

Review

Soil as a Source of Fungi Pathogenic for Public Health

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Abstract: Soil is an environment for huge diversity of fungi, which fulfill various tasks and support the maintaining of soil health. At the same time, varieties of soil fungal species, which produce numerous airborne spores and a range of mycotoxins, are known to be pathogenic for human health. The present review aims to summarize the current knowledge on soil fungi causing public health problems, including dermatoses, allergies, pulmonary diseases, wound infections, infections of the central nervous system, etc.

Keywords: human infections; mycotoxins; sick building syndrome; soil fungi

1. Introduction

Soil is a complex environment hosting a vast amount and diversity of living organisms. Fungi are one of the most diverse groups of soil organisms, which excrete a huge variety of enzymes and organic acids and play an essential role in soil processes including the decomposition of organic matter, e.g., [1,2], and soil aggregation and stabilization [3]. At the same time, many species of soil fungi are known to be pathogenic for human health. In the modern world, elevated anthropogenic pressure from industrial and agricultural activities disrupts the stability and functioning of the soil ecosystem, thus influencing different aspects of its fungal diversity. In return, fungi, due to the exceptional plasticity of their genomes [4], develop various adaptations for survival in a changing environment, which may include also the increase of potential pathogenicity. Now, the information on soil as an important source of pathogenic fungi is rather restricted and fragmentally dispersed over different published sources. The present review aims to summarize the current knowledge on soil fungi from different taxonomic and functional groups causing public health problems, such as dermatoses, allergies, pulmonary diseases, infections of the central nervous system, wound infections, and others, and to observe the main morphological, physiological, and biochemical factors supporting their pathogenic potential. This issue is especially relevant in the context of the “One Health” approach, which purposes to connect, balance, and optimize the health of people, plants, animals, and their environment [5,6].

Because in the framework of one review it is impossible to observe the pathogenic potential of all, or even the majority of soil-inhabiting fungi, I focused only on the most frequently and abundantly distributed groups of soil filamentous fungi dangerous for public health.

2. Groups of Soil Filamentous Fungi Dangerous for Public Health

2.1. *Penicillium*

Penicillium is the most diverse and ubiquitous genus of soil fungi accounting for more than 350 accepted species [7]. Species of the genus are abundantly present in different types of soil all over the world, preferring soils rich in organic matter in the cool-temperate climatic zones [1]. Penicilli produce a huge number of small (mostly 2–5 µm in diameter) one-celled asexual spores—conidia. Such spores can easily move from soil to air, being potentially able to enter the human respiratory tract (Figure 1) and, together with other



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airborne fungi, cause allergy and more severe pulmonary diseases in sensitive and immunocompromised persons, e.g., [8]. High concentrations of *Penicillium* species were found in the indoor air of buildings with so called “sick building syndrome” (SBS) associated with indoor air quality problems [9], which may cause allergic rhinitis, headaches, flu-like symptoms, watering of eyes, and difficulty in breathing [10]. *Penicillium* spp. are known as frequent contaminants of various food products, which are able to produce different kinds of mycotoxins [11–13]. For example, *P. expansum*, a necrotrophic plant pathogen, which causes blue mold rot in apples during storage, is a serious concern for human health because of the production of patulin, a neurotoxic carcinogenic secondary metabolite that contaminates apples and apple-based products, e.g., [14,15]. The production of patulin, together with other mycotoxins, such as rubratoxin B, is also characteristic for *P. digitatum*—the fungus which causes green mold postharvest rots in citrus fruits [16]. Moreover, *P. digitatum* has been reported as a virulent pathogen causing fatal pneumonia in an immunocompromised patient [17]. It is also worth mentioning other typical and widely distributed soil *Penicillium* species which can potentially threaten public health: *P. aurantiogriseum* and *P. verrucosum* contaminated farm-stored cereal grains and are able to produce nephrotoxins [18], and *P. chrysogenum* and *P. decumbens* caused brain and kidney infections, respectively, in immunodepressed patients [8]. Additionally, *P. decumbens* and *P. simplicissimum* can cause different infections in patients with AIDS [19,20].

