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INDOOR AIR QUALITY

The Fungi: How They Grow and Their Effects on Human Health

A primer on how fungi are formed, how they spread in buildings, and how individuals react through allergy symptoms, irritation, and toxicoses due to exposure

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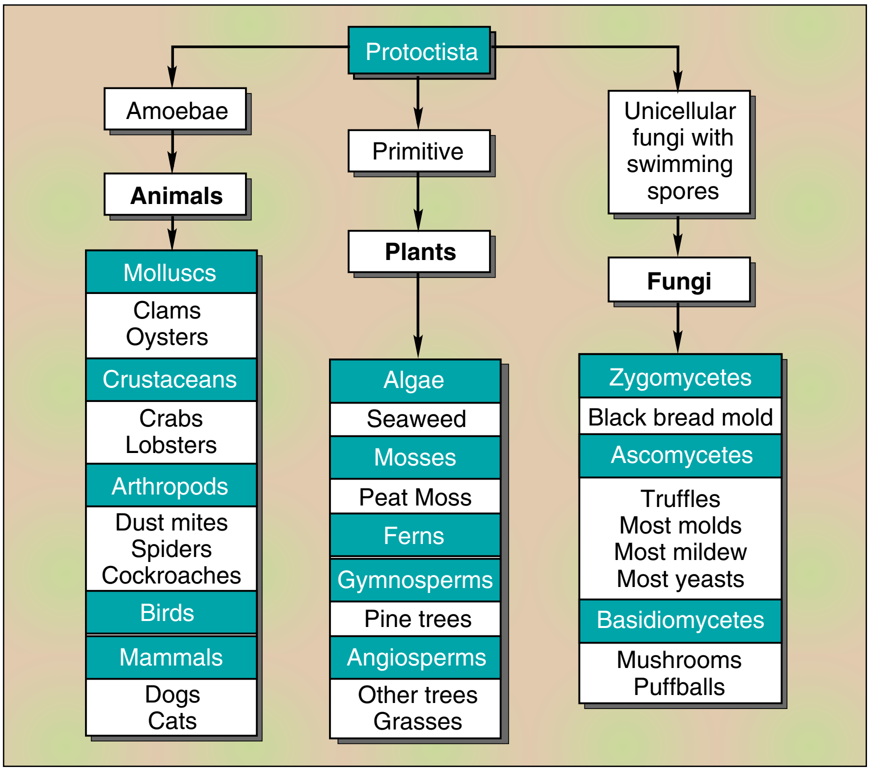
Fungi can colonize building materials when sufficient water is present and release substances into the air that can cause discomfort and the perception of poor air quality. This article is written for buildings professionals to provide a primer on the fundamentals of fungal ecology and the basic effects of fungi on human health. It focuses on the nature of fungi, how they grow and reproduce, and how they affect human health.

Fig. 1 is a diagram that demonstrates the position of the fungi among other living organisms. Note that fungi are neither plant nor animal but belong to a kingdom of their own. It is especially important not to consider fungi as plants. Plants are able to convert carbon dioxide directly into carbohydrates for food. Fungi must find complex carbon in the environment as do animals. However, while animals ingest the complex food and degrade it internally, fungi excrete chemicals (enzymes) into the environment that degrade the complex source into soluble form. Bacteria are not directly related to fungi, plants, or animals although they can perform many of the same activities as fungi.

Fungal names and relationships

Yeast, mold, mildew, and *mushroom* are all terms that are commonly used to refer to fungi. Yeasts are unicellular organisms that constitute a structurally and biochemically distinct group within the fungi. Yeasts are best known as the agents used to make bread rise and to ferment fruit juices into wine and beer, but they can also grow in buildings where abundant water is available.

