full-text for their final inclusion or exclusion in the systematic review. All the stages were compared by two researchers (KCSE and LDV). Any discrepancies were discussed and agreed upon prior to inclusion or exclusion criteria. When the inclusion of a study was unclear, a third reviewer (MA) was consulted and consensus reached by discussion. Fig. 1 shows the flow diagram of the study selection process. Finally, reference lists of included articles were checked for further studies meeting the inclusion criteria.

2.5. Risk-of-Bias assessment

The risk of bias was evaluated by two independent researchers (KCSE and MA) and disagreements were resolved in a consensus meeting. Each study was examined based on four criteria: (1) study period continuous greater than one growing season or study punctual but performed in more than one growing season; (2) study carried out in more than one field cultivated with cereal; (3) proper collection of samples in correspondence with the method used; (4) correct taxonomic criteria for fungal identification; (5) identification of a specific pathogen and also other airborne fungi present; (6) day and night airborne fungal presence; (7) influence of meteorology on airborne fungi; (8) monitoring of fungal infections in the cereal field and (9) presentation of a fungal concentration prediction model. A detailed description of each criterion is shown in Table S1. Researchers assigned a value of 0 (when the criterion was not met) and 1 (when the criterion was met) to each study. The scores of each criterion were summarized for all studies. Studies were considered ‘high risk’ when the scores were 0–3, ‘moderate risk’ when the scores were 4–5, and ‘low risk’ when the scores were 6–9.

2.6. Data collection and extraction

The extracted data from the included studies were (1) study (i.e. first author’s name and year of publication); (2) location; (3) time period; (4) method of fungi collection; (5) air flow; (6) high; (7) identification

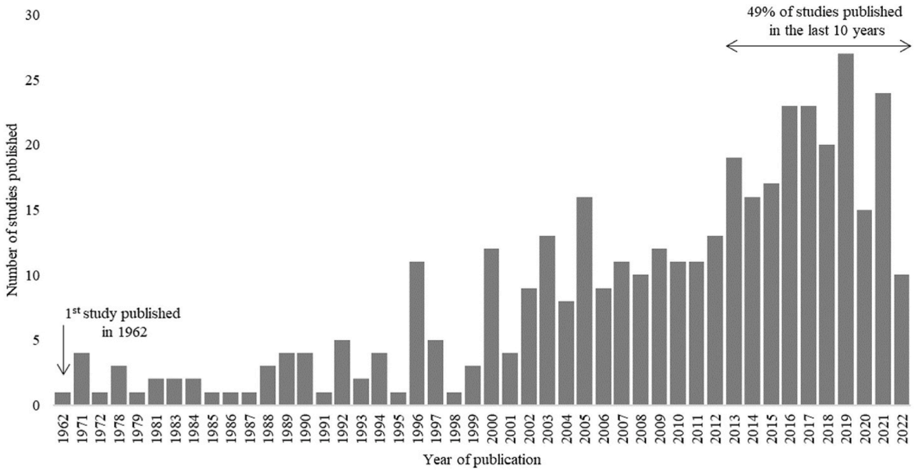

Fig. 2. Number of publications (n = 396) focused on fungal detection in aerobiological studies of cereal crops.

method; (8) identified fungi; (9) influence of meteorology on airborne fungi. Data extraction was independently double-checked by two researchers (MFG and FJ).

3. Results

3.1. Study selection

A total of 396 studies were identified in the selected database. Fig. 2 depicts the number of studies published in our search. After examining titles and abstracts, 215 full-text articles were further screened. Finally, 43 unique studies met the inclusion criteria and were included in the present review. Agreement between researchers (KCSE and LDV) in the study selection was high (100%). The flow diagram summarizing the study selection process of the systematic review is shown in Fig. 1.

3.2. Risk-of-Bias assessment

Overall, the quality of the included studies was moderate (53.49%) (i.e. moderate risk of bias). In regard to wheat studies (n = 21), 33.33% were categorized as 'low risk of bias', 47.82% were categorized as 'moderate risk of bias' and 14.29% were classified as 'high risk of bias'. For rice studies (n = 15) 26.67% were categorized as 'low risk of bias', 60.00% were categorized as 'moderate risk of bias' and 13.33% were categorized as 'high risk of bias'. In the rest of the cereals, 14.29% presented a "low risk of bias", 37.50% "moderate risk of bias" and 50% "high risk of bias". A detailed description of the study quality score is shown in Table S1.

These investigations were generally carried out in continuous periods longer than one growing season, or on an ad hoc basis but conducted in more than one growing season (n = 31); a smaller group (n = 10) were conducted in more than one field cultivated with a cereal. Most of the studies carried out an adequate sampling in correspondence with the method used (n = 43) and identification of the fungi (n = 41). The identification of a specific pathogen and also of other airborne fungi was only performed in 19 studies and in 12 studies their daytime and nighttime detection was performed. The influence of meteorology on airborne fungi and the monitoring of fungal infections in the cereal field was conducted in about half of the studies. However, few models were presented to predict the concentrations of pathogens (n = 3).

3.3. Data extraction: study characteristics

The characteristics of the 43 unique studies included for each cereal type, are available in Tables 1–3. Table 1 shows the aeromycological studies in wheat crops, Table 2 in rice crops and Table 3 in other cereals (corn, sorghum, and barley). Tables 4–6 show the collection methods of the fungal propagules identified and their relationship with the meteorological variables for each cultivar. Twenty-one studies on the aerial mycobiota of wheat crops, 15 on rice and 8 on other cereals (corn, sorghum and barley) were identified (one of the studies in corn was also conducted in wheat). No aeromycological study was found in oat, rye, and millet crops.