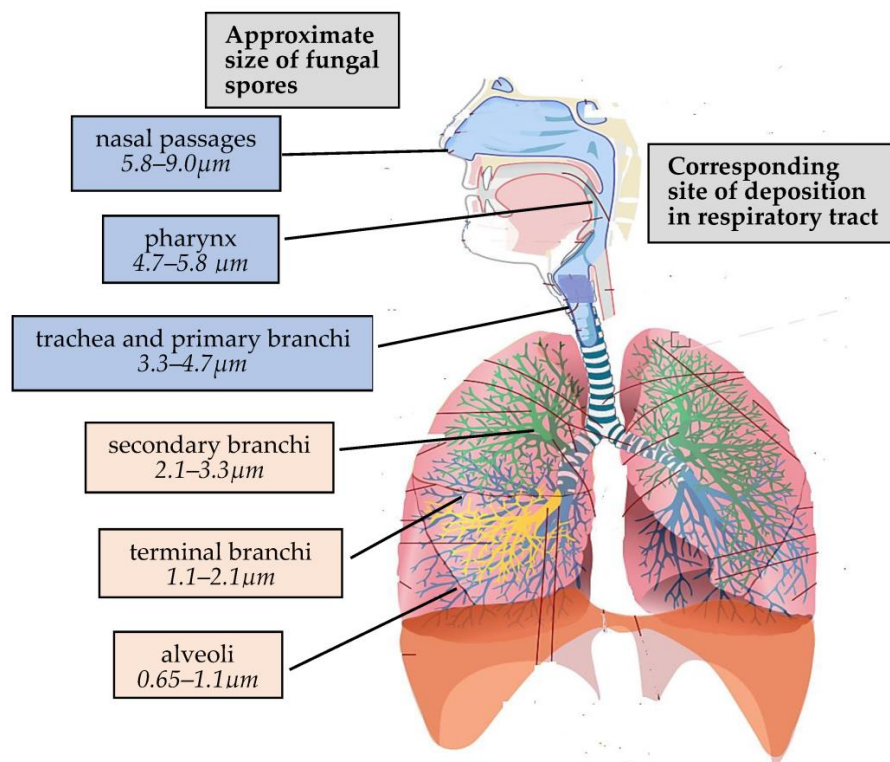


Figure 1. Possible deposition of fungal spores in different parts of human respiratory tract (adapted from https://en.wikipedia.org/wiki/Respiratory_system#/media/File:Respiratory_system_complete_en.svg. (accessed on 15 July 2024). Data from <https://andersencascading.com/about-andersen-cascade-impactor/>) (accessed on 15 July 2024).

2.2. *Aspergillus*

Aspergillus is the second richest genus of soil fungi, following *Penicillium* (near 340 species [21]). These two genera are taxonomic relatives belonging to the same family—Aspergillaceae, but they display different, even opposite life-history strategies and geographical trends, with *Aspergillus*, consisting of many thermotolerant and thermophilic and osmotolerant and osmophilic species more widely distributed in the soil of warm xeric regions, e.g., [1,22]. Similar to *Penicillium* spp., aspergilli produce masses of small one-celled spores (2–7 μm

in diameter), which easily become airborne and can be inhaled by humans and penetrate their respiratory track (Figure 1). According to the official website of allergens (www.allergen.org), some species of *Aspergillus*, including *A. fumigatus*, *A. niger*, *A. flavus*, *A. versicolor*, and *A. oryzae*, are allergenic, with different kinds of allergens identified [23]. Numerous *Aspergillus* species are also known as the contaminants of various food products, such as maize, rice and cereal grains, vegetables, coffee and cocoa beans, dried fruits, grapes, nuts, etc., e.g., [24]. Because many *Aspergillus* spp. are xerotolerant, they are able to grow on food products even during their storage at low air humidity [25]. Various *Aspergillus* species are toxigenic and produce different kinds of mycotoxins, among which are aflatoxins (cancerogenic and mutagenic, via *A. flavus* and *A. parasiticus*), ochratoxin A (nephrotoxic and cancerogenic, via *A. niger*, *A. carbonarius*, and *A. ochraceus*), terrein (tremorgenic, via *A. terreus*, *A. lentulus*, and *A. fisheri*), patulin (carcinogenic, genotoxic, and immunosuppressive, via *A. clavatus* and *A. giganteus*), gliotoxin (immunosuppressive, via *A. fumigatus* and *A. chevalieri*), e.g., [24,26]. Consequently, aspergilli (*A. fumigatus*, *A. flavus*, *A. niger*, *A. candidus*, and *A. tubingensis*) are known as casual agents of different infections in immunocompromised patients, such as sinusitis, keratitis, cutaneous and invasive aspergillosis, wound infections, osteomyelitis, brain granuloma, and otomycosis, e.g., [27]. Worldwide, *Aspergillus* spp. cause nearly 3 million cases of chronic pulmonary diseases, leading to more than 1 million deaths per year ([28] and references therein). Among *Aspergillus* spp., *A. fumigatus* is the predominant human-pathogenic species and the most common cause of invasive aspergillosis—allergic bronchopulmonary aspergillosis, lung aspergilloma, e.g., [29]. *A. fumigatus* is a widely distributed soil fungus known as one of the most frequent and abundant thermotolerant species in a variety of desert regions [30]. *A. fumigatus* possesses a set of strong virulence traits. It is able to grow and sporulate at 37 °C and tolerate temperatures up to 50 °C [31]. The fungus produces conidia, which, in comparison with other *Aspergillus* species, are smaller and much more hydrophobic; hence, they can disperse more quickly in the environment and enter easily into the respiratory tract, reaching the human alveoli [32]. Conidia of *A. fumigatus* contain melanin-like pigments, which are known to protect against enzymatic lysis and environmental stress, contributing to weakening the host immune response and promoting the fungus survival and propagation, e.g., [32]. Additionally, the secretion of enzymes and toxic secondary metabolites as well as high genetic diversity help *A. fumigatus* in the successful adaptation to host conditions, e.g., [33,34]. As a result, World Health Organization categorized *A. fumigatus* as a critical group of fungal pathogens [35].