Mold is essentially a description of fungi growing on surfaces (*e.g.,* a moldy orange, moldy cheese, moldy shower stalls, etc.). Mildew usually refers to fungi growing on fabrics. The terms *mold* and *mildew* are often used to refer to exactly the same fungi. Even



1 Classification of living organisms.

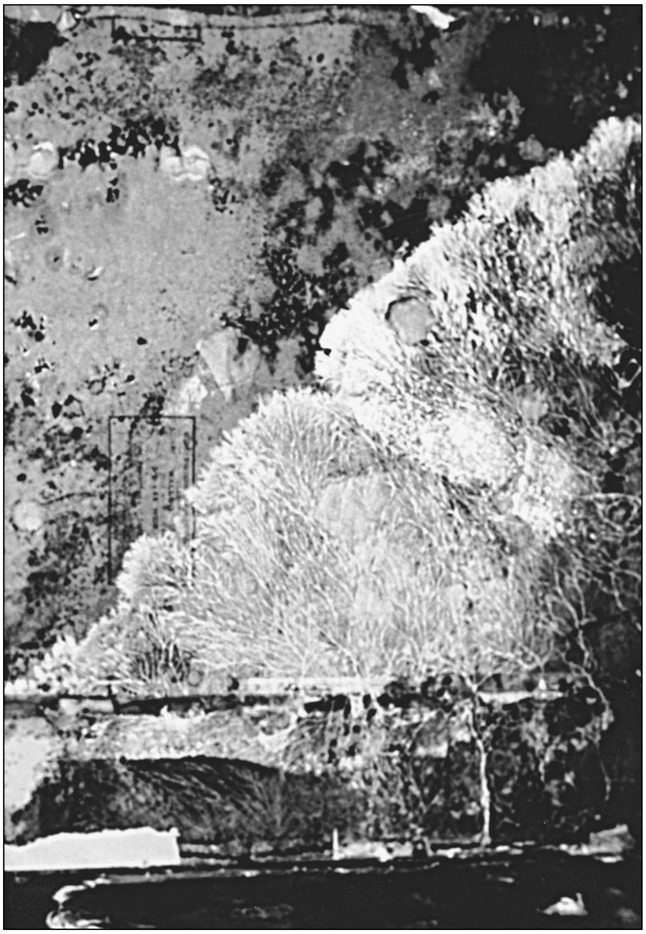
fungi that produce mushrooms can be called mold if only the mycelium is seen. The mycelium in Fig. 2 (called mold by the occupant of this building) is that of a mushroom-producing fungus. Many of the common wood-rotting fungi belong to this group.

Fungi are divided into large groups based on the structure of their spore-producing apparatus. Only members of three of these groups are common contaminants of building materials—Zygomycetes, Basidiomycetes, and Ascomycetes. Zygomycetes are relatively common in building (house) dust and require relatively simple carbon sources and very wet conditions.

Basidiomycetes include all of the mushrooms and shelf fungi (including those that degrade wood products) and a few important yeasts found in buildings. Most Basidiomycetes produce spores for dissemination in large fruiting bodies.

By far, the largest group of fungi that colonize building materials belongs to the Ascomycetes. These are the fungi most commonly called mold and mildew and usually produce masses of dry, readily dispersed spores on surfaces as well as musty odors in buildings.

Fungi are named following strict rules. Each fungus that is clearly different from all others is described in Latin and given a distinctive binomial (two-part) name that includes the genus and the species. Thus, *Cladosporium* is a generic name and *sphaerospermum* is the species name, the entire proper name for the fungus being *Cladosporium sphaerospermum*, an ascomycete form that is commonly isolated from building materials. In all mycological works, this name will be followed by the abbreviation of the name of the person who originally described and named the fungus. This allows a precise designation of the fungus that is independent of future name changes.



2 Mycelium of a wood-rotting fungus growing under the siding of a house.

Unfortunately, this convention is rarely followed in indoor air quality literature, and its utility is only beginning to be recognized in medical literature. The naming convention is important in IAQ investigations responding to occupant health complaints that involve fungal contamination. Knowledge of the precise name of the fungi present may be necessary to understand relationships between exposure and disease.

