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EXPERIMENTAL ARTICLES

Ecological Diversity of Micromycetes in Aerial Environments of Russian Libraries

T. D. Velikova[a], *, E. A. Popikhina[a], E. S. Trepova[a], **, and S. S. Khazova[a]

[a] *Federal Center for Library Stock Preservation, National Library of Russia, St.-Petersburg, 191069 Russia*

**e-mail: fcc@nir.ru*

***e-mail: k.trepova@gmail.com*

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Abstract—The structure of micromycete communities in the library aerial environment was investigated in 57 Russian cities located in seven federal districts (Northwestern, Central, Southern, Volga, Ural, Siberian, and Far Eastern). A total of 107 micromycete species belonging to 41 genera were isolated and identified. Due to mostly similar conditions, the aerial ecosystem of internal spaces of the library storage facilities was relatively stable, with moderate diversity and high evenness, as was confirmed by the relevant indices: the Shannon index varied from 2.7 to 3.4, the McIntosh diversity index, from 22.7 to 140.8, and the Menhinick index, from 2.1 to 3.0. The Simpson's dominance index and the Berger–Parker index did not exceed 0.11 and 0.24, respectively. The McIntosh and Pielou's evenness indices were 0.71–0.78 and 0.79–0.85, respectively. High similarity of the taxonomic structures, independent of climatic conditions of the studied regions, was revealed, as was confirmed by the values of the Stugren–Radulescu and Morisita–Horn coefficients: 0.08–0.77 and 0.04–0.47, respectively. The typical members of the studied mycobiota were *Aspergillus versicolor* (7.5–14.3), *Cladosporium cladosporioides* (17.5–40.5), *C. herbarum* (0.8–53.6), and *Penicillium aurantiogriseum* (6.5–32.4). Most other species were scarce, with frequencies of occurrence not exceeding 7.1%.

Keywords: fungi, micromycetes, aeromycota, biodiversity, libraries, written heritage

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Spores of mold fungi are a major component of atmospheric air bioaerosols. The presence of significant amounts of micromycetes in the air of libraries can be hazardous to the health of custodians and readers on the one hand, and to documents on the other, as many species have cellulase and proteolytic activity and are capable of damaging library materials.

Fungi are found in all repositories in various countries with a wide range of climatic conditions, and their source is the outdoor air. Indoor conditions in libraries, archives, and museums are generally similar, but the ventilation and air conditioning systems in the buildings affect the concentrations of airborne microorganisms.

The most comprehensive analysis of aeromycota of cultural heritage objects summarized the results of studies from 27 different countries (Pinheiro et al., 2019). According to this review, a total of 580 fungal species representing 207 genera were identified. The fungal genera most commonly found in archives and libraries were *Alternaria*, *Aspergillus*, and *Penicillium*; elevated frequency of occurrence was reported for *Chaetomium*, *Fusarium*, and *Geotrichum* by Pinheiro et al. (2019). Many fungi isolated from air are capable of degrading cellulose (García et al., 2014). Members of the genera *Alternaria*, *Aspergillus*, *Chaetomium*, *Cladosporium*, *Mucor*, *Penicillium*, *Rhizopus*, *Stachybotris*, *Stemphylium*, and *Trichoderma* occur ubiquitously (Zyska, 1997; García et al., 2014). The most common findings were *Paecilomyces* (Maggi et al., 2000; Bogomolova, 2012; Caicedo et al., 2023), *Candida* and *Rhodotorula* (Borrego and Perdomo, 2014), *Aureobasidium* (Popikhina et al., 2018; Chuenko et al., 2020), *Botrytis*, *Cephalosporium*, *Phoma* (Zielińska-Jankiewicz et al., 2008; Popikhina et al., 2018), *Cephalosporium*, *Humicola*, *Phoma* (Rojas et al., 2012; Zerek, 2014; Ghosh et al., 2014), *Ulocladium* (Trepova et al., 2011; Velikova et al., 2012; Lebedeva and Mamaeva, 2012). The most frequent findings in the air and on the surfaces were fungi of the genera *Aspergillus*, *Penicillium*, and *Cladosporium* (Borrego and Perdomo, 2016; Pyrri et al., 2020); furthermore, *Aspergillus* is the dominant genus in tropical regions.

In addition to the ubiquitously occurring ten fungal genera listed above, the air mycobiota of each library also includes specific micromycetes with high abundances. For instance, significant numbers of *Arthrinium* and *Epicoccum* were observed in libraries of Michigan (Burge et al, 1978); *Chrysonilia* and *Curvularia* were found in Columbia (Caicedo et al., 2023); *Curvularia*, *Drechslera*, *Fusarium*, *Geotrichum*, *Hel-*