2.3. *Fusarium*

The genus *Fusarium* is widely distributed in soil and accounts for more than 300 phylogenetically distinct species [36]. This genus includes many species of plant pathogens, capable of causing diseases of almost all economically important plants, e.g., [1]. *Fusarium* spp. can produce a variety of toxic secondary metabolites, such as nivalenol, moniliformin, trichothecenes, zearalenone, fumonisins, etc. with carcinogenic, hepatotoxic, nephrotoxic, cardiotoxic, anorexic, and haematotoxic effects, posing significant threats to food safety and public health [27,37]. Accordingly, some *Fusarium* species are known as opportunistic pathogens, causing fusarioses, which are, after aspergilloses, the second most common fungal infections in humans [38], and the World Health Organization categorized *Fusarium* spp. into a high group of fungal pathogens [35]. *F. oxysporum*, a ubiquitous species possessing the ability to survive in different environments, from deserts to temperate forests and grasslands [1], can induce superficial and subcutaneous infections such as keratitis (an inflammation of the cornea) and onychomycosis (nail infection), in immunocompetent persons [27]. *F. verticilloides* was reported to be among the causative agents of oesophageal cancer in immunocompromised individuals [39]; this species can also cause keratomycosis and necrotic lesions on the skin [27]. Most virulent of all *Fusarium* species and often associated with fusariosis, *F. solani* has been reported to induce a range of diseases in both immunocompetent and immunocompromised patients, including keratitis, onychomy-

cosis, cutaneous and sub-cutaneous infections, arthritis, mycetoma, and sinusitis [27,40]. Moreover, aggressive fusarial infections penetrating the entire body and bloodstream (disseminated infections) may be caused by species from the *F. solani* complex, *F. oxysporum*, *F. verticillioides*, and *F. proliferatum* [41]. Possibly, most of the disseminated fusarioses are caused by the inhalation of airborne microconidia. Yet, the bigger size of the microconidia in comparison with the conidia of aspergilli ($8\text{--}16 \times 2\text{--}4 \mu\text{m}$ of *F. solani* versus $2.5\text{--}3 \mu\text{m}$ of *A. fumigatus*) makes infection via inhalation less probable than in aspergillosis [38].

2.4. *Trichoderma*

Trichoderma is a genus of typical soil fungi with worldwide distribution [1]. *Trichoderma* spp. are characterized by very fast growth and mass production of small one-celled conidia ($1.5\text{--}4 \mu\text{m}$). Several strains of *Trichoderma* species are effective against common soil-borne pathogens and are used as biocontrol agents, e.g., [42]. Some species of the genus are known to induce serious diseases in immunocompromised and immunocompetent patients, such as invasive pulmonary infection, peritonitis, infection of the central nervous system (CNS), endocarditis, skin infection, fungaemia, and disseminated disease, especially in patients with hematological problems and those undergoing continuous peritoneal dialysis and intensive chemotherapy [43–45]. *T. longibrachiatum* is the most common species associated with invasive fungal infections, followed by *T. atroviride*, *T. citrinoviride*, *T. harzianum*, *T. koningii*, *T. pseudokoningii*, and *T. viride* [46,47]. *Trichoderma* species are able to produce trichothecenes—mycotoxins which are known as strong inhibitors of protein synthesis that can be absorbed into the body through the skin and which, like many other mycotoxins, are resistant to heat [48].