The 30.23% of these studies were conducted in Europe (Switzerland, Belgium, Germany, Italy, France, Spain, Hungary, and United Kingdom) and the same percentage (30.23%) in Asia (China, India and Taiwan), 37.21% in America (United States, Canada and Cuba) and a study in Africa in Tunisia (2.33%). The time period data collection started for the oldest study in 1984 and ended for the most recent study in 2021.

3.4. Synthesis of findings

3.4.1. Fungi collection methods

Fungal propagules were collected mainly by non-viable methodologies and samples were analyzed by direct microscopy, real-time PCR, duplex real-time PCR, multiplex qPCR, YBR Green qPCR and scanning electron microscope with energy dispersive X-ray spectrometer (SEM - EDS). For this sampling, the Burkard Automatic Cyclone Air Sampler, Burkard Cyclone One-vial (qPCR), Burkard Multi-Vial Cyclone Samplers, Burkard 7-day spore-monitoring trap, Burkard personal volumetric sampler, Marple eight-stage cascade impactor, Automatic volumetric spore trap VPPS-2000 Lanzoni, Kramer-Collins 7-day continuous deposit spore sampler, Rotorods samplers, Hirst spore, Modified Cyclone-based spore trap (AirSampler) and exposure microscope slides covered with glycerine were used. The air flow in the samplers varied from 4 to 16.5 L min −1. The collectors were placed at variable heights, depending on the physiological stage of the crop at the time of sampling.

The Surface Air System (SAS), Agroscope (AGS), Burkard jet spore sampler (JSS) and Andersen were used in the investigations that used a viable methodology. The air flow they established for the collection was 20, 28.3 and 100 L min −1. In addition, 16 studies used the exposure Petri plate. The air samples were collected at different heights. The culture media used were Potato Dextrose Agar (PDA), Pentachloronitrobenzene media (PCNB), *Fusarium*-selective medium (FSM), *Fusarium*-selective medium (FSM) with an increased level of neomycin sulfate to 0.175 g/L, malt extract agar with streptomycin, malt extract agar with streptomycin and sodium deoxycholate, DIFCO and PCNB-Rose Bengal agar.

3.4.2. Fungal diversity identified and relation with meteorological variable

Most of the studies that were included do not identify the diversity

Table 1
Summary of aeromycological studies on wheat crops.

Study	Location	Time period
Forrer et al. [16]	Zurich, Switzerland	Spot samples (2007–2010) 5 June 2007 19–29 May 2008 2, 5, 9 and 12 June 2008 17 June - 19 June 2008 8, 9 and 10 June 2009 April–August 2010
Araujo et al. [12]	Alberta, Canada	Growing seasons 2015, 2016, and 2017
Gu et al. [5]	Gansu, China	
	South mountain	March 2013–December 2015
	Middle valley	April 2013–December 2015
	North mountain	
Hassine et al. [8]	Oued-Beja experimental station of the Regional Field Crop Center in Tunisia	17 November 2016–13 July 2017
Gu et al. [20]	Gangu, Northwestern China	
	- South mountain	March 2013–December 2015
	- Middle valley	April 2013–December 2015
	- North mountain	
Shiro et al. [17]	Brandenburg, Germany	–
Newlands [15]	Lethbridge, Canada	June–October 2015
Hellin et al. [7]	Walloon region, Belgium	
	- Perwez	15 April to 15–31 July 2011–2013
	- Voroux-Goreux	
	- Niverlée	
	- Tournai	1 September 2011–31 August 2012
	- Aye	15 April to 15–31 July 2011
	- Naast	15 April to 15–31 July 2012
	- Aisemont	15 April to 15–31 July 2013
Duvivier et al. [6]	Walloon region, Belgium	March 2009–July 2013
	- Perwez	
	- Voroux-Goreux	
	- Niverlée	
	- Tournai	
	- Gembloux	
Telloli et al. [21]	Po Valley at Mezzano, Ferrara, Italy	25 June - 17 November 2009
Cao et al. [22]	Langfang City, Hebei Province, China	October 2009, November 2010, December 2011
Manstretta et al. [23]	RVALIS—Institut du végétal, Boigneville, France and Horta, Ravenna, Italy	2013 and 2014
Cao et al. [14]	Hebei Province, China	Growing seasons 2009–2010, 2010–2011 and 2011–2012
Schmale et al. [24]	Virginia Tech’sKentland Farm in Blacksburg, VA, United States	2006–2007
Schmale et al. [25]	Robert B. Musgrave Research Farm in Aurora, NY, United States	2002 and 2004
Schmale et al. [26]	Robert B. Musgrave Research Farm in Aurora, NY, United States	2002, 2004 and 2005
Schmale et al. [13]	Robert B. Musgrave Research Farm in Aurora, NY, United States	May and June 2002 and June 2004
Maldonado-Ramirez et al. [27]	Robert B. Musgrave Research Farm in Aurora, NY, United States	May and June 1999–2002
Rossi et al. [28]	Piacenza, Italy	May–June 1994–1997 2 to 4 times per year (1994–1997)
Uddin and Chakraverty [9]	Barbagan-Dangadighila, India	25 November 1990–10 March 1991
Eversmeyer and Kramer [29]	Rocky Ford experimental plots Kansas, United States	Made from mid-April to mid-June for five years
	Ashland Agronomy Farm Kansas, United States	Mid-September to mid-November for three years

Table 2
Summary of aeromycological studies on rice crops.