minthosporium, and *Sirosporium* were typical for Indian libraries with humidity levels reaching 90% in summer (Ghosh et al., 2014); *Eidamella*, *Fusidium*, *Mortierella*, and *Myxotrichum* were present in the library of the Lviv University (Yavorska et al., 2016); *Alternaria*, *Eurotium*, *Fusarium*, and *Chrysonilia* were abundant in the National Museum of Music in Cuba (García et al., 2014), while *Alternaria* and *Cladosporium* dominated in the library of the Technical University in Romania (Apetrei et al., 2009). In archives of Warsaw, the most frequently found micromycetes represented the genera *Epicoccum*, *Fusarium*, and *Scopulariopsis*, while in the library of Warsaw University, the most frequent genera were *Gliomastix*, *Rhizoctonia*, *Rhodotorula*, and *Stysanus* (Zielińska-Jankiewicz et al., 2008). Along with fungi occurring in other libraries, some rare species of the genera *Bipolaris*, *Chaetosartorya*, *Emericella*, *Cunninghamella*, *Monocillium*, *Pithomyces*, *Periconia*, and *Staphylotrichum* were isolated from the air of seven historical buildings in Havana that serve for the storage of documents, books, pictures, photographs, and pre-Columbian cultural artifacts (Rojas et al., 2012). Other rare species representing *Beltraniella*, *Chrysosporium*, *Harposporium*, *Neurospora*, *Nigrospora*, and *Scolecobasidium* were detected in the air of the National Archive of Cuba (Borrego et al., 2022). In the National Library of Greece, there were fungi of some genera that were not reported from other libraries: *Acrodontium*, *Arthrinium*, *Chalastospora*, *Dichobotrys*, *Myrothecium*, and *Spiniger* (Pyrri et al., 2020), and members of *Syncephalastrum* were detected in the medical library of Iran (Chadeganipour et al., 2013).

Micromycetes of the genera *Exophiala*, *Gilmaniella*, *Oidiodendron*, *Phaeococcomyces*, *Sphaerostilbella*, *Phialemonium*,* and *Pseudogymnoascus** were isolated from the air of the Scientific Library of St. Petersburg University (*taxa are listed according to the modern nomenclature) (Bogomolova, 2014). Numerous fungal genera were identified in the air of the Russian National Library; some genera were detected in all repositories: *Acremonium*, *Chrysonilia*, *Microascus*, *Oospora*, *Scopulariopsis*, *Sporotrichum*, and *Torula*, while others were present only in some storerooms: *Chloridium*, *Hormodendrum*, *Monocillium*, *Phialophora*, *Rhinocladium*, *Tubercularia*, *Verticillium* (Trepova et al., 2011; Popikhina et al., 2018), *Aureobasidium*, *Pseudocosmospora**, *Sphaerostilbella*, *Stachylidium, Talaromyces* (Bogomolova, 2014; Velikova et al., 2012), *Ascochyta*, *Geotrichum*, *Fusarium*, *Paecilomyces*, and *Trichosporiella* (Lebedeva and Mamaeva, 2012). Fungi of the genera *Acrothecim*, *Chloridium*, *Curvularia*, *Epicoccum*, *Helminthosporium*, *Pellicularia*, *Pullularia*, *Rhizoctonia*, *Sepedonium*, *Thielavia*, *Trichocladium*, and *Verticillium* were detected in libraries of Poland (Zerek, 2014), while members of *Arthrobotrys*, *Chrysonilia*, *Dendryphium*, *Exophiala*, *Hormiscum*, and *Mortierella* were identified in institute libraries of Kyiv (Chuenko et al, 2020).

Dust is a carrier of fungal spores and, in addition to its physical impact on document materials, it also represents a specific microenvironment and trophic resource for microorganisms. In the State Archive in Rome, dust from a poorly ventilated room was found to contain fungi of the genera *Acremonium*, *Alternaria*, *Arthrinium*, *Aspergillus*, *Chaetomium*, *Cladosporium*, *Emericella*, *Penicillium*, *Periconia*, *Pithomyces*, *Torula*, and *Trichoderma* (Maggi et al., 2000); dust of the National Archive of Cuba contained *Aspergillus*, *Cladosporium*, and *Penicillium* (Borrego et al., 2022), and in the library of the Technical University in Iaşi (Romania), the dust in the vicinity of computers contained members of *Aspergillus*, *Penicillium*, *Cladosporium*, *Alternaria*, *Fusarium*, and *Chaetomium* (Apetrei et al., 2009).

The quantitatively dominant groups were the genera *Aspergillus* (11–48%), *Penicillium* (23–89%), *Cladosporium* and *Fusarium* (10–18%), *Rhizopus* (6%); *Alternaria* and *Trichoderm*a were less abundant (Rojas et al., 2012; Caicedo et al., 2023).

Among members of the genus *Aspergillus*, *A. niger* was present ubiquitously and commonly dominated. Along with *A. niger*, the following species were most abundant in various library environments: *A. flavus* in the library of the Madrid Museum (Rodrigo, 1974), *A. caespitosus*, *A. sydowii*, and *A. versicolor* in the National Library of Greece (Pyrri et al., 2020), *A. fumigatus* and *A. versicolor* in the library of the University of Michigan (Burge et al., 1978), and *A. caespitosus*, *A. fumigatus*, *A. flavus*, *A. candidus*, *A. flavus*, *A. fumigatus*, and *A. ochraceus* in libraries of India (Ghosh et al., 2014). In addition to those listed above, the following *Asperigillus* species were isolated from the air of the Russian National Library *A. clavatus*, *A. flavipes*, *A. terreus*, and *A. repens* (Lebedeva and Mamaeva, 2012). In Yerevan, 16 species of the genus *Aspergillus* were isolated from the air of libraries, in particular, *A. awamori*, *A. candidus*, *A. carbonarius*, *A. kambarensis*, *A. nidulans*, *A. restrictus*, *A. recurvatus*, *A. sulphureus*, and *A. terricola* (Eloyan et al., 2016). *A. sydowii*, *A. japonicus*, and *A. versicolor* were found in archives in Italy (Maggi et al., 2000). In Ukraine, the predominant species in the library air was *A. tenuissima*, while *A. flavus* and *A. fumigatus* were minor species (Chuenko et al., 2020). A new species was isolated from a museum repository in Cuba: *Aspergillus carneus* (García et al., 2014).