2.5. *Paecilomyces*

The genus *Paecilomyces* includes ubiquitous, saprobic fungi commonly distributed in soil, decaying plants, insects, and nematodes [1]. Similar to *Penicillium*, *Paecilomyces* is characterized by verticillate sporulation with abundant production of small one-celled conidia ($2.5\text{--}5 \mu\text{m}$), which easily become airborne and can contaminate food products and grains [46]. *P. variotii* and *P. lilacinus* (current name *Purpureocillium lilacinum*) are the most common *Paecilomyces* species associated with diseases of immunocompromised and immunocompetent persons [49,50]. *P. lilacinus* was found to cause severe human infections, including oculomycosis and cutaneous and sub-cutaneous infections [46,49]. Organ and bone marrow transplantation, corticosteroid therapy, cancer, primary immunodeficiency, AIDS, diabetes mellitus, and hepatic cirrhosis were the most common predisposing factors for the development of the *Paecilomyces*-induced diseases. Many cases of hyalohyphomycoses in humans caused by *P. variotii* with different clinical manifestations have been reported [50,51]. They are mainly associated with peritonitis (most common), endocarditis, pyelonephritis, sinusitis, pneumonia, fungemia, osteomyelitis, and cutaneous and disseminated infections. The thermotolerant nature of *P. variotii* is considered to be one of the factors contributing to its pathogenic potential [52].

2.6. *Cladosporium*

Cladosporium is a genus of melanin-containing fungi widely distributed in soil, as well as in living and dead plant material [53]. *Cladosporium* spp. produce long chains of dark-colored 0–3-septated conidia, mostly $4\text{--}13 \mu\text{m}$ long, which are wind-dispersed. Conidia of *Cladosporium* spp. were found in high concentrations in the fungal profiles of indoor air in buildings with SBS [9,54]. Indoors *Cladosporium* species may grow on wet surfaces, appearing on walls as brown, green, or black spots. *C. cladosporioides*, one of the most common fungi in soil and outdoor air, can initiate asthmatic reactions due to the presence of allergens and beta-glucans on its spore surface [55]. The species is known as a causal agent of superficial infections in humans [46]. It can also occasionally induce pulmonary and cutaneous phaeohyphomycosis [46,56]. Another widely distributed *Cladosporium* species, *C. herbarum*, was reported as a possible agent of keratitis and pulmonary mycosis [46]. It

is also worth mentioning that *Cladosporium* spp., together with yeasts *Candida* spp., were frequently found in the microbiome accompanying wound infections [57].

2.7. *Alternaria*

Alternaria is another genus of melanized fungi, which frequently occur in soil, being especially abundant in arid regions, and are also known as major plant pathogens [53]. The species of *Alternaria* are characterized by large (mostly up to 120 µm long) dark-colored, many-celled and thick-walled conidia produced mainly in short chains. *Alternaria* spp. have been reported as common allergens associated with SBS [9] and as causing allergic rhinitis or hypersensitivity reactions that may result in asthma. Human alternarioses in immunosuppressed persons are caused mainly by *A. alternata*, followed by *A. tenuissima* and *A. infectoria*. Their most frequent clinical manifestations are expressed in cutaneous and subcutaneous infections, followed by oculomycosis, invasive and non-invasive rhinosinusitis, and onychomycosis [46,58]. *A. alternata* has also been associated with human DNA damage. The fungus produces the mycotoxin alternariol interfering with the human DNA topoisomerase (enzymes that regulate excessive or insufficient winding of DNA), which can cause DNA instability and subsequently the break of double DNA strands [59].

2.8. *Stachybotrys*

Melanin-containing species from the genus *Stachybotrys* are typical soil fungi, with *S. chartarum* being the most common species of the genus distributed worldwide [1]. *Stachybotrys* spp. produce comparatively large ellipsoid one-celled conidia, 10–13 µm long, in slimy masses. Conidia of *S. chartarum* dispersed in indoor air are considered as one of the serious cases of SBS, causing visible growth on water-damaged surfaces, e.g., [60]. *S. chartarum* is able to produce mycotoxins and other biologically active compounds, which are of great concern to human health, e.g., [61,62]. *S. chartarum* produces a variety of macrocyclic trichothecenes and related trichoverroids, which are highly toxic, possessing a potential ability to inhibit protein synthesis [61]. In addition, the fungus produces compounds which are considered as immunosuppressive agents, and the combination of trichothecenes and these immunosuppressive agents may be responsible for the reported high toxicity of *S. chartarum* [61]. The pathogenicity of *S. chartarum* to humans is associated with numerous fatal or life-threatening cases of pulmonary hemorrhage ([63] and references therein). Although *S. chartarum*, unlike, for example, *A. fumigatus*, is poorly adapted to dispersion by air, is unable to grow at 37 °C, and has no possibility to enter lung tissues [64], namely, the ability to produce a wide range of highly toxic secondary metabolites makes the exposure to this fungus very dangerous for human health.