Study	Location	Time period
Ortega et al. [18]	Lombardy, Italy	25 June - 12 September 2016
Saha et al. [30]	Barasat and Basirhat, India	111–118 days in Barasat 113–121 days in Basirhat
Huang et al. [31]	Chiayi Agricultural Experiment Station, Taiwan	2012 and 2013
Almaguer et al. [11]	Bauta, Cuba	2007
Almaguer et al. [32]	Bauta, Cuba	March 2007–February 2008
Almaguer et al. [33]	Bauta, Cuba	March 2007 and the last week of February 2008
Muñoz et al. [10]	Vegas Bajas del Guadiana in the province of Badajoz, Spain	9 July - 27-August 1998, 8 June - 27 July 1999
Castejón-Muñoz [34]	Sartenejales and Casudis, Sevilla, Spain	Growing seasons 2002 and 2003
Uddin [35]	Barrackpore, West Bengal, India	1 February - 9 May 1990 20 January - 28 April 1991
Chakraborty et al. [36]	Madhyamgram Field Station, India	July 1994–June 1999
Picco and Rodolfi [37]	Pavia, Italy	10 June - 7 October 1996
Uddin and Chakraverty [38]	Barrackpore, West Bengal, India	22 July 1990–9 December 1990
Uddin and Chakraverty [39]	Barrackpore, West Bengal, India	1 April 1992 7 may 1992 15 december 1992
Atluri et al. [40]	Bhimavaram, Andhra, Pradesh, India	22, 24, 25 March 1983
Atluri et al. [41]	Bhimavaram, Andhra, Pradesh, India	9, 10, 19, 20, 21, 22 March 1983

Table 3
Summary of aeromycological studies on corn, sorghum and barley crops.

Study	Location	Time period
Corn		
Dónat et al. [42]	Agricultural Research Institute of the Hungarian Academy of Sciences in Martonvásár, Hungary	2005 and 2008 29 October 2007
Schmale et al. [25]	Robert B. Musgrave Research Farm in Aurora, NY, United States	2003 and 2004
Inch et al. [43]	Glenlea, Manitoba, Canada	1 July - 28 August 1999 1 July - 28 August 2000
Schmale et al. [44]	Robert B. Musgrave Re-search Farm in Aurora, NY, United States	29 July - 5 August 2003 5–12 August 2004
Schmale and Bergstrom [45]	Robert B. Musgrave Re-search Farm in Aurora, NY, United States	July and August 2002 and 2003
Sorghum		
Funnell-Harris and Pedersen [46]	Lincoln an Ithaca, United States	2005–2006 growing seasons
Barley		
Fountaine et al. [47]	United Kingdom	4 October 2003–23 August 2004
Martin and Clough [48]	Charlottetown, Prince Edward Island, Canada	July–September 1980 July–September 1981

present in the air of the cultivation areas but focus on specific genera or species. The only studies that perform a comprehensive analysis of aeromycobiota are those of Almaguer et al., in 2012 [32] and 2013 [11], Muñoz et al. [10], Uddin [35], Chakraborty et al. [36], Picco and Rodolfi [37], Uddin and Chakraverty in 1996 [9], 1995 [38] and 1994 [39], Atluri et al. [40,41]. The rest of the studies identified species of *Alternaria* or *Blumeria* or *Bipolaris* or *Cladosporium* or *Gibberella* or *Fusarium* or *Magnaporthe* or *Puccinia* or *Pyrenophora* or *Pyricularia* or *Rhynchosporium* or *Ustilaginoidea* or *Zymoseptoria*.

The number of taxa identified in the studies carried out on cereals through the methodologies used is summarized in Tables 4–6 At large, the genera that were detected by both the non-viable and viable methods were *Alternaria, Aspergillus*, *Beltrania*, *Bipolaris*, *Botrytis*, *Cercospora*, *Chaetomium*, *Cladosporium*, *Curvularia*, *Epicoccum*, *Fusarium*, *Humicola*, *Nigrospora*, *Penicillium*, *Pithomyces*, *Pyricularia*, *Stachybotrys*, *Stemphylium*, and *Torula*. The genera *Acremoniella*, *Acremonium*, *Aureobasidium, Brachysporium*, *Candida*, *Cephalosporium*, *Chrysonilia*, *Cunninghamella, Dendrographium*, *Diplodia*, *Dreschlera*, *Eurotium*, *Gibberella*, *Gliocladium*, *Graphium*, *Helminthosporium*, *Lacellina*, *Monilia*, *Monocillium*, *Monodictys*, *Mortierella*, *Mucor*, *Paecilomyces*, *Pestalotia*, *Phoma*, *Pullularia*, *Rhizopus*, *Sclerotium*, *Scopulariopsis*, *Sordaria*, *Spicaria*, *Trichoderma*, and *Verticillium* were detected only by the culture method.

