# Chapter 4
# Development of Mould in Indoor Environments

**Abstract** Mould spores are widely disseminated in the environment. Even inside the buildings, we can find hundreds of species of fungi, proliferating with a favourable combination of conditions (oxygen, appropriate temperature, moisture, nourishment from the substrate) in which to germinate, grow, and sporulate. The presence of mould in buildings is not welcome for two main reasons: they are responsible for several types of illnesses and pathologies experienced by building occupants, grouped under the name of "Sick Building Syndrome", and their presence contributes to the defacement of paint and finishes. In recent years, since buildings are always more airtight and highly insulated, internal moisture load risks to become always greater if not managed by an adequate strategy. Consequently, the presence of moulds has considerably increased, despite the fact that living spaces should have better quality. Attention should be paid to the correct application of all that leads to minimisation of mould risk in buildings.

**Keywords** Mould · Spore · Germination · Condensation · Water activity · Substrate · Bioreceptivity · Sick building syndrome

## 4.1 Mould Life Cycle

Mould represents all species of microscopic fungi that grow in the form of multicellular filaments, called *hyphae*. In contrast, microscopic fungi that grow as single cells are called *yeasts*. A connected network of tubular branching hyphae has multiple, genetically identical nuclei and is considered a single organism, referred to as a colony.

Fungi are ubiquitous eukaryotic organisms, comprising an abundance of species. The main characteristic of mould fungi is that they do not have chloroplasts and therefore they are not able to carry out photosynthesis.

Over 1.5 million of fungal species exist on earth, 65,000 of which have been identified. Although they are all slightly different, mould species that grow in

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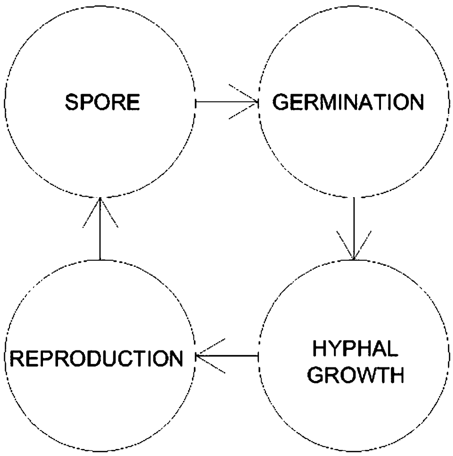


**Fig. 4.1** Representation of the life cycle of mould

building spaces exhibit a similar life cycle. The typical life cycle of fungi consists of four stages: spore, germination, hyphal growth (vegetative growth), and reproduction (Moon 2005).

During the germination phase, the spores settle on surfaces and remain inactive until they can absorb moisture and nutrients from the substrate. If the substrate does not provide adequate nourishment and moisture, the spores do not germinate. The growth of hyphae occurs immediately after germination and as these thicken, they form a mass called *mycelium*. From this time onwards, the fungi metabolise the substrate material by extracting the necessary nutrients and retaining the moisture needed for growth. In the final phase, the fungi constitute a reproductive organism producing spores (Fig. 4.1).

Concerning mould growth in buildings, it is often categorised into visible or non-visible states (Moon 2005). Viitanen et al. have developed a seven-level mould growth index (Viitanen et al. 2000). Sedlbauer et al. used another index for mould growth intensity with six levels (Sedlbauer et al. 2003) (Table 4.1).

From the study on the life cycle of moulds, it emerges that the mould needs adequate nourishment from the substrate and moisture for its growth. The control of environmental conditions in buildings is then critical for mould prevention, as reported in the following sections.

## 4.2 Main Causes and Conditions of Growth

The problem of mould growth inside buildings has been observed in different geographical areas and various types of building (Daquisto et al. 2004) (Fig. 4.2).

Fungi may be transported into buildings on the surface of new materials or on clothing. They may also penetrate buildings through active or passive ventilation.

**Table 4.1** Indices of fungal growth: the seven-level mould growth index on the *left* (Viitanen et al. 2000); the six-level index on the *right* (Sedlbauer et al. 2003)

| Index of mould development | Growth rate | Intensity of growth | Characteristics |
|---|---|---|---|
| 0 | No growth (inactive spores) | 0 | No detectable growth |
| 1 | Growth observed only with a microscope (early stages of development of the hyphae) | 1 | Growth visible only with a microscope |
| 2 | Moderate growth detected under the microscope (covering more than 10 %) | 2 | Growth visible to the naked eye |
| 3 | Moderate growth detected visually (new spores produced) | 3 | Remarkable growth |
| 4 | Growth detected visually (covering more than 10 %) | 4 | Strong growth |
| 5 | Abundant growth detected visually (covering more than 50 %) | 5 | Total growth |
| 6 | Dense growth (covering over 100 %) | – | |

Fungi are therefore found in the dust and surfaces of every house, including those with no problems with damp.