2.9. *Mucorales*

Fungi from this order are typical inhabitants of different soil types in various geographic regions [1]. Mucoromycetes produce numerous globose or oval one-celled spores, mostly 5–9 µm long, inside of a large sporangium. Some mucoromycetes are frequent food contaminants [11], for example, *Rhizopus stolonifer*, commonly known as “black bread mold”. Several members of Mucorales have been reported as causative agents of rather rare but severe human diseases called mucormycosis (or zygomycosis, in the name of former division Zygomycota, which included the order Mucorales) [46,65], with the thermotolerant *R. oryzae* being the most common agent of the infections. More than 10 thousand cases of mucormycosis have been estimated per year worldwide [66]. Consequently, the World Health Organization categorized Mucorales into a high group of fungal pathogens [35]. Similar to aspergillosis, mucormycosis is usually initiated by inhalation of spores, followed by penetration of invasive hyphae, which can block blood vessels causing infarcts and hematogenous dissemination [67]. Hematogenously disseminated infection occurs in immunocompromised patients suffering from diabetes mellitus, as well as receiving cytotoxic chemotherapy with potential involvement of different organs. Invasive mucormycosis can invade the human CNS resulting in meningitis, encephalitis, hydrocephalus, and cerebral

abscesses [68]. Mucormycosis can also manifest as pulmonary (via *R. oryzae* and *Mucor indicus*), gastrointestinal (via *R. oryzae*, *R. azygosporus*, and *M. indicus*), as well as cutaneous and subcutaneous (via *M. hiemalis*, *R. microsporus*, and *Syncephalastrum racemosum*) infections [46,69]. Some species of Mucorales are able to produce mucoricin, a toxin, which can inhibit protein synthesis and which is important in the pathogenesis of mucormycosis [70].

2.10. Keratinophilic Fungi

Geophilic keratinophilic fungi belong to a highly specialized group, which possess an ability to invade and degrade native keratin via the enzyme keratinase [71]. Most of these fungi inhabit the soil as saprotrophs and are involved in organic matter decomposition. Some geophilic species of keratinophilic fungi are able to colonize keratinized tissues in humans and animals (skin, hair, and nails), causing cutaneous infections called dermatophytoses (ringworm, tinea) and affecting nearly a billion people throughout the world [66]. Dermatophytosis more frequently occurs in regions with a warm and humid climate [72]. The group of dermatophytic fungi includes numerous species, with the most clinically important for humans (so called anthropophilic dermatophytes) belonging to the genera *Microsporum*, *Trichophyton*, and *Epidermophyton*. Some dermatological infections caused by geophilic species such as *Trichophyton terrestre* can occur in agricultural workers as professional diseases, e.g., [73]. Fungi from the above-mentioned genera can reproduce both asexually, via micro- and macroconidia, and sexually (*Arthroderma*- and *Nannizia*-states, producing ascospores inside fruiting bodies almost exclusively in the soil) [1,71]. Among these fungi, *N. gypsea* is a common and cosmopolitan geophilic species, being an important cause of skin infection in humans and considered as an agent of the professional disease of gardeners, e.g., [74]. Conidia or hyphal fragments of dermatophytes are deposited on the outermost layer of the epidermis after being in contact with infected persons, animals, or fomites or via airborne spreading. Dermatophyte hyphae usually colonize the superficial layer of the skin because of their inability to penetrate the viable tissue of an immunocompetent person [72].

3. Conclusive Remarks

The current review observes only the most frequent and abundant groups of filamentous soil fungi which can be dangerous for public health; basic information on the medical importance of these fungal groups is summarized in Table 1. Additionally, the synergetic health effect of several fungal species should be taken into account [27]. The pathogenic potential of the reviewed fungi is mainly associated with the following morphological, physiological, and biochemical traits: (i) the ability to produce a high number of spores, which easily become airborne and may penetrate the human respiratory tract and contact with the skin; (ii) the ability to excrete various toxic secondary metabolites; (iii) the production of melanin or melanin-like pigments protecting against enzymatic lysis and environmental stress, thus stimulating the fungus survival and propagation; and (iv) the ability of thermotolerant species to grow at 37 °C, i.e., the temperature of the human body.