Only by the non-viable method of direct microscopic count, they identified *Arthrobotrys*, *Bovista*, *Cochilobolus*, *Erysiphe*, *Fusicladium*, *Ganoderma*, *Gomphus*, *Heliconia*, *Leptosphaeria*, *Myrothecium*, *Nakataea*, *Oidium*, *Paraphaeosphaeria*, *Periconia*, *Periconiella*, *Pleospora*, *Polythrincium*, *Podospora*, *Pyrenophora*, *Stigmina*, *Spegazzinia*, *Thelephora*, *Tetracoccosporium*, *Tetraploa*, *Tilletia*, *Torula*, *Trichoconis*, *Ustilaginoidea*, *Ustilago*, *Venturia*, Ascospores, Aspergilli group, Basidiospores, Myxomycetes, Teleutospores, and Uredospores. By the same method, the following species were detected: *Puccinia graminis f. sp. tritici*, *Puccinia recondita* f. sp. *tritici*, *Bipolaris oryzae*, *Blumeria graminis f. sp. tritici*, *Cladosporium cladosporioides*, *Cladosporium herbarum*, *Cochiliobolus miyabeanus*, *Erysiphe graminis*, *Fusarium graminearum*, *Leptosphaeria errstornoide*, *Nakataea sigmoidea*, *Pyrenophora tritici-repentis*, *Pyricularia oryzae*, *Pyrenophora teres*, and *Ustilaginoidea virens*.

Molecular methods (real-time PCR, duplex real-time PCR, multiplex qPCR, YBR Green qPCR) were used to detect *Blumeria graminis f. sp. tritici*, *Fusarium graminearum*, *Puccinia striiformis f. sp. tritici*, *Puccinia triticina*, and *Zymoseptoria tritici* species in wheat crops. In rice crops, *Bipolaris oryzae*, *Magnaporthe oryzae*, and *Pyricularia oryzae* were identified by this methodology, while in barley *Rhynchosporium secalis*. One of the studies used the Scanning Electron Microscope with Energy Dispersive X-ray Spectrometer (SEM-EDS) method to identify *Alternaria*, *Arthrinium*, *Stemphylium*, Family Pucciniaceae, and Family Trichocomaceae.

The relationship of fungal propagules identified with meteorological variables was variable in the different studies. In these investigations, the main variables analyzed were temperature, relative humidity, and rainfall. Wind direction and speed, solar radiation, dew point, and Vapor Pressure Deficit were also taken into account.

4. Discussion

The purpose of this work was to systematically review studies focused on fungal detection in aerobiological studies of main cereal crops. For this purpose, we analyzed the period in which sampling was carried out in cereal fields, the methodologies for collecting fungal propagules from the air and their precise identification, as well as their relationship with meteorological variables.

The combination of viable and non-viable methods was used only in few studies. Combining a methodology based on identification by direct microscopy, or molecular detection with the isolation and identification of viable propagules allows generalizing conclusions about the genera and species that form the environmental fungi. Biomolecular techniques for fungal identification have opened new fields in taxonomy and ecology by improving species identification. However, few researchers have worked on these topics applied to aerobiology in cereal crops compared to other branches of science. Nevertheless, in the review carried out, the works that used different types of PCR as an expression of the most modern methods stand out. Examples of this are Araujo et al. [12], Gu et al. [5], Hassine et al. [8] Gu et al. [20], Newlands [15], Hellin et al. [7], Duvivier et al. [6, Cao et al. [22], Cao et al. [22], Huang et al. [31], Funnell-Harris and Pedersen [46], and Fountaine et al. [47]. The most comprehensive solution consists of combining both methodologies to determine the content of phytopathogenic fungi present in cereal fields. This alternative was used only by Rossi et al. [28], to detect several *Fusarium* species in a wheat growing area. Despite this, the use of non-viable methods is the only one that allows continuous air monitoring and the establishment of hourly and daily variations of phytopathogens, useful information to understand the epidemiology of diseases. The latter is the most widely used because the results are obtained faster and after the methodology is implemented it is cheaper. On the other hand, the same collectors are not used in all aeromycological studies and therefore, it is not possible to obtain homologous data for the different biogeographic and bioclimatic areas.

Cereals are affected by several different pathogens during their phenological stage; although, in all studies, several of these pathogens are not monitored. The monitoring of several pathogens guarantees that several of the diseases that affect these crops can be prevented and, as a consequence, increases yields and product quality. The main cereal pathogens included in this review include *Puccinia*, *Fusarium*, *Zymoseptoria*, and *Pyricularia* species. *Puccinia graminis* f. sp. *tritici*, *P. striiformis*, *Puccinia triticina*, *Zymoseptoria tritici*, and *Fusarium graminearum* are the main phytopathogens of wheat together with *Parastagonospora nodorum*, *Pyrenophora tritici-repentis*, *Bipolaris sorokiniana*, and

Table 4
Summary of the collection methods of the fungi identified and their relationship with meteorological variables in wheat crops.