To proliferate, mould requires a favourable combination of environmental conditions in which to germinate, grow, and sporulate (Moon 2005). In the next section, we will go deeper into all these conditions.

### *4.2.1 Environmental Factors*

Environmental conditions for fungal spore settling in buildings, include oxygen, appropriate temperature, and moisture or water activity (Hens 1999). Water activity (*aw*) is a measure of water availability and is defined as the ratio of the vapour pressure of the material pore ($p$) to that of pure water ($p_o$) at the same temperature ($Aw = p/p_o$). It takes values between 0 (dry substance) and 1 (pure water). In the substrate, the presence of many different components makes the relationship between humidity and water activity extremely complex and nonlinear. It is described by the curve of the water adsorption isotherm. The fungal growth on building materials is therefore linked to the curve of water adsorption of the material constituting the substrate.

Minimum water activity required for fungal growth on building surfaces varies from less than 0.80 to greater than 0.98 (Grant et al. 1989). Based on their water requirements, indoor fungi can be divided into:

(1) primary colonisers, which can grow at a water activity less than or equal to 0.80;
(2) secondary colonisers, which grow at a water activity level of 0.80–0.90;

**Fig. 4.2** Massive proliferation of mould inside a building

(3) tertiary colonisers, which require a water activity greater than 0.90 to germinate and start mycelial growth (Grant et al. 1989).

High levels of humidity, some surface and interstitial condensation may be sufficient for most primary and secondary colonisers, while tertiary colonisers generally require higher condensation levels, in combination with poor ventilation, or water damage from leaks, flooding and groundwater intrusion (Haseltine and Rosen 2009).

As most indoor fungi grow at 10–35 °C, common indoor temperatures are also not a limiting factor. However, although temperature and nutrients are not critical, they may affect the rate of growth and the production of certain allergens and metabolites (Nielsen et al. 2004).

For their life indoors, Fungi also need nutrients, which may include carbohydrates, proteins and lipids, coming from indoor environments. Moreover, they can even grow on inert materials such as ceramic tiles and can obtain sufficient nutrients from dust particles and soluble components of water.

From the studies in this field, a clear uniformity in defining the following four distinctive basic factors for the formation of mould is seen: temperature, moisture, nutrients (due to the type of support) and exposure time (Fig. 4.3).

Mould fungi especially grow on materials in the following specific conditions:

- presence of oxygen;
- temperatures between 22 and 35 °C (Baughman and Arens 1996);
- indoor relative humidity ranging between 71 and 95 % (Ayerst 1969);
- adequate substrate to provide the nutrients (Hens 1999).

Although each fungal species has a preferential humidity of growth, which varies according to the temperature and time of persistence of favourable environmental conditions, the International Energy Agency indicates an average of 80 % RH as a critical threshold for the formation of moulds (IEA 1990).

Other secondary factors for mould growth are: the pH value and the roughness of the substrate on which moulds grow, light, biotic interactions between different cultures, and indoor air velocity (Adan 1994; Krus et al. 2001).

### 4.2.2 *Influence of the Type of Support*

Most fungi are saprophytes, which means that they can feed on carbohydrates, proteins and lipids. In indoor environments, sources are varied and abundant: plants, pets, dust and building materials (such as wallpaper and fabrics),

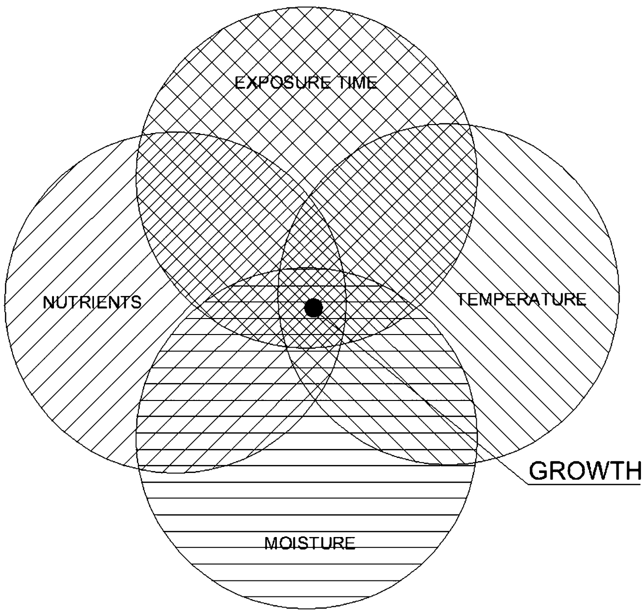


**Fig. 4.3** Requirements for fungal growth indicated by various authors

condensation/deposit of cooking vapours, paint and glue, wood, packed products (such as food), books and paper objects.