The genus *Penicillium* was most commonly represented by the following species: *P. herquei* (Ghosh et al., 2014), *P. notatum* and *P. lanosum*, *P. chrysogenum*, *P. brevicompactum* (Bogomolova, 2014), *P. chermesinum*, *P. citreonigrum*, *P. citrinum*, *P. coprophylum*, *P. corylophilum*, *P. digitatum*, *P. griseofulvum*, *P. italicum*, *P. lividum*, *P. miczynskii*, *P. oxalicum*, *P. puberulum*, *P. restrictum*, *P. rugulosum*, *P. viridicatum*, *P. waksmani* (Maggi et al., 2000). In the Russian National Library, there were also *P. camemberti*,

P. commune, *P notatum*, *P. corymbiferum*, *P. ochlochloron*, *P. oxalicum, P. simplicissium*, *P. solitum*, and *P. glabrum* (Trepova et al., 2011; Velikova et al., 2012; Popikhina et al., 2018). The dominant species was *P. aurantiogriseum*, although its presence was rarely reported in the air of other libraries.

During mycological analysis of library air, an issue of extreme importance is isolation of fungi producing cellulolytic and proteolytic enzymes, since they are potential agents of biological damage to library materials (Ghosh et al., 2014; Yavorska et al., 2016). In case of detecting fungi of the genera *Chaetomium*, *Trichoderma*, and *Stachybotrys*, it is essential to monitor the state of documents to prevent colonization of paper surfaces. The presence of elevated concentrations of *Stachybotrys atra*, *Trichoderma viride*, and *Stachybotrys chartarum* (Pinheiro et al., 2019; Pyrri et al., 2020) in the air of libraries is inadmissible, since they represent a hazard both for valuable documents and for the health of librarians, conservation professionals, and readers. The range of fungi potentially capable of causing aspergillosis and mycosis with various clinical manifestations includes *A. flavus*, *A. fumigatus*, *A. versicolor*, *A. candidus*, *A. clavatus*, *A. glaucus*, *A. nidulans*, *A. niger*, *A. restrictus*, *A. sydowii*, and *A. terreus*, which are consistently detected in library air; among them, the most hazardous are the first three species.

The goal of this work was to evaluate species richness and taxonomic structure of micromycetes isolated from the air of libraries in various regions of Russia and to identify the micromycete complex typical of library air environments.

MATERIALS AND METHODS

Microbial samples from the library air were collected by aspiration using a MAS-100 Eco device (Merck Millipore, Germany). Air samples were collected on the Czapek–Dox medium from different floors of the library or different tiers in tier-type repositories according to the envelope scheme: one sample in the center and four in the corners of the room. The petri dishes were incubated for 5–14 days at 29 ± 2°C.

Micromycetes from the air samples were isolated, and the cell morphology was analyzed using conventional techniques of light microscopy on Olympus BX 53 M (Olympus Corp., Japan) and Leica DM 2000 (Leica Microsystems, Germany). Micromycetes were identified based on the cultural and morphological traits according to the manuals by different authors (Raper et al., 1968; Raper et al., 1977; Sutton et al., 1997; Domsch et al., 2007). The taxon names are given according to Index Fungorum, a database of mycological nomenclature.

The presence of fungi in air samples was characterized by frequency of occurrence.

The hierarchy of mycobiota was analyzed based on ratios of taxonomic ranks: species per family (S/F), genera per family (G/F), species per genus (S/G), and species per class (S/C).

The structure of the fungal communities was analyzed using the Shannon diversity index, the evenness indices by Pielou and McIntosh (D_{Mc}), the dominance indices by Simpson (D) and Berger–Parker, and the diversity indices by McIntosh (U) and Menhinick.

The similarity of airborne mycobiota of different regions was analyzed using the Stugren–Radulescu binary coefficient of species difference (p_s) and the Morisita–Horn similarity index (C_{MH}) (Leont'ev, 2008; Magurran, 2013).

This work summarizes data on the mycological status of the air of oblast and regional libraries in 57 cities situated in seven Federal Districts (FDs) of Russia:

— eight cities of the Northwestern FD (Nw);

— eleven cities of the Central FD (C);

— six cities of the Southern FD (St);

— eleven cities of the Volga FD (V);

— Chelyabinsk and Khanty-Mansiysk cities in the Ural FD (Ur);

— nine cities of the Siberian FD (Sb);

— seven cities of the Far Eastern FD (FE).

The composition of aeromycota observed in different FDs of Russia was compared to the species composition of micromycetes isolated from the air of six libraries of St. Petersburg (SPb).

The data were processed by multivariate statistic analysis using Microsoft Excel and Statistica Ultimate Academic 13.3.

RESULTS AND DISCUSSION

The total number of air samples collected in the library storerooms in all regions was 1409, and the total number of identified isolates was 2221. Altogether, 107 micromycete species representing 41 genera were identified (Table 1).

The air in the repositories was always of satisfactory quality, and the number of colony-forming units did not exceed the threshold of 500 CFU/m^3 recommended by the World Health Organization (WHO, 1990).

Since R. Whittaker introduced the basic notions of diversity, no rigorous methods for its quantification have been developed to date. The best option for assessing biodiversity remains calculating and discussing the multifractal spectra of the species structure of communities (Rosenberg, 2013).