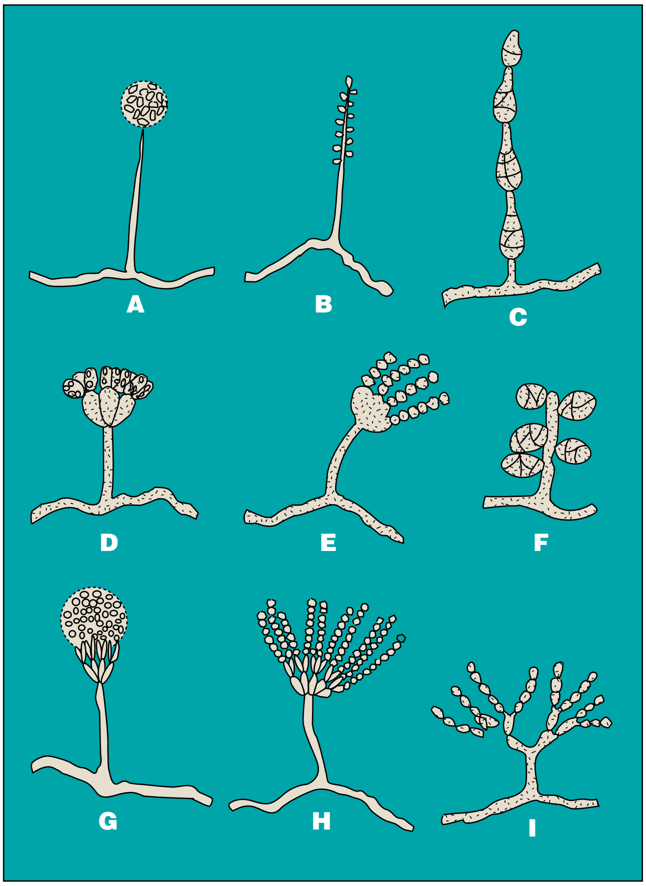
Shape and structure of fungi

The fungal cell is similar to that of plants and animals, containing all of the same organelles (nucleus, mitochondria, ribosomes, membrane systems, etc.). Like plants, the fungal cell is bounded by a rigid cell wall. However, while plant cell walls contain cellulose as the basic structural material, fungal cell walls contain a material that is similar to that in insect exoskeletons (chitin). Most fungal walls also contain substances called glucans that can be toxic to animal cells.

Fungi can exist as single cells (yeasts). However, most fungal bodies are composed of long chains of cells called hyphae. A mass of hyphae is called a mycelium. The mycelium is essentially the digestive organ of the fungus. Each growing hyphal strand secretes enzymes designed to digest the substrate (such as a cellulose-based building material) so that the dissolved nutrients can be absorbed. To serve this function, the fungus mycelium must remain in intimate contact with the growth surface. In Fig. 2, which is a photograph of a fungal mycelium growing on the plywood sheathing of a house, the hyphal strands have actually penetrated the wood, either through existing pores or by dissolving their own pathways through the material. Hyphal strands will twine around fibers in much the same way although for different reasons, as, for example, bind weed or Kudzu vines entangle themselves around any available support. This means that removing surface growth alone leaves fungal material that could begin to grow again should conditions be appropriate.

Fungi produce new cells in the same way that animals and plants do—by mitosis (nuclear division) and cell division. The fungi are unusual, however, in their mode of dissemination. Nearly all fungi produce at least one, and often several, spore forms that travel through the air and survive until they impact on a suitable substrate for growth. Each spore is able, under appropriate conditions, to reproduce the entire organism. The kinds of fungi that most commonly colonize building materials produce a great many small, dry, waxy spores that are readily released and remain airborne for long periods of time. These spores are always present in the outdoor air as well as in all buildings, providing a continuing source of organisms to colonize appropriate substrates.

Fig. 3 includes drawings of several kinds of fungi in this sporulating state. Some fungi produce spores that are wet rather than waxy, the spores being produced in balls of slime (Fig. 3 A, D, and G). Most of these require very wet conditions for growth, and it is not clear how readily their spores are released in the dry state. Others produce dry spores that readily become airborne with minimal disturbance (Fig. 3 B, C, E, F, H, I). Many of these fungi will grow under relatively dry conditions. Mushrooms, shelf, or bracket fungi and cup fungi produce spores in large fruiting bodies. The mushrooms and cup fungi produce spores that are forcibly discharged into the air. Many of these fungi have developed the ability to use cellulose and lignin (the structural component of wood). They rarely colonize materials in intact buildings and then only when abundant water is present over relatively long periods of time, usually months.