Several authors have studied the relationship between construction materials and mould growth. However, the results available are not easily resumable because of the great variety of materials and other factors that intervene to influence the development of moulds (Fig. 4.4).

Fungi are able to grow on almost all natural and synthetic materials, especially if they are hygroscopic or wet. Inorganic materials get frequently colonised as they absorb dust and serve as good growth substrates for *Aspergillus fumigatus* and *Aspergillus versicolor* (Haleem Khan and Mohan Karuppayil 2012). Wood is highly vulnerable to fungal attack. *Cladosporium* and *Penicillium* (*Penicillium brevicompactum* and *Penicillium expansum*) are reported to infest wooden building materials. Dried wood surfaces are more susceptible to fungi (Sailer et al. 2010). Acylated wooden furniture, wood polyethylene composites, plywood and modified wood products are susceptible to infestation by *Aspergillus*, *Trichoderma* and *Penicillium.* Inner wall materials used in buildings, such as prefabricated gypsum board, highly favour the growth of *Stachybotrys chartarum*. Gypsum supports fungal growth, as it is hygroscopic. Paper and glue used in indoor surfaces are very good growth substrates for most of the indoor fungi (Haleem Khan and Mohan Karuppayil 2012).

*Aspergillus* and *Penicillium* grow superficially on painted surfaces, and *Aureobasidium pullulans* have been found to deteriorate the paints (Shirakawa et al. 2002). Acrylic painted surfaces are attacked by *Alternaria*, *Cladosporium* and *Aspergillus* (Shirakawa et al. 2011).

Sedlbauer provides the following clear classification of substrates in relation to their sensitivity to the development of mould (Krus et al. 2001; Sedlbauer et al. 2001):

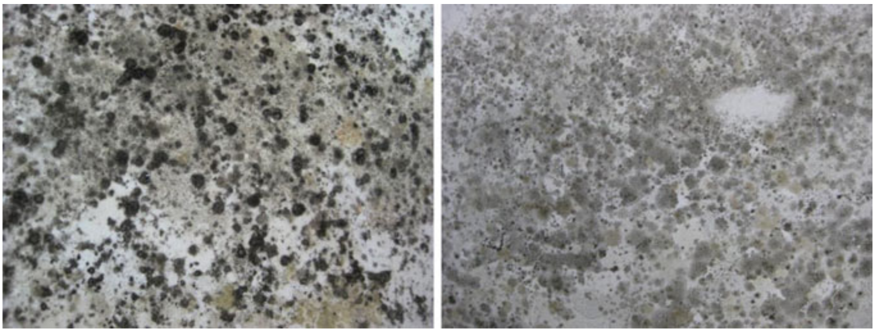

**Fig. 4.4** Development of different types of moulds on the same substrate (internal mortar of a building)

Substrate category 0: Optimal culture medium;

Substrate category I: Biologically recyclable building materials like wall paper, plaster cardboard and building materials made of biologically degradable raw materials, material for permanently elastic joints;

Substrate category II: Building materials with porous structure such as renderings, mineral building material, certain types of wood as well as insulation material not covered by I;

Substrate category III: Building materials that are neither degradable nor contain any nutrients.

On the basis of these categories, the author developed an "isopleth system" (see Sect. 5.1) which allows the determination of the timing of germination of spores and growth of mycelium on the basis of limit curves of temperature and relative humidity (Krus et al. 2001).

Some building materials which are particularly rich in carbon, like cellulose or carbonates (wallpaper, wood-based building materials), are more conducive to the development of moulds compared with others that have lower carbon content (for example, plaster and glass wool) (Górny et al. 2003; Vacher et al. 2010).

Some paint components encourage microbial growth on the surface. Cellulosic components can act as nutrients for microorganisms that produce cellulase enzymes.

Vacher et al. studied the susceptibility to mould growth for various coatings and paint (acrylic-based painting, paint containing glycerine, wallpaper ordinary 80 g/m$^2$ and a wallpaper thick 240 g/m$^2$), applied on three types of substrates (Vacher et al. 2010):

- non-biodegradable;
- biodegradable and those treated with biocidal products;
- biodegradable and those free from biocides.

The outcome was that on aluminium and biocide-containing or untreated plasterboard surfaces, both acrylic-based and glycerol-based paints led to fungal growth, while unpainted aluminium and biocide-containing plasterboard were relatively or completely resistant. Researchers argued that the composition of the coatings and paints is as important as the substrate in making predictions about the biological degradation caused by mould. Therefore, the resistance of the vertical walls to mould contamination must refer to the exact composition of the surface coating (paint, wallpaper, etc..).