Table 1. Typical groups of soil filamentous fungi pathogenic for human health.

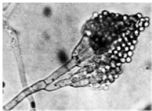


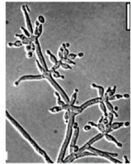
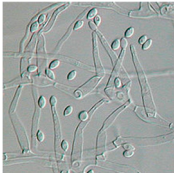
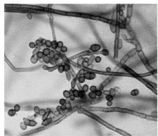
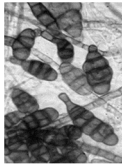

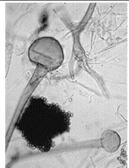

Taxonomic (Functional) Group	Sporulation	Diseases Cased	References	Pathogenicity (Biosafety Level, BSL) ¹
<i>Penicillium</i>		Allergy, pneumonia, brain infections, kidney infection	[8,17–19]	BSL-1
<i>Aspergillus</i>		Allergy, sinusitis, bronchopulmonary infection, keratitis, osteomyelitis, brain granuloma, otomycosis	[27,35,46]	BSL-1; BSL-2 (<i>A. fumigatus</i> , <i>A. flavus</i>)

Table 1. Cont.

Taxonomic (Functional) Group	Sporulation	Diseases Cased	References	Pathogenicity (Biosafety Level, BSL) ¹
<i>Fusarium</i>		Keratitis, sinusitis, onychomycosis, cutaneous and sub-cutaneous infections, disseminated infections	[27,35,39–41]	BSL-1; BSL-2 (<i>F. oxysporum</i> , <i>F. solani</i> , <i>F. verticillioides</i>)
<i>Trichoderma</i>		Pulmonary, CNS, and skin infections, peritonitis, endo-carditis, disseminated infections	[43–48]	BSL-1
<i>Paecilomyces</i>		sinusitis, pneumonia, oculomycosis, cutaneous infections, peritonitis, endocarditis, pyelonephritis, disseminated infections	[46,49–51]	BSL-1; BSL-2 (<i>P. variotii</i>)
<i>Cladosporium</i>		allergy, pulmonary and cutaneous infections, keratitis, wound infections	[46,56,57]	BSL-1
<i>Alternaria</i>		allergic rhinitis, cutaneous and subcutaneous infections, onychomycosis	[46,58]	BSL-1
<i>Stachybotrys</i>		allergy, pulmonary hemorrhage	[63]	BSL-1
Mucorales		infarct, hematogenous dissemination, CNS infections, pulmonary, gastro-intestinal, and cutaneous infections	[35,46,65,67–69]	BSL-1; BSL-2 (<i>R. microsporus</i> , <i>S. racemosum</i>)
Keratinophilic fungi		cutaneous infections (dermatophytoses)	[71,72]	BSL-1, BSL-2

Picture of *Paecilomyces*—adapted from https://en.wikipedia.org/wiki/Paecilomyces_variotii (accessed on 4 July 2024); picture of keratinophilic fungi—adapted from https://en.wikipedia.org/wiki/Microsporum_gypseum (accessed on 4 July 2024); other pictures were made by the author and have not been previously published; ¹—according [46].

In the constantly changing world, under strong anthropogenic impact leading to global warming, soil becomes the source of an increasing amount of pathogenic fungi with a growing public health threat. Soil fungi possessing high genetic plasticity and adaptation potential develop resistance to antifungal drugs—for example, *A. fumigatus*, the main agent of invasive pulmonary aspergillosis, demonstrated azole resistance, which has been associated with the use of agricultural fungicides structurally similar to medical

triazoles [6]. Therefore, for future perspective, a deeper understanding of the composition and function of the soil mycobiome and its relationships with the environment is crucial for maintaining a soil environment which poses the least danger for human health. It is also essential to pay more attention to the cumulative health effect of several soil fungal species, as well as to study the influence of modern agricultural practices on the pathogenic potential of soil fungi.

It is a well-established fact that the great majority of listed fungal infections affect only immunocompromised patients who suffer from acute or chronic diseases, received cytotoxic chemotherapy, underwent organ transplant surgery, etc. Nevertheless, serious attention should be paid to the keeping of a healthy, undamaged indoor environment in order to avoid “sick building syndrome” and the associated appearance of fungal growth and sporulation, which may cause allergy and other health problems in immunocompetent persons.

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