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Mathematical Modelling of Fungal Growth in Biodegraded Building Materials

Garima Arya
Research Scholar, Department of Microbiology, Gurukula Kangri Vishwavidhalaya, Haridwar, India
Dr. Jugmendra Singh
Associate Professor, Department of Applied Sciences and Humanities,
Panipat Institute of Engineering Technology, Panipat, India

Abstract:
A mathematical model for apical growth, septation, and branching of mycelial microorganisms is presented. The model consists of two parts: the deterministic part of the model is based on fundamental cellular and physical mechanisms; it represents the kinetics for growth of hyphal tips and septation of apical as well as intercalary compartments. In regard to random occurrences of hyphal growth and branching, the stochastic part deals with branching processes, tip growth directions, and outgrowth orientations of branches. The model can explain the morphological development of mycelia up to the formation of pellets. The results, as predicted by the model, correspond very closely to those observed in experiments.

Keywords: *Fungi, building material, model, relative humidity, temperature*

1. Introduction

Fungi are a crucial component of most biodegraded and non biodegraded building materials (1). Fungi are responsible for decomposing wood, organic matter, distributing nutrients through the environment and supporting plants and animal life through symbiotic relationships. Certain species of fungi are common pathogens causing disease and infection in indoor environment. The highly integrated nature of fungi in relation to the environment and all life emphasizes the importance of developing a greater understanding of the growth and morphology of such organisms. Mathematical modeling (2,3) has provided a means through which key processes can be isolated to analyze and simulate a target system to allow observations and form predictions regarding unknown phenomena. Numerous models of fungal colonies have been produced and are generally categorized into two main groups; continuous and discrete. The following study combines the approaches so that the constructed hybrid model comprises a discrete network that represents the fungal mycelia and a continuous component to account for the continuous substrates and other compounds crucial to fungal growth and development. Key processes (4) such as uptake, translocation and anastomosis are included in addition to the implementation of a flexible hyphal orientation scheme that facilitates a variety of tropisms to different influential factors. The hybrid model (3) is used to investigate several scenarios such as the polarization of growth in response to isolated nutrient resources, competition between multiple colonies and fungal development and persistence in polluted environments. These investigations demonstrate the versatility of the hybrid model and highlight the potential for further applications.

1.1. Prediction of hypha Growth by Fungal Index

Fungal index was proposed as a parameter to characterize the indoor environmental capacity for fungal growth and is widely used in India. This fungal index is based on the growth response of a xerophilic fungus *Eurotium herbariorum* as a function of ambient temperature and relative humidity (5). Fungal index is also based on isopleth diagrams under steady-state environmental conditions. The prediction results of fungal index were also used to evaluate the sensitivity (6) of the reaction diffusion model.

1.2. Numerical Analysis

In this analysis, heat and moisture transfer and fungal growth on an indoor wall surface were analyzed for four building materials: (i) concrete single wall, (ii) gypsum plaster single wall, (iii) insulation board and (iv) composite wall consisting of (i), (ii), (iii) and an air layer, under summer climate conditions in Haridwar, Uttarakhand. A two-dimensional plane of 200 mm (y), 200 mm (z) on a wall surface (indoor side) was targeted as the object surface in this analysis (8). An equally spaced mesh with 1 mm intervals was adopted for the y and z directions for analysis of the reaction diffusion model. A uniform distribution of nutrient concentration was assumed as the initial condition. As the initial condition of active fungus, u = 1.0 was set at the center of the analytical plane (point x=100 mm and y=100 mm). The initial concentration of inactive fungus was assumed to be zero (v= 0.0). A free slip condition (zero gradient) was assumed as the boundary condition at the edge of the analytical plane.

2. Materials and Method

2.1. Measurements in Used Objects

The new developed prediction models shall be verified by means of some selected examples of mould fungus formation in used buildings. For this purpose, a typical microbial infestation in 2 different rooms as well as at the outside facade is referred to. For several years, redevelopments of old buildings are carried out with the aim to make improvements with respect to energy(9). Damages by mould fungi could then be observed again and again in the uninsulated dwellings (10,11). In some objects, the thermal and hygric situation at wall structures with mould infestation was measured; they can be used to verify the prediction model. To investigate the moisture balance in the area of the window lintels and of the air gap between the insulant plates further, since it is a decisive factor for the assessment of mould fungus formation, two-dimensional hygrothermal calculations (12) are carried out with the WUFI program. Here the following wall structure is assumed (from the inside to the outside):

i. Wall material: 150 mm concrete
ii. Insulating material: 160 mm polystyrene in the middle of the wall and 160 mm mineral wool in the window lintel
iii. Plaster: 5 mm synthetic resin plaster or, for comparison 10 mm mineral plaster.

An initial moisture content of 15 vol.% for concrete and of 10 vol.-% for plaster is assumed. New approaches and functional features. The current standard methods to assess mould fungus formation usually take stationary boundary conditions into account. Whereas in most of the cases in India only the relative humidity is indicated as criterion, isopleth systems are used as basis for the assessment more frequently by international experts. Relative humidities are stated here, depending on the temperature. If these humidities are exceeded, mould fungus formation may take place.