3 Diagrams of sporulating fungi: A) *Acremonium* (wet-spored), B) *Tritarachium* (wet-spored), C) *Alternaria* (dry-spored), D) *Stachybotrys* (dry-spored), E) *Memnoniella* (dry-spored), F) *Ulocladium* (dry-spored), G) *Gliocladium* (wet-spored), H) *Penicillium* (dry-spored), and I) *Cladosporium (dry-spored).*

Food processing

All fungi require oxygen, water, carbon, nitrogen, and a variety of micronutrients for growth. Oxygen is rarely limiting in buildings although its lack does prevent most fungi from growing submerged in stagnant water. There are fungi that will grow over a temperature range from near freezing to well in excess of human body temperature, although most have temperature optima within the human comfort range.

Water requirements for fungi vary over a broad range and are usually referred to in terms of the water activity (a_w) at which the fungus can grow. This is the equilibrium relative humidity in the immediate vicinity of the substrate material expressed as a decimal. For reference, animal cells require an a_w near 0.99 to 1.00, which is essentially saturation. Some fungi can grow and reproduce at a_w as low as 0.69 although optimal growth probably occurs at somewhat higher levels. Many fungi have an a_w optima in the 0.80 to 0.90 range. This essentially means that if the humidity at a surface reaches 80 percent, then, providing the surface contains the appropriate nutrients and no inhibitors, some fungi will be able to begin to grow and possibly reproduce. Of course, this humidity level must be maintained long enough for the fungus to become established (at least 48 continuous hours although data supporting this figure are lacking). The more water that is available, the more fungi there are that can colonize the surface.

We have focused on water activity rather than ambient humidity. However, it is the combination of ambient humidity and surface temperatures that leads to increases in water and often condensation on the surfaces of building materials leading to microbial growth.

Temperature also plays a direct role in the colonization of surfaces with fungi. At relatively low temperatures (50 to 60 F), spores take longer to germinate and growth is slower to become established than at, say, 60 to 70 F. Water activity optima are usually higher at low temperatures than at high. This means that high water activity levels must be maintained for longer periods in cold than in warm environments for growth to occur.

Carbon, nitrogen, and a variety of mineral elements are also essential for fungal growth. There are fungi that can use most complex carbon-containing compounds, but most favor sugars, with some able to utilize cellulose and lignin. Fungi are unique in their ability to degrade the latter two highly resistant polymers. Nitrate or ammonia can provide nitrogen to fungi as can amino acids and proteins. A common nitrogen source for dust-borne fungi is keratin, the structural protein from human skin. Again, fungi are among very few organisms that can degrade this highly resistant polymer. The mineral element needs of fungi are met by trace amounts of these necessary nutrients that occur as part of the carbohydrates and proteins used as carbon and nitrogen sources and dissolved in water.

In the process of degrading complex carbohydrates and proteins to release essential nutrients, fungi produce carbon dioxide, water, and a variety of other compounds that range from volatile aldehydes, alcohols, and ketones to complex secondary metabolites, including antibiotics and mycotoxins. The volatile compounds are responsible for the odors commonly associated with fungal growth, and although their health impact has not been studied, these odiferous compounds are blamed for a variety of building-related complaints. The antibiotics and mycotoxins (which are not volatile) have significantly affected humanity although they play an unknown role for the fungus. Well-known fungal antibiotics include penicillin (which is toxic for some kinds of bacteria) and cyclosporin (which is toxic for human immune cells and facilitates organ transplants). Important mycotoxins are aflatoxin (the most potent known carcinogen) and trichothecene toxins (produced by members of many genera, including *Fusarium* and *Stachybotrys*). Although most fungi probably produce these secondary metabolites, the conditions under which they do so are not clear, and it is likely that production is highly substrate-dependent.