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
Forrer et al. [16]	Agroscope (AGS) Burkard jet spore sampler (JSS)	–	20, 50 or 90 cm 50 cm	Viable PCNB Agar	*Fusarium graminearum* *F. avenaceum* *F. equiseti* *F. cerealis* *F. oxysporum* *F. tricinctum* *F. poae*	RH
Araujo et al. [12]	Burkard Automatic Cyclone Burkard Cyclone One-vial	16.5	90–100 cm	Non viable Real time PCR	*Puccinia striiformis* f. sp. *tritici* *Puccinia triticina*	–
	Passive spore trapping	–	–	Non viable Direct microscopy	*Puccinia graminis* f. sp. *tritici* *Blumeria graminis* f. sp. *tritici* *Pyrenophora tritici-repentis*	
Gu et al. [5]	Burkard Multi-vial Cyclone Samplers	16.5	3 m	Non viable Real time PCR	*Blumeria graminis* f. sp. *tritici*	WV, T and SR
Hassine et al. [8]	Burkard 7-day spore-monitoring trap	10	1 m	Non viable Real time PCR	*Zymoseptoria tritici*	RH, R and T
Gu et al. [20]	Burkard Multi-vial Cyclone Samplers	16.5	3 m	Non viable duplex real-time PCR	*Puccinia striiformis* f. sp. *tritici* *Blumeria graminis* f. sp. *tritici*	–
Shiro et al. [17]	Passive spore trapping	–	10, 30, 60 and 90 cm	Non viable Direct microscopy	*Fusarium* *Alternaria*	T, RH and SH
Newlands [15]	Burkard Cyclone Samplers	–	–	Non viable Direct microscopy, PCR and multiplex qPCR	*Puccinia striiformis* f.sp. *tritici*	T
Hellin et al. [7]	Burkard 7-day spore-monitoring trap	10	1 m	Non viable Real time PCR	*Fusarium graminearum*	–
Duvivier et al. [6]	Burkard 7-day spore-monitoring trap	10	1 m	Non viable Real time PCR	*Puccinia triticina*	T, R and RH
Telloli et al. [21]	Marple eight-stage cascade impactor	2	5.7 m and 2 m	Non viable SEM - EDS	*Aspergillus* sp. Family Pucciniaceae Family *Trichocomaceae* *Alternaria* sp. *Stemphylium* sp. *Arthrinium* sp.	–
Cao et al. [22]	Burkard 7-day spore-monitoring trap	–	–	Non viable Real time PCR	*Blumeria graminis* f. sp. *tritici*	–
Manstretta et al. [23]	Leaf-like traps are made of horizontal slides and Ear-like traps are made of vertical slides	–	90 cm	Non viable Direct microscopy	*Fusarium graminearum*	–
Cao et al. [14]	Burkard 7-day spore-monitoring trap	10	0.6 m	Non viable Direct microscopy	*Blumeria graminis* f. sp. *tritici*	T, RH, R, SR, WS and VPD
Schmale et al. [24]	Exposure Petri plate in UAVs	–	40–320 m	Viable FSM	*Fusarium graminearum*	–
Schmale et al. [25]	Exposure Petri plate	–	–	Viable FSM modified	*Fusarium graminearum*	–
Schmale et al. [26]	Exposure Petri plate	–	30 cm	Viable FSM modified	*Fusarium graminearum*	–
Schmale et al. [13]	Exposure Petri plate	–	31 cm	Viable FSM modified	*Fusarium graminearum*	–
Maldonado-Ramirez et al. [27]	Exposure Petri plate in RPVs	–	60 m	Viable FSM	*Fusarium graminearum*	–
Rossi et al. [28]	Automatic volumetric spore trap VPPS-2000 Lanzoni	10	1.5 m	Non viable Direct microscopy	*Fusarium*	T, R
	Exposure Petri plate	–	–	Viable PCNB Agar PCNB Agar	*Fusarium nivale* *F. graminearum*	

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Table 4 (*continued*)

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
					F. culmorum *F. poae* *F. avenaceum* *F. tricinctum* *F. moniliforme* *F. crokwellense*	
Uddin and Chakraverty [9]	Exposure Petri plate	–	81 cm (Max)	Viable MEA with streptomycin	*Cladosporium* spp. *Aspergillus* spp. *Penicillium* spp. *Curvularia* spp. *Nigrospora sphaerica* *Alternaria* spp. *Helminthosporium* spp. *Dreschlera* sp. *Fusarium* spp. *Sclerotium rolfsii* *Stemphylium rolfsii* *Epicoccum purpurascens* *Humicola fuscoatra* *Cephalosporium* spp. *Trichoderma lignorum* *Chaetomium* spp. *Stachybotrys* spp. *Rhizopus* spp. *Mucor* spp. *Dendrographium* sp.	T, HR, R
Eversmeyer and Kramer [29]	Kramer-Collins 7-day continuous deposit spore sampler	–	1, 6, 14 cm	Non viable Direct microscopy	*Puccinia graminisf.* sp. *tritici* *Puccinia recondita* f. sp. *tritici* *Erysiphe graminis* *Cladosporium*	T, HR, R, DP

Captions: UAVs: Autonomous unmanned aerial vehicles, RPVs: Remote-piloted vehicles, FSM: *Fusarium*-selective medium, SEM - EDS: Scanning Electron Microscope with Energy Dispersive X-ray Spectrometer.
T: Temperature, RH: Relative Humidity, SH: Soil Humidity, WV: Wind Velocity, WD: Wind direct, SR: Solar radiation, R: Rainfall, VPD: Vapor Pressure Deficit, DP: Dew point.