In all FDs, the level of species diversity was moderate with 26 to 72 species; the Shannon index ranged from 2.7 to 3.4. The largest number of species (72) was isolated from repository air in the Central FD; here, the Shannon index had the maximum value of 3.4. The major shortcoming of the Shannon index in comparison to other indices is that it is too much affected

Table 1. List of micromycetes species isolated from library storeroom air in Russia

Micromycete species	SPb	Nw	C	St	V	Ur	Sb	FE
Acremonium charticola (Lindau) W. Gams		+	+					
Acremonium rutilum W. Gams			+					
Alternaria alternata (Fr.) Keissl.		+	+	+	+	+	+	+
Alternaria consortialis (Thüm.) J.W. Groves et S. Hughes		+	+	+	+		+	+
Alternaria tenuissima (Kunze) Wiltshire	+			+				
Ascospirella lutea (Zukal) Houbraken, Frisvad et Samson					+			
Aspergillus alliaceus Thom et Church								+
Aspergillus candidus Link								+
Aspergillus elegans Gasperini	+							
Aspergillus fischeri Wehmer	+							
Aspergillus flavipes (Bainier et R. Sartory) Thom et Church				+				
Aspergillus flavus Link	+	+	+	+	+		+	+
Aspergillus fumigatus Fresen.		+	+	+	+		+	
Aspergillus neoniveus Samson, S.W. Peterson, Frisvad et Varga			+					
Aspergillus nidulans (Eidam) G. Winter			+					
Aspergillus niger Tiegh.	+	+	+	+	+	+	+	+
Aspergillus ochraceus G. Wilh.		+	+		+		+	+
Aspergillus repens (Corda) Sacc.		+				+		+
Aspergillus sclerotiorum G.A. Huber			+					
Aspergillus silvaticus Fennell et Raper			+					
Aspergillus sulphureus (Fresen.) Thom et Church				+	+			
Aspergillus sydowii (Bainier et Sartory) Thom et Church	+	+	+	+	+			+
Aspergillus terreus Thom	+							
Aspergillus terricola Marchal et É.J. Marchal				+				
Aspergillus ustus (Bainier) Thom et Church		+	+	+	+		+	+
Aspergillus versicolor (Vuill.) Tirab.		+	+	+	+	+	+	+

Table 1. (Contd.)

Micromycete species	SPb	Nw	C	St	V	Ur	Sb	FE
Aspergillus wentii Wehmer								+
Aureobasidium pullulans (de Bary et Löwenthal) G. Arnaud			+		+		+	
Beauveria bassiana (Bals.-Criv.) Vuill.			+					
Bisifusarium dimerum (Penz.) L. Lombard et. Crous			+					
Botrytis cinerea Pers.	+	+	+	+	+	+	+	+
Chaetomium globosum Kunze		+	+	+	+	+		
Cladosporium brevicompactum Pidopl. et Deniak		+			+			
Cladosporium cladosporioides (Fresen.) G.A. de Vries	+	+	+	+	+	+	+	+
Cladosporium herbarum (Pers.) Link		+	+	+	+	+	+	+
Cladosporium sphaerospermum Penz.		+	+	+		+		+
Cordyceps farinosa (Holmsk.) Kepler, B. Shrestha et Spatafora		+	+	+				
Cosmospora butyri (J.F.H. Beyma) Gräfenhan, Seifert et Schroers				+				+
Didymella glomerata (Corda) Qian Chen et L. Cai				+			+	
Fusarium anguioides Sherb.		+						
Fusarium poae (Peck) Wollenw.			+					
Fusarium solani (Mart.) Sacc.			+					+
Fusarium sporotrichioides Sherb.								+
Geotrichum candidum Link			+	+		+	+	
Hypomyces chrysospermus Tul.						+		
Ilyonectria radicicola (Gerlach et. L. Nilsson) P. Chaverri et Salgado						+		
Microascus brevicaulis S.P. Abbott			+		+			
Monilia pruinosa Cooke et Massee			+					
Mucor circinelloides Tiegh.				+				
Mucor plumbeus Bonord.		+	+	+	+		+	+
Mycelia sterilia light-colored			+	+	+	+	+	+
Mycelia sterilia dark-colored			+	+		+		+
Neurospora sitophila Shear et B.O. Dodge		+	+	+	+			
Oospora lutea Kamyschko		+	+	+	+			+

Table 1. (Contd.)

Micromycete species	SPb	Nw	C	St	V	Ur	Sb	FE
Paecilomyces variotii Bainier	+		+	+	+		+	+
Penicillium aurantiogriseum Dierckx	+	+	+	+	+	+	+	+
Penicillium brevicompactum Dierckx		+	+	+	+	+		+
Penicillium camemberti Thom		+	+	+	+	+	+	+
Penicillium canescens Sopp	+	+	+					
Penicillium chrysogenum Thom		+	+	+				+
Penicillium commune Thom		+	+	+	+	+	+	+
Penicillium corylophilum Dierckx		+	+					
Penicillium decumbens Thom			+		+			+
Penicillium elegans Sopp					+		+	
Penicillium expansum Link							+	
Penicillium glabrum (Wehmer) Westling		+	+	+	+			+
Penicillium granulatum Bainier	+	+	+		+			
Penicillium herquei Bainier et Sartory			+		+			
Penicillium hirsutum Dierckx			+				+	
Penicillium implicatum Biourge			+		+			+
Penicillium janczewskii K.W. Zaleski					+			
Penicillium jensenii K.W. Zalessky	+	+		+		+		+
Penicillium lanosum Westling	+		+		+		+	+
Penicillium miczynskii K.W. Zalessky		+						+
Penicillium multicolor Grig.-Man. et Porad.	+							
Penicillium nalgiovense Laxa	+			+				
Penicillium ochrochloron Biourge	+	+	+		+		+	
Penicillium purpurescens (Sopp) Biourge		+						
Penicillium simplicissimum (Oudem.) Thom		+	+		+			+
Penicillium solitum Westling			+		+		+	+
Penicillium spinulosum Thom	+							
Penicillium thomii Maire			+					+

Table 1. (Contd.)