Fungi in the environment

Fungi are responsible for most aerobic (oxidative) decay processes in the environment and play an essential role in the natural ecosystem. For example, fungi turn fallen leaves and dead trees into soil by digesting the complex carbohydrates (cellulose, lignin) into soluble forms. Composting utilizes this natural ability of fungi to process dead organic material. In colonizing building materials, which contain dead organic material, fungi are merely fulfilling their mission within the natural ecosystem.

In addition to their role as decay organisms, many fungi form symbiotic relationships with plants. For example, most trees grow in association with fungi of the group Basidiomycetes. Neither the fungus nor the tree will thrive in the absence of the other. Finally, fungi are well-recognized as food, and many kinds are readily purchased in supermarkets. A few examples include mushrooms, mold-processed cheeses (*e.g.,* blue cheese, Stilton, etc.), and mold-fermented soy products (*e.g.,* soy sauce, miso, tempeh). In addition to these human uses, some insects actively cultivate fungi for food while for some insects, fungi are an implacable enemy, lying in wait to trap and squeeze their victims to death.

Fungal-related diseases

Allergies (hay fever, asthma, allergic pneumonia) are caused by exposure to agents that stimulate a disease-causing immune response. The development of an allergy is a two-step process. The first step is exposure to an allergen that causes sensitization but no symptoms. Allergens are usually proteins that are often derived from living organisms (Table 1). Sensitization means that the immune system has been stimulated to produce antibodies or activated cells that specifically recognize the allergen. The second step is symptom development, which requires exposure to an allergen after sensitization has occurred. Such exposure leads to the release of chemicals such as histamine that are powerful irritants, causing redness, swelling, and, in some cases, permanent changes in lung tissue.

The amount of any allergen that must be inhaled for sensitization to occur is unknown. Likewise, the amount of any allergen

Table 1—Some effluents of living organisms and their potential health effects.

	Bacteria	Fungi	Arthropods	Mammals
Allergens	Unidentified proteins from many bacteria	Alt a 1 (Alternaria), Asp f 1 (Aspergillus), Cla h 1(Cladosporium)	Der f 1, Der p 1 (dust mites), Bla g 1 (cockroach)	Fel d 1 (cat), Can f 1 (dog)
Infectious agents	Living cells (tuberculosis, whooping cough)	Living cells (Aspergillosis, athletes foot, yeast infections)	None	None
Toxicoses	Endotoxin (asthma, respiratory irritation), volatile organics (irritation)	Alfatoxin (cancer), satratoxin (immunosuppression), volatile organics (irritation)	None	None

Criteria for documenting a relationship between fungal exposure and disease

- The disease has been diagnosed by an expert physician and is known to be caused by exposure to the proposed agent.
- There is objective clinical evidence that the proposed agent caused the disease (*i.e.,* the patient has developed a strong antibody response to the agent, the fungus causing an infection was cultured from the patient, and the toxin was measured in the patient's blood or tissues in concentrations sufficient to cause disease).
- Other agents that might cause the same disease are not present in the environment and the affected individual/individuals are not likely to have been exposed elsewhere.
- Exposure to the proposed agent has been directly measured and levels are high enough to have logically caused the disease, or the agent has been measured in a reservoir and a clear pathway for exposure sufficient to cause the disease has been documented.
- Either all at-risk individuals with equal exposure have developed the disease or there is a logical explanation for why they have not.
- Unexposed individuals in a similar environment have not developed the disease.
- Removal of the individuals from the environment or removal of the exposure results in the disappearance of disease (where reversible disease has occurred).

required to trigger symptoms remains unknown. These missing pieces of information are the reason why standards for safe exposures to allergens have yet to be developed.