Ritschkoff et al. conducted experiments on wood-based composite materials (chipboard planks, wood wool and plywood boards), plaster, concrete, insulating materials (glass wool and rock wool) in different temperature and relative humidity conditions (Ritschkoff et al. 2000). Their results show that all the materials in a building may contribute to the growth of moulds if their relative humidity reaches 90 %. Some inorganic materials, such as metals and plastic, are not in themselves nutrients that are suitable for mould fungi, although the dust that deposits on them may represent a source of nourishment.

D'Orazio et al. showed that there is a direct correlation between the growth rate of some fungal species (*S.chartarum, P.Chrisogenum and A. versicolor*) and the content in organic matter, which various coatings and indoor finishes are able to provide as nutrients for the spores (D'Orazio et al. 2009). The authors underlined that, although various types of plaster and finish (experimentally analysed) belong to the same class of substrate (II), according to Sedlbauer's classification (Sedlbauer 2001), in reality there are sometimes quite remarkable differences in the results for the various substrates. Experimental results showed that the species *S. chartarum* (the most toxic for human health) had the most widespread development on the various types of support surface used.

Viitanen et al. developed a mathematical model for determining risk and durability of various materials to fungal growth under different conditions (Viitanen et al. 2011). They underlined that perhaps the most difficult requirement of the calculation is assessing the sensitivity of the material. Künzel states that "The ultimate goal of building physics related durability research should be the development of material specific degradation models" (Künzel 2011).

## 4.3 Effects on Human Health

Many people live more than 80 % of their time indoors; consequently, the indoor air quality (IAQ) has a fundamental effect on comfort, health and productivity, and has become a health priority for children according to the European Environmental Agency (Tamburlini et al. 2002).

The concentration of microorganisms inside buildings is often higher than that in the atmosphere and is responsible for several types of illnesses and pathologies experienced by the occupants and link with the time spent indoor, grouped under the name of "sick building syndrome" (SBS). Headaches, pressure on the head and throbbing and feelings of tiredness are the most common signs of SBS (Haleem Khan and Mohan Karuppayil 2012).

Numerous epidemiological studies have demonstrated that long-term exposure in unhealthy environments, subject to the proliferation of moulds and fungi, is one of the main causes of allergies and irritative reactions. Engvall et al. have shown that SBS is most frequent in places with a high level of humidity together with pungent odours and moulds (Engvall et al. 2002). Araki et al. has studied the possible causal relationship between SBS and indoor air quality (Araki et al. 2012). They describe how the pathology is found more often in environments characterised by the presence of moulds. This phenomenon is mainly due to the facility with which spores and their metabolic waste can be inhaled or ingested.

In many types of fungi, the spores are only 2 μm in size and can therefore easily penetrate the bronchial tubes. Spores that have a diameter of greater than 10 μm cannot arrive at the bronchial cavities but are retained in the mucous membranes of the pharynx and may give rise to allergic rhinitis.

At least 600 species of fungi are in contact with humans and less than 50 are frequently identified and described in epidemiologic studies on indoor environments (Haleem Khan and Mohan Karuppayil 2012).

Moulds may cause respiratory symptoms as sinusitis similar to the common cold due to inflammation of paranasal sinuses. Mucous membrane irritation syndrome, characterised by symptoms such as rhinorrhoea (running nose), nasal congestion and sore throat, and irritation of nose and eyes, has been found in people exposed to damp buildings (Lanier et al. 2010).

High concentration of moulds, especially *A. alternate,* that develop in very damp environments may be involved in severity of asthma in children and young adults.

Exposure to buildings contaminated with fungi and mycotoxins (*trichothecene*) may develop hypersensitivity pneumonitis, which are a granulomatous lung disease due to exposure and sensitisation to antigens inhaled. This disease can be acute or chronic (Haleem Khan and Mohan Karuppayil 2012).

Exposure to a variety of fungi such as *Aspergillus spp*. and *Fusarium spp*. may result in serious respiratory infections in immunocompromised people. Chronic obstructive pulmonary disease, asthma and cystic fibrosis are disorders among people that are potentially infected with *Aspergillus* (Baxter et al. 2011).

Rheumatic diseases, due to inflammation and stiffness in muscles, joints or fibrous tissue, are exacerbated by environmental conditions, which include dampness, fungi and their products indoors (Breda et al. 2010).

A link between respiratory exposure to fungal material and seasonal allergy was first proposed in 1873 by Blackley, who listed 106 fungi genera including members who elicited allergy (Blackely 1873). The major allergic diseases caused by fungi are allergic asthma, allergic rhinitis, allergic sinusitis, bronchopulmonary mycoses and hypersensitivity pneumonitis (Haleem Khan and Mohan Karuppayil 2012).

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