Micromycete species	SPb	Nw	C	St	V	Ur	Sb	FE
Ramichloridium apiculatum (J.H. Mill., Giddens et A.A. Foster) de Hoog						+		
Rectifusarium ventricosum (Appel et Wollenw.) L. Lombard et Crous			+					
Rhizopus stolonifer (Ehrenb.) Vuill.	+	+	+	+	+			+
Phoma herbarum Westend.			+			+		
Sarocladium strictum (W. Gams) Summerb.		+	+			+		+
Scopulariopsis brumptii Salv.-Duval			+					
Sporothrix schenckii Hektoen et C.F. Perkins								+
Sporotrichum verticillatum Spreng.			+	+	+			+
Stachybotrys chartarum (Ehrenb.) S. Hughes		+	+					
Stemphylium botryosum Wallr.			+					
Taeniolella stilbospora (Corda) S. Hughes			+					
Talaromyces duclauxii (Delacr.) Samson, N. Yilmaz, Frisvad et Seifert			+					
Talaromyces funiculosus (Thom) Samson, N. Yilmaz, Frisvad et Seifert	+			+	+			
Talaromyces purpureogenus Samson, N. Yilmaz, Houbraken, Spierenb., Seifert, Peterson, Varga et Frisvadm	+		+		+			+
Talaromyces ruber (Stoll) N. Yilmaz, Houbraken, Frisvad et Samson						+		
Talaromyces rugulosus (Thom) Samson, N. Yilmaz, Frisvad et Seifert	+							
Talaromyces variabilis (Sopp) Samson, N. Yilmaz, Frisvad et Seifert	+	+	+					+
Torula expansa (Kunze) Pers.					+			+
Torula herbarum (Pers.) Link		+	+	+	+	+	+	+
Torula lucifuga Oudem.	+	+	+	+		+	+	
Trichoderma koningii Oudem.			+					
Trichoderma polysporum (Link) Rifai			+					
Trichoderma pseudokoningii Rifai	+							
Trichoderma viride Pers.		+	+	+	+		+	+
Trichosporum macrosporum Kamyschko				+				
Tritirachium roseum J.F.H. Beyma								+
Verticillium terrestre (Pers.) Sacc.			+					

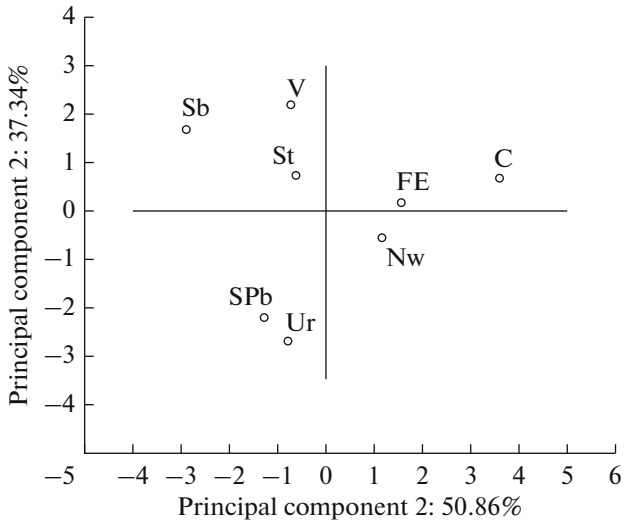

Fig. 1. Distribution of air mycobiota diversity in libraries in Russia in the space of principal components.

by rare species (Odum, 1983). The values of the McIntosh diversity index (*U*), which depends on the number of species and the number of samples in the set, confirmed this notion and indicated that species richness was the highest in the airborne fungal complexes isolated in the Central FD (140.8), whereas the airborne fungal communities of the libraries of the Ural FD and St. Petersburg had the lowest species richness with *U* values of 22.7 and 22.8, respectively. In aeromycota of other districts, the values of species richness ranged from 72.6 to 107.9.

To compensate the effect of different sample sizes, we calculated the Menhinick index, which showed a significantly lower dispersion of species richness values than the McIntosh diversity index: from the highest in the libraries of St. Petersburg and the Ural FD (3.0) to the lowest in the Siberian FD (2.1), indicating that the aeromycota of library repositories had a high species richness in all regions.

In all samples of airborne micromycetes, the levels of dominance were low. This was demonstrated by the low values of the Simpson's dominance index (*D*), which did not exceed 0.1 in any district except the Siberian FD, where it was only slightly higher: 0.11. The values of the alternative Berger–Parker index, which shows the degree of dominance of the most abundant species, were also low, ranging from 0.16 (minimum) in the Far Eastern FD to 0.24 (maximum) in the Southern and the Volga FDs.

Species evenness in the air of repositories was calculated using two indices that depend in different ways on the sample size. In all regions, this parameter was consistently high, as indicated by the values of both the Pielou's index (0.79–0.85) and the McIntosh evenness index (0.71–0.78), which were not significantly affected by the size of the samples or by the number of species identified. This suggests a lack of species competition in each micromycete complex isolated from the air of libraries.

Considering the large number of diversity indices used, each with its own limitations and sensitivity, it may be difficult to evaluate comprehensively the results obtained. In order to take into account the influence of each index, we applied principal component analysis (PCA) to visualize the spatial distribution of micromycete complexes isolated from the air of repositories in different districts (Fig. 1).

The matrix of differences included the number of species and the indices of species richness, dominance, evenness, and diversity (Table 2).