Magnaporthe oryzae [49]. These last four species were not identified in any of the studies included in this review. In the case of rice cultivation, the main fungal pathogens are *Pyricularia oryzae* (sometimes named by its teleomorphic *Magnaporthe grisea* before 2013), *F. moniliforme*, *Bipolaris oryzae*, *Sarocladium oryzae*, *Microdochium oryzae*, and *Tilletia barclayana*. In none of the included studies were the genera *Sarocladium* and *Microdochium* identified [50]. *Acremonium maydis*, *Claviceps gigantea* (anamorph *Sphacelia* sp.), *Cochliobolus heterostrophus* (anamorph *Bipolaris maydis*, *Gibberella moniliformis* (anamorph *Fusarium verticilloides*), *Gibberella zeae* (anamorph *Fusarium graminearum*), *Glomerella graminicola* (anamorph *Colletotrichum graminicola*), *Khuskia oryzae* (anamorph *Nigrospora oryzae*), *Peronosclerospora maydis*, *Peronosclerospora philippinensis*, *Peronosclerospora sacchari*, *Peronosclerospora sorghi*, *Sclerophthora rayssiae* var. Zeae, *Setosphaeria turcica* (anamorph *Exserohilum turcicum*), *Stenocarpella maydis*, and *S. macrospora*, *Ustilago maydis* are the main fungal pathogens of corn worldwide [51]. Nonetheless, the studies included in this review focus mainly on *Fusarium graminearum*. *Claviceps sorghi*, *Periconia circinata*, *Peronosclerospora sorghi*, *Colletotrichum graminicola* Ces., *Sporisorium sorghi*, *Cercospora sorghi*, *Exserohilum turcicum*, and *Ascochyta sorghi* are the fungi that mainly cause damage to sorghum crops [52]. In the only aeromycological study found in this crop, *Fusarium* species were identified [46] *Pyrenophora graminea*, *Drechslera graminea* [anamorph], *Pyrenophora teres* f.sp. *teres*, *Drechslera teres* f.sp. *maculata* [spot form], *Drechslera teres* [anamorph]., *Pyrenophora tritici-repentis* [anamorph *Drechslera tritici-repentis*], *Gibberella zeae* [teleomorph], *Fusarium graminearum* [anamorph], *Rhynchosporium secalis*, *Phaeosphaeria nodurm* [teleomorph], *Stagonospora nodorum* [anamorph], *Alternaria* spp., *Cochliobolus sativus*, *Fusarium* spp., *Cladosporium* spp., *Ustilago hordei*, *Claviceps purpurea*, *Tilletia controversa*, *Fusarium culmorum*, *Cephalosporium gramineum*, *Cochliobolus sativus* [teleomorph], *Bipolaris sorokiniana* [anamorph], *Septoria passerinii*, *Ustilago nuda*, and *Ustilago avenae* are reported to cause the main fungal diseases of barley [53]. Even though only detection studies of *Rhynchosporium secalis* and *Pyrenophora teres* were found. Therefore, we believe that it is necessary to conduct aeromycological studies that cover a greater diversity of phytopathogens of these cereals.

The taxonomy of the reported fungi sometimes followed the dual nomenclature in the articles published before the International Code of Nomenclature for algae, fungi, and plants [54] change. The pleomorphism in fungal pathogens is one of the most difficult elements of fungal taxonomy with which plant pathologists have had to contend. This pleomorphism arises from the fact that many ascomycete fungi occur in either their sexual (teleomorph) or asexual (anamorph) states alone, or in combination. To complicate this situation further, some fungi have more than one asexual morph (synanamorph) and these are often linked to unique ecological niches [55].

In addition to monitoring plant pathogens in the air, it is important to identify them in plants. Because in order to affect the crop, it is not enough to find the virulent pathogen and the susceptible host plant, but there must also be adequate environmental conditions for the development of the pathogen. However, it is not taken into account in all the included studies. This monitoring makes it possible to determine some factors that influence the development of fungal infection, to apply more precise control measures and to evaluate their effectiveness.

Meteorological variables affect the growth and sporulation of fungi, as well as the release, dispersal and deposition of their spores. Therefore, in all work where the concentration of propagules is determined, both seasonal variation and meteorological variables are related. In this

Table 5
Summary of the collection methods of the fungi identified and their relationship with meteorological variables in rice crops.

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
Ortega et al. [18]	Burkard 7-day spore-monitoring trap	10	1,5 m	Non viable qPCR	*Pyricularia oryzae* *Bipolaris oryzae*	T, RH, WS
Saha et al. [30]	Burkard personal volumetric sampler	10	1 m	Non viable Direct microscopy	*Ustilaginoidea virens*	–
Huang et al. [31]	Modified Cyclone-based spore trap	4	–	Non viable YBR Green qPCR	*Magnaporthe oryzae*	–
Almaguer et al. [11]	Surface Air System (SAS)	100		Viable PDA Agar	*Curvularia trifolii* *Curvularia aeria* *Curvularia clavata* *Curvularia pallescens* *Bipolaris australiensis* *Bipolaris hawaiiensis* *Bipolaris sorghicola*	T
Almaguer et al. [32]	Surface Air System (SAS)	100	–	Viable PDA Agar	*Bipolaris* *Curvularia* *Alternaria* *Pyricularia* *Fusarium* *Cercospora* *Penicillum* *Aspergillus* *Cladosporium* *Lacellina* *Nigrospora* *Chrysonilia* *Epicoccum* *Pestalotia* *Monodictys* *Eurotium* *Chaetomium* *Acremonium* *Drechslera* *Phoma* *Torula* *Paecilomyces*	T, RH, DP
Almaguer et al. [33]	Surface Air System (SAS)	20 L	2 m	Viable PDA Agar	*Alternaria* *Curvularia* *Bipolaris* *Cercospora* *Pyricularia*	T, RH
Muñoz et al. [10]	Burkard personal volumetric sampler	10 L	12 cm	Non viable Direct microscopy	*Alternaria* Ascospores *Aspergillus* Basidiospores *Botrytis* *Bovista* *Cercospora* *Cladosporium herbarum* *C. cladosporioides* *Curvularia* *Chaetomium* *Drechslera* *Epicoccum* *Fusarium* *Heliconia* *Leptosphaeria* Myxomycetes *Nigrospora* *Oidium* *Paraphaeosphaeria* *Peronospora* *Pithomyces* *Pleospora* *Polithryncium* *Spegazzinia* *Stemphylium* *Telephora* *Tilletia* *Torula*	T, RH, R, WV, WD