The actual number of people at risk for developing any kind of allergy is unknown. There is a genetic component that makes some people more likely than others to develop hay fever or asthma. For example, about 25 percent of the population of the United States can probably develop hay fever. However, it appears that the nature of allergen exposure also plays a strong role, and some particularly potent allergens may produce sensitization in most exposed individuals. Allergic pneumonia is a relatively rare disease, sensitization for which apparently results from exposure to high levels of some allergens. For example, exposure to *Penicillium* growing in a large ventilation system has been blamed for this disease (Fergusson *et al. Thorax* 39:294, 1984). Only a small percentage of exposed individuals usually develop this disease although cases have been reported where more than 75 percent of exposed workers have developed the disease. Why some individuals become sensitized and others do not after identical allergen exposures is unknown.

Symptoms of allergic disease (especially asthma) can be triggered in allergic individuals by nonspecific factors that have nothing to do with allergen exposure, further complicating the documentation of relationships between exposure to allergens and symptoms in building occupants. For example, viral respiratory disease is a strong stimulus for the development of asthma symptoms in sensitive people. Cold air, exercise, stress, and exposure to irritating chemicals will also induce symptoms in the absence of allergen exposure. This means that while increased rates of asthma symptoms in building occupants may be due to allergen exposure, they also can be the result of increased stress, epidemics of influenza or colds, or other factors.

Infections occur when a fungus grows in human tissue. The most common fungal infections (for example, athlete's foot) are caused by organisms that do not grow on building materials. However, there are several common environmental fungi that can cause infections. The most familiar of these is *Aspergillus fumigatus*. Note, however, that fungal infections specifically related to building occupancy are very rare because the immune system of normal people is sufficiently powerful to prevent invasion of nearly all fungi. Fungi that colonize building materials rarely cause infections and then only in people with severely damaged immunity. Diseases such as AIDS, some cancers, and treatment with some drugs will cause immune system damage. Contamination of hospitals or nursing homes with these opportunistic fungi can become a serious problem. On the other hand, these same fungi are important members of natural microbial communities and are usually present in outdoor air. This means that in specialized environments designed to protect individuals with poor immunity, special precautions are necessary not only to prevent colonization of materials but to prevent penetration of the fungi from the outside air.

Many fungi produce toxic compounds that affect human health. For example, antibiotics are fungal toxins that kill bacteria and some other fungi. In individuals, the effects of fungal toxic materials have been recognized in relation to ingestion of mushrooms or moldy food or through the use of the toxins as medicines.

It is usually assumed that the effects of toxins are primarily related to the amount of exposure rather than to differing sensitivities in exposed individuals as occurs for the allergic and infectious diseases. This means that at high levels of exposure, all exposed individuals are likely to be affected. However, there does appear to be a range of sensitivities to most toxic substances at low exposure levels.

Reports of disease resulting from exposure to fungal toxins in buildings are anecdotal and generally lack sufficient data to document a clear connection between exposure and disease. One case where documentation of the exposure/disease relationship was relatively complete is the study reported by Croft *et al. (Atmosph Environ* 20:549-552, 1986). Other studies have reported the presence of a potentially toxigenic fungus in one or more reservoirs but have not made a clear connection to actual exposures intense enough to produce the reported symptoms. However, because of the potential severity of the resulting diseases, a conservative approach to the control of toxigenic fungi is essential.

Exposure and disease

The fact that a particular agent can cause disease is not proof that it commonly does so. Nor is the existence of a case of a fungal-related disease adequate proof that exposure occurred in a particular environment. Rigorous criteria exist for documenting a relationship between exposure and disease. As far as is possible, these criteria should be met before conclusions are made. They are summarized in the accompanying sidebar. Very few, if any, case reports fulfill all of these criteria, and few even document the first three, which are essential if a connection is to be made between fungal contamination in a building and existing disease.

Conclusion

Fungi are unique organisms, many of which can utilize building materials as food sources, provided adequate water is present. There is good evidence that fungi cause disease and that these diseases can result from growth of the fungi in buildings. The evidence is much less convincing, however, that the growth of fungi in buildings commonly causes disease, and the conditions under which such disease occurs are not clear. When reading literature on fungal disease in buildings, one must assess the quality of the evidence presented. The most important pieces of evidence are 1) a recognized relationship between the agent and the disease and 2) documentation that exposure to the agent has actually occurred. **HPAC**

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