The divergence by the first and the second principal components described 50.9 and 37.3% of the total variation, respectively. The remaining factors accounted for 11.8% of the total variation; they were not included in the further analysis. In the space of principal components, the aeromycotas of the districts were clearly separated into three clusters. One group was formed by the fungal complexes of the Southern and the Volga districts with moderately continental climate; however, they were remote from the com-

Table 2. Ecological diversity of micromycetes in the air of library storerooms in different regions of Russia

Parameter	SPb	St	V	C	FE	Sb	Nw	Ur
Total number of isolates (*N*)	73	237	347	551	388	228	323	74
Total number of samples	37	146	243	372	213	155	217	26
Total number of species	26	43	45	72	50	31	43	26
Shannon diversity index (*H*)	2.70	2.98	2.89	3.40	3.12	2.76	3.08	2.77
McIntosh diversity index (*U*)	22.8	72.6	107.9	140.4	103.9	75.8	86.7	22.7
Simpson's dominance index (*D*)	0.09	0.09	0.09	0.06	0.07	0.11	0.07	0.08
Berger–Parker dominance index	0.21	0.24	0.24	0.19	0.17	0.26	0.16	0.20
Menhinick species richness index	3.0	2.8	2.4	3.1	2.5	2.1	2.4	3.0
McIntosh evenness index (D_{Mc})	0.78	0.74	0.73	0.78	0.77	0.71	0.77	0.78
Pielou's evenness index (*E*)	0.83	0.79	0.76	0.79	0.80	0.80	0.82	0.85

Table 3. Ratios of taxonomic ranks in the hierarchy of air mycobiota of library storerooms in different federal districts of Russia

Rank ratios	Taxonomic ratios in different regions							
	SPb	Nw	C	St	V	Ur	Sb	FE
Species/Family	3.7	2.9	3.2	2.4	2.9	1.9	3.0	3.4
Genus/Family	1.4	1.2	1.5	1.2	1.2	1.2	1.2	1.3
Species/Genus	2.6	2.4	2.2	2.1	2.4	1.6	2.5	2.6
Species/Class	5.2	8.6	10.0	5.9	7.3	4.6	5.0	6.7

plexes of the Central and the Ural regions, which have fairly similar climate conditions. At the same time, the cluster formed by the Far Eastern and the Northwestern FDs, where the climate is strongly affected by sea air masses, did not include the aeromycota complexes of St. Petersburg libraries. The third cluster was formed by aeromycotas of libraries of the Ural FD and St. Petersburg, which have dramatically different climates. This result confirms the hypothesis that the geographical location and the regional climate have little effect on the ecological diversity of aeromycota within library repositories, in particular, because only a fraction of fungal species inevitably introduced from outdoors can adapt to the rather special conditions of these environments and remain viable.

The diversity indices suggest that fungal species in the air of library storage facilities formed a fairly stable ecosystem due to similar storage conditions in most cases: during the surveys conducted in summer and autumn, the air temperature was 20–25°C and relative humidity did not exceed 50% (Trepova et al., 2011). In most of the surveyed libraries, there was no climate control equipment, and normalization of the temperature and humidity conditions was achieved by ventilation.

Divisions. The taxonomic structure of aeromycota of document repositories was represented by three divisions: *Ascomycota* accounted for 90% of the species richness and was present in all regions; *Mucoromycota* accounted for 2 to 7% of the species richness and was absent in the Ural FD, and the least abundant division *Basidiomycota* (1–4%) was not represented in the Siberian and the Northwestern FDs.

We compared the hierarchical proportions between the taxonomic ranks of aeromycota of repositories located in different FDs of Russia (average values) and of St. Petersburg libraries and obtained the following results: 2.8 and 3.7 species per family (*S*/*F*), respectively; 1.3 and 1.4 genera per family (*G*/*F*), respectively; 2.3 and 2.6 species per genus (*S*/*G*), respectively; 6.9 and 5.2 species per class (*S*/*C*), respectively. The ratios of taxonomic ranks were relatively stable and exhibited little change depending on distance (Table 3).

Classes. In all districts of Russia, the classes with the highest species richness were *Eurotiomycetes*, *Sordariomycetes*, and *Dothideomycetes*. Their shares in the total number of species ranged considerably: from 36.0 to 80.0% for *Eurotiomycetes*, from 12.0 to 36.0% for *Dothideomycetes*, and from 4.0 to 28.0% for *Sordariomycetes*; other classes accounted for less than 7.1% of the species richness. Members of most classes occurred ubiquitously, but micromycetes of the class *Tritirachiomycetes* were detected only in the Far Eastern FD.

A comparison of the species richness of different classes across districts revealed the following features: the numbers of *Eurotiomycetes* species were the highest in the Volga and the Far Eastern FDs (60.0% of the total number of species); *Sordariomycetes* species were the most numerous in the Ural and the Central FDs (28.0 and 25.4%, respectively), and *Dothideomycetes* species, in the Ural and the Siberian FDs (36.0 and 25.8%, respectively). Fungi of the class *Leotiomycetes* occurred in all FDs, and their species richness was the highest in the Southern FD (7.1% of the total number of species).

Among micromycetes isolated from the air of book repositories in St. Petersburg, the largest number of species represented the class *Eurotiomycetes* (80.0%); furthermore, the number of *Eurotiomycetes* species was higher than in any other district of Russia. At the same time, species of the classes *Agaricomycetes*, *Saccharomycetes*, and *Tritirachiomycetes* were not detected in the air of St. Petersburg libraries, although they occurred in several other regions.