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Table 5 (*continued*)

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
					Uredospore Smooth *Ustilago* Rough *Ustilago* *Venturia*	
Castejón-Muñoz [34]	Exposure microscope slides covered with glycerine	–	35 and 70 cm	Non viable Direct microscopy	*Pyricularia oryzae*	T, RH
Uddin [35]	Exposure Petri plate	–	–	Viable MEA with streptomycin	*Aspergillus* *Aspergillus niger* *A. fumigatus* *A. terreus* *A. parasiticus* *A. nidulans* *A. ochraceus* *A. sydowii* *Penicillium* *P. rubrum* *P. islandicum* *Curvularia* *C. lunata* *C. pallescens* *Cladosporium* *C. herbarum* *C. cladosporioides* *Alternaria* *A. tenuissima* *A. humicola* *A. tenuis* *Fusarium* *Sclerotium rolfsii* *Helminthosporium* *H. sativum* *Nigrospora sphaerica* *N. oryzae* *Epicoccum purpurascens* *Cephalosporium* *Humicola* *Chaetomium* *Chaetomium globosum* *Rhizopus* *Pestalotia truncata* *Pullularia pullulans* *Trichoderma lignorum* *Mucor* *Stemphylium* *Sordaria fimicola* *Candida* *Beltrania* *Dendrographium* *Torula herbarum* *Graphium* *Spicaria divaricata* *Monilia*	T, RH, R
Chakraborty et al. [36]	Burkard 7-day spore-monitoring trap	–	0.5 m	Non viable Direct microscopy	*Alternaria* Ascospores Aspergilli group Basidiospores *Beltrania* *Cercospora* *Chaetomium* *Cladosporium* *Curvularia* *Drechslera* *Epicoccum* *Fusarium* *Fusicladium* *Ganoderma* *Gomphus* *Humicola* *Nigrospora* *Periconia* *Periconiella* *Podospora*	T, RH, R, WS

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Table 5 (*continued*)

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
					Stigmina Teleutospores *Tetracoccosporium* *Tetraploa* *Torula* Uredospores	
	Exposure Petri plate	–	–	Viable DIFCO medium	*Alternaria tenuis* *Aternaria alternata* *Alternaria padwickii* *Cladosporium herbarum* *C. cladosporioides* *Curvularia lunata* *Curvularia pallescens* *Drechslera oryzae* *Fusarium roseum* *Nigrospora oryzae* *Nigrospora spherica* *Aspergillus flavus* *Aspergillus japonicus* *Aspergillus fumigatus* *Mucor racemosus* *Penicillium citrimum* *Rhizopus nigricans*	
Picco and Rodolfi [37]	Automatic volumetric spore trap VPPS Lanzoni	10	1.5 m	Non viable Direct microscopy	*Pyricularia grisea* *Bipolaris oryzae*	T, RH, R
	Exposure Petri plate	–	–	Viable PDA Agar	*Acremoniella atra* *Acremonium fusidioides* *A. kiliense* *Alternaria alternata* *Aspergillus fumigatus* *A. niger* *Aureobasidium pullulans* *Botrytis cinerea* *Cladosporium* spp. *Cunninghamella elegans* *Curvularia lunata* *Epicoccum nigrum* *Fusarium avanaceum* *F. moniliforme* *F. oxysporum* *F. solani* *F. tricinctum* *Gliocladium* *Monocillium mucidum* *Mortierella isabellina* *Nigrospora oryzae* *Penicillium citrinum* *P. funicolosum* *P. glabrum* *P. janthinellum* *P. oxalicum* *P. purpurogenum* *Penicillium* sp. *Pithomyces chartarum* *P. maydicus* *Scopulariopsis brevicaulis* *Trichoderma viride*	
Uddin and Chakraverty [38]	Exposure Petri plate	–	162 cm (Max)	Viable MEA with streptomycin and sodium deoxycholate	*Aspergillus* spp. *Cladosporium* spp. *Curvularia* spp. *Penicillium* spp. *Alternaria* spp. *Fusarium* spp. *Helminthosporium oryzae* *Cephalosporium* spp. *Trichoderma* spp. *Mucor* sp. *Nigrospora* spp.	T, RH, R

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Table 5 (*continued*)

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
					Humicola spp. *Chaetomium* sp.	
Uddin and Chakraverty [39]	Exposure Petri plate	–	–	Viable MEA with streptomycin and sodium deoxycholate	*Aspergillus parasiticus* *A. ochraceus* *A. candidus* *Aspergillus* spp. *A. niger* *Penicillium* spp. *Cladosporium herbarum* *Alternaria* spp. *Alternaria tenuissima* *Drechslera* spp. *Curvularia* spp. *C. interseminata* *C. geniculata* Yeast *Trichoderma lignorum* *T. koningi* *Fusarium* spp. *Cephalosporium* sp. *Diplodia* sp. *Verticillium* sp. *Brachysporium* sp.	T, RH, R
Atluri et al. [40]	Rotorods sampler	–	1.5 m	Non viable Direct microscopy	*Nigrospora* *Myrothecium* *Trichoconis* *Ustilaginoidea virens* *Drechslera* *Periconia* *Cladosporiurn* *Arthrobotrys* *Cercospora* *Stachybotrys type* *Pyricularia oryzae* *Nakataea sigmoidea* *Cochiliobolus miyabeanus*	
Atluri et al. [41]	Rotorods sampler	–	1.5 m	Non viable Direct microscopy	*Nigrospora* *Cladosporiurn* *Periconia* *Stachybotrys type* *Trichoconis* *Myrothecium* *Cercospora* *Usrilaginoidea virens* *Drechslera* *Leptosphaeria errstornoide*	