Families. Analysis of taxonomic groups in storeroom aeromycota identified four principal families that were detected in libraries of all Russian regions and St. Petersburg. The family *Aspergillaceae* dominated the species richness spectrum: depending on the region, it accounted for 36.0 to 80.0% of the total species richness; all other families were less abundant. *Aspergillaceae* was followed, by a wide margin, by the family *Cladosporiaceae* with 4.0–16.0% of the total number of species in each region; the family *Pleosporaceae* occupied the third place (4.0–12.0% of species), and the family *Torulaceae* with 4.0–6.5% species was the fourth. An even smaller share of the total species richness (2.0 to 4.0%) belonged to the family *Hypocreaceae*. During the library survey, all these families occurred ubiquitously in all districts of Russia.

Table 4. Similarity of airborne micromycete complexes in libraries of Russia

Federal districts	SPb	St	V	C	FE	Sb	Nw	Ur	The Stugren–Radulescu coefficient
SPb		0.77	0.59	0.67	0.59	0.63	0.54	0.69	
St	0.63		0.21	0.26	0.18	0.49	0.08	0.77	
V	0.78	0.86		0.08	0.08	0.08	0.25	0.55	
C	0.73	0.87	0.88		0.17	0.32	0.13	0.52	
FE	0.47	0.28	0.61	0.61		0.39	0.14	0.47	
Sb	0.66	0.79	0.82	0.78	0.54		0.31	0.41	
Nw	0.41	0.69	0.87	0.78	0.55	0.58		0.38	
Ur	0.26	0.04	0.17	0.47	0.52	0.40	0.37		
	The Morisita–Horn coefficient								

We should also mention those families that were detected in the air of repositories in only one region: members of *Mytilinidiaceae* were present only in the Central FD (1.4% of the total number of species) and members of *Trichocomaceae*, only in the Volga FD (2.2%).

Genera. Fungi isolated from the library air during the survey represented 41 genera; depending on the ecosystem, the number of genera ranged from 10 to 32. The largest number of genera was detected in the air of libraries of the Central FD (Table 2).

In the spectrum of genera, the dominant group was *Penicillium*, which included 18.6–33.3% of the total number of species; the second leading genus with a slightly lower species richness was *Aspergillus* (11.5–23.5% of species). The species richness of other genera ranged from 0.3 to 15.4% of the total number of species. Noteworthy, the air of repositories of the Ural FD was characterized by the species richness of the genus *Cladosporium* slightly exceeding that of the genus *Aspergillus*. The distinguishing feature of the aerial environment in the libraries of the Southern FD was that *Aspergillus* dominated over *Penicillium*, both in the number of species and in the number of isolates. This result is consistent with the notion that elevated temperatures are favorable for *Aspergillus* fungi (Apetrei et al., 2009). The genus composition of the aeromycota of St. Petersburg libraries was similar to that of other regions. Studies from various libraries worldwide have regularly reported the presence of the genera *Stachybotris* and *Stemphylium* (Velikova et al., 2012; García et al., 2014; Zerek, 2014; Popikhina et al., 2018); however, we rarely observed these potentially pathogenic fungi in our survey: members of *Stachybotris* were detected only in the Central and Northwestern FDs and *Stemphylium* were found only in the Central FD.

Species. The species composition of micromycetes isolated from the aerial environments of libraries located in St. Petersburg and different districts of Russia was analyzed based on the binary Stugren–Radulescu coefficient, the Morisita–Horn index, and cluster analysis. On the one hand, this revealed the biological diversity features specific for each individual region and, on the other hand, established their similarities.

The values of the coefficients confirmed that the species composition of micromycetes differed among the libraries of the seven federal districts. Particularly high values of the binary Stugren–Radulescu coefficient were obtained when comparing the aeromycota of the libraries of St. Petersburg to the other regions of Russia and the libraries of the Ural FD to those of other districts (Table 4).

The most pronounced differences were observed for two pairs of library aeromycota complexes: between the Ural FD and St. Petersburg and between the Ural and the Southern FDs. This was demonstrated by the rather low values of the Morisita–Horn similarity index, which takes into account not only the primary data on the number of species but also the total number of isolates and the individual numbers of isolates for each species.

In all districts, the air of repositories was found to contain the following ten micromycete species: *Alternaria alternata* (Fr.) Keissl., *Aspergillus niger* Tiegh., *Aspergillus versicolor* (Vuill.) Tirab., *Botrytis cinerea* Pers., *Cladosporium cladosporioides* (Fresen.), *Cladosporium herbarum* (Pers.) Link, *Penicillium aurantiogriseum* Dierckx, *Penicillium camemberti* Thom, *Penicillium commune* Thom, and *Torula herbarum* (Pers.) Link., and four species were present in all districts, including the libraries of St. Petersburg: *Aspergillus niger*, *Botrytis cinerea*, *Cladosporium cladosporioides*, and *Penicillium aurantiogriseum*.

For each district, the core aeromycota, i.e., a complex composed of characteristic species, was identified based on the frequency of occurrence and uniformity of species distribution using cluster analysis (in Table 5, these cells are highlighted in bold).