Captions: PDA: Potato Dextrose Agar, MEA: Malt Extract Agar, T: Temperature, RH: Relative Humidity, WS: Wind Velocity, WD: Wind direct, R: Rainfall.

review, this relationship was not evaluated in all studies. Temperature, relative humidity and rainfall were the main meteorological variables that were related to the air concentration of fungi. This relationship was variable, since it depended on the phytopathogen to be determined and the climatic conditions of the region where the study was carried out. For example, Schiro et al. [17] found a negative correlation between temperature and *Fusarium* concentrations in the air of a wheat field in Germany. While Rossi et al. [28] found for this same genus a positive relationship with temperature in Italy. All these studies put emphasis on the statistical analysis of the correlation between the level of concentration of particular fungal spore types and weather parameters, but do not examine the complex composition of spores and its dependence on meteorological factors and in some of them the analysis is only at the qualitative level. The relationship between meteorological variables and aeromycology is undoubtedly an important tool for detecting conditions conducive to the emission and dissemination of fungal propagules and determining their possible influences.

The use of predictive models for cereal pathogens can be useful in preventing or reducing yield losses, depending on the appropriate timing for spraying chemicals [56]. However, there are few studies included in this review that propose predictive models. This may be due to the fact that in order to design these models it is necessary to have a multi-year database with information on pathogen concentrations and their relationship with different abiotic factors for each growing area. Researches that proposed prediction models were conducted on wheat crops. These were Newlands [15], Cao et al. [14], and Rossi et al. [28]. Newlands [15] proposed a spatially explicit complex model for wheat rust prediction in southern Alberta, Canada. Rossi et al. [28] found two regression equations that gave an accurate estimate of airborne *Fusarium* dynamics on rainy and non-rainy days in Italy, which included mean air temperature, the amount and intensity of rainfall on the previous day, and the number of hours with high relative humidity. While Cao et al. [14] in China proposed cumulative logit models to relate wheat powdery mildew development to meteorological variables and airborne conidial density to be further evaluated.

Table 6
Summary of the collection methods of the fungi identified and their relationship with meteorological variables in corn, sorghum and barley crops.

Study	Method of fungi collection	Air flow (L min $^{-1}$)	High (above the ground)	Identification method	Identified fungi	Influence of Meteorology on airborne fungi
Corn						
Dónat et al. [42]	Andersen Hirst spore traps	28.3 10	–	Viable PCNB-Rose Bengal agar	*Gibberella fujikuroi*	
Schmale et al. [25]	Exposure Petri plate	–	–	Viable FSM	*Fusarium graminearum*	
Inch et al. [43]	Rotorods samplers		–	Non viable	*Fusarium graminearum*	
	Burkard 7-day spore-monitoring trap	12	–	Direct microscopy		
Schmale et al. [44]	Exposure Petri plate	–	–	Viable FSM	*Fusarium graminearum*	
Schmale and Bergstrom [45]	Exposure Petri plate	-	-	Viable FSM	*Fusarium graminearum*	T, R
Sorghum						
Funnell-Harris and Pedersen [46]	Exposure Petri plate		–	Viable	*Fusarium thapsinum*	T, RH
				PDA Agar and PCR	*Fusarium verticillioides* *Fusarium proliferatum* *Fusarium andiyazi* *Fusarium graminearum* *Fusarium subglutinans* *Fusarium incarnatum* *Fusarium equiseti*	
Barley						
Fountaine et al. [47]	Burkard 7-day spore-monitoring trap	–	–	Non viable Real time PCR	*Rhynchosporium secalis*	
Martin and Clough [48]	Kramer-Collins 7-day continuous deposit spore sampler	10	120 cm	Non viable Direct microscopy	*Pyrenophora teres*	T, RH, SR, WS

Captions: PCNB: Pentachloronitrobenzene, FSM: *Fusarium*-selective medium, PDA: Potato Dextrose Agar, T: Temperature, RH: Relative Humidity, WS: Wind Velocity.

5. Conclusions

Our systematic review provides an important contribution to the field by synthesizing aeromycological studies that have been conducted on wheat, rice, corn, sorghum, and barley crops. The thorough analysis by two independent investigators of the risk of bias, the study selection and data collection procedure, and the extensive analyses performed are strengths to be acknowledged. Despite these strengths, one limitation is the use of a single database for searching articles. It was observed that most of the aeromycological studies on these cultivars are directed to the detection of a specific phytopathogen through appropriate collection and identification methods. The use of a worldwide methodology for collection and identification of fungal propagules in cereal crops is suggested to allow comparison of results between different geographical locations. Likewise, future research should include the relationship of the fungi identified with the affections caused to plants in the field at the time of sampling and their relationship with meteorological factors by quantitative methods, allowing the design of predictive models.

Author contributions

Conceptualization, K.C.S.E.; methodology, K.C.S.E. and L.D.V.; validation, M.F.G., M.A. and F.J.R.R.; formal analysis, K.C.S.E., L.D.V. and M.A.; data curation, M.F.G and F.J.R.R.; writing—original draft preparation, K.C.S.E.; writing—review and editing, K.C.S.E., L.D.V., M.F.G., M.A. and F.J.R.R.; visualization, K.C.S.E. and M.F.G.; supervision, M.A. and F.J.R.R. All authors have verified the underlying data, and read and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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