All samples were dominated by micromycetes of the genus *Cladosporium*: in nearly all districts, the

Table 5. Members of air mycobiota of library storerooms in Russia

Micromycete species	Federal districts of Russia							
	SPb	NW	C	St	V	Ur	Sb	FE
Alternaria alternata (Fr.) Keissl.	0	2.8	**10.5**	**19.9**	4.5	10.2	7.7	4.2
Aspergillus flavus Link	**18.9**	0.9	4.6	2.7	**9.1**	0	5.2	2.8
Aspergillus niger Tiegh.	10.8	6.5	1.6	**9.6**	5.3	3.6	7.7	8.5
Aspergillus versicolor (Vuill.) Tirab.	0	**11.1**	**9.4**	**7.5**	**11.9**	14.3	**11.0**	**8.5**
Botrytis cinerea Pers.	2.7	5.1	4.6	2.7	0.4	10.7	1.9	3.3
Cladosporium cladosporioides (Fresen.) G.A. de Vries	**40.5**	**17.5**	**28.5**	**39.9**	**34.2**	**25.0**	**38.1**	**24.4**
Cladosporium herbarum (Pers.) Link	0	1.4	1.3	1.4	0.8	**53.6**	2.6	6.6
Cladosporium sphaerospermum Penz.	0	0.46	0.81	**6.2**	0	7.1	0	4.7
Geotrichum candidum Link	0	0	**6.7**	0.7	0	3.6	1.9	0
Neurospora sitophila Shear et B.O. Dodge	0	0.5	0.8	**8.2**	2.1	0	0	0
Paecilomyces variotii Bainier	2.7	0	0.3	2.7	3.7	0	3.2	4.2
Penicillium aurantiogriseum Dierckx	**32.4**	**23.5**	**11.3**	**9.6**	**13.6**	3.6	6.5	6.6
Penicillium camemberti Thom	0	4.6	4.3	2.7	4.1	3.6	3.9	0.5
Penicillium commune Thom	0	**18.4**	8.3	**10.3**	**10.7**	14.3	3.2	**12.2**
Talaromyces funiculosus (Thom) Samson, N. Yilmaz, Frisvad et Seifert	**16.2**	0	0	0.7	0.4	0	0	0
Trichoderma viride Pers.	0	2.8	**2.4**	0.7	**12.3**	0	3.9	1.4
Torula herbarum (Pers.) Link	0	2.3	3.0	3.4	1.2	3.6	1.9	0.9

dominant species was *C. cladosporioides*. The only exception was the Ural FD, where the most frequent was *C. herbarum*, which was rare or occasional in the air of libraries of other FDs. Along with members of *Cladosporium*, the complexes of characteristic species regularly included *A. versicolor* and *P. aurantiogriseum*. Moreover, *P. aurantiogriseum* had a high frequency of occurrence, while according to the literature data analyzed in the introduction, it was reported only in the aeromycota of Cuban archives (Borrego et al., 2014, 2022).

Most species in the described complexes had low abundance: the species beyond the characteristic complexes had the frequencies of occurrence ranging from 1.2 to 7.1% and were considered scarce. If the frequency of occurrence did not exceed 1.2%, the species were considered occasional findings. Members of 43 species were detected in only one district and were also occasional.

Thus, cluster analysis of aeromycota composition in library repositories of different regions showed that the composition of the most frequently occurring micromycete species was similar even in geographically remote regions and the differences were mainly due to scarce and occasional species.

Similarly to the distribution by diversity obtained by principal component analysis, the grouping of the districts by the composition of storeroom aeromycota determined by clustering analysis showed that climate did not affect clustering. In this case, we obtained two large clusters: one of them included St. Petersburg, the Ural FD, and the Far Eastern FD, and the other one comprised the Northwestern FD, the Southern FD, the Siberian FD, the Central FD, and the Volga FD (Fig. 2).

To sum up, in this work we carried out a large-scale survey of aeromycota of library repositories that

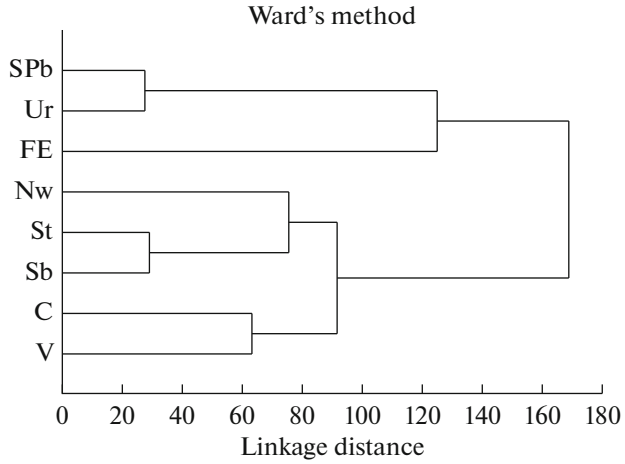

Fig. 2. Cluster analysis of composition of micromycete complexes isolated from air of libraries in Russia.

included nearly all regions of Russia and identified the core aeromycota for each region. The species *C. cladosporioides* was a member of core aeromycota everywhere, irrespective of climate conditions where a particular library was located.

Our analysis of the ecological diversity of the airborne mycobiota of enclosed spaces with homogeneous microclimate conditions, specifically library repositories, revealed moderate species diversity and sufficient stability of the described complexes and demonstrated a high degree of similarity of taxonomic structures and lists of characteristic species regardless of the climatic conditions of the surveyed regions. The microclimate conditions prevailing in the book repositories and the absence of emergency situations in the active phase explain the stability of these ecosystems and, as a consequence, the absence of true dominants and the presence of a large proportion of accompanying and scarce species capable of surviving in the established conditions.

Aeromycota of library repositories definitely influences and largely determines the spectrum of fungal species that colonize the surface of documents and act as potential agents of biological damage. Most micromycetes growing on the paper of library documents possess cellulase activity (Borrego et al., 2008) and may be of interest for further research as producers of cellulolytic enzymes.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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