3. Results and Discussion

3.1. Time Course of Temperature/Relative Humidity on the Inner Surface of Building Materials

Table2 depicts the time courses of temperature and relative humidity on the surface of target building materials (indoor side) and the outdoor climate conditions in summer. The calculation period covered was the first week of July in Haridwar, Uttarakhand, India. The initial conditions of room air temperature and relative humidity were set at 25 ºC and 85% RH, respectively, and the room air temperature and relative humidity were fixed at constant values. The heat and moisture transfer analyses were carried out at one hour intervals.

The outside temperature changed within the range of 19 ºC - 32 ºC on the basis of the AMeDAS data (13) of a standard year. Wall surface temperature (indoor side) became constant at about 25 ºC in cases (iii) insulation board and (iv) composite wall. In cases (i) concrete single wall and (ii) gypsum plaster single wall, although the wall surface temperature (indoor side) fluctuated, the temperature changes were smaller than the outdoor temperature fluctuation. Table 1 shows a list of model parameters and other boundary conditions used for the numerical analysis. Stochastic fluctuation as shown in equation (2) was coupled in this analysis.

Calculation period	Total 150h, Time Steps:1[h], Start:10/08, End:06/2012
Initial Condition (wall inside) Indoor Climate	Initial Temperature: 25 ºC, Initial Relative Humidity [-]: 0.6 Initial Water Content[kg/m3] of Concrete: 47.9 Insulation Board: 0.11, Gypsum Plaster: 2.13
Outdoor Climate	Fukuoka; AMeDAS standard year (10/08 to 06/2012)
Model parameters of Reaction diffusion model	$\sigma 1$=4.0×10^{-4}, $\sigma 2$=2.0, $f1$=1.5, $f2$=1.0, θ=4.0×10^{3}, $\sigma 3$=3.0, $a1$=1/1200, $a2$=1/60, $n0$=0.5 for PDA, Dn=1.5×10^{-7},

Table 1: Numerical and boundary conditions

3.2. Time Course of Hypha Growth by Numerical Prediction

Figure 3 depicts the time course of fungal growth on each wall surface (indoor side). The prediction results of (1) the WUFI-Bio model overestimated the fungal growth response compared with the results of (2) fungal index. In the cases of (i) concrete wall and (ii) gypsum plaster board in particular, large differences were observed in the fungal growth response after 24 h from the start of analysis, although a difference in hyphal growth could not be confirmed at an earlier stage of analysis in (2) fungal index.

3.3. Biological Background and Model Formulation

The fungal mould growth provides continuous, quantitative data that can be used for predictive mathematical modelling of microbial activity. Most curve fits made all gave reasonable results, but it is clear that it is not possible to draw any conclusions about which model that has the highest relevance from a microbiological point of view as many models give similar fits. The model development in this study was only a first step in a conceptual or mechanistic model of fungal *growth*. Because we used the data in this experiment to develop a fungal growth. In this case, a truly independent data set will be difficult to obtain because some of the coefficients will change with hybrid. The fungal growth may be in the following categorize. Mould fungi can be found in the following classes (14):

- zygomycetes
- ascomycetes and
- deuteromycetes (Fungi imperfecti).

Table 1 shows about 200 species occurring in buildings. This list contains those species that the various authors (7,15,16,17).The surface temperature at the samples was 14 °C and 18.5 °C respectively. The time course of the air humidity fluctuations was investigated in the following combinations:

I Category 95 % for 24 h/d
II Category 95 % for 6 h/d and 60 % for 18 h/d
III Category 95 % for 3 h/d and 60 % for 21 h/d
IV Category 95 % for 2 h/d and 60 % for 22 h/d
V Category 95 % for 1 h/d and 60 % for 23 h/d
VI Category 95 % for 0.5 h/d and 60 % for 23.5 h/d

In comparison with the investigations carried out by researchers (18), Table 5contains a list of some literature data on the dependence of fungal growth on time and special substrates. The individual data are explained in the following:

(i)The number of daily hours when the mould fungus starts to grow at temperatures below 20 °C and relative humidities (19) of more than 75 %. A range is regarded as safe, if, over a long period, the relative humidity of 75 % is not exceeded more than 8 to 12 hours perday, and if the limit of 75 % relative humidity is not exceeded more than12 hours on 3 successive days.

(ii) Equal or a little smaller values for the daily time required for exceeding the relative humidity of 75 or 80 % are given by published papers (20,21). But it is always emphasized that the stated condition for the relative humidity at the place of growth must last for 5 successive days.

(iii) According to the time of wetness value definition (Time-of-wetness: hours of highhumidity per time unit) by Adan (2), growth takes place, though delayed, if a relative humidity of at least 80 % is exceeded 4 hours a day.

It is obvious that bacterial cells and cellular fragments, fungal spores and by-products of microbial metabolism, present as particulate, liquid or volatile organic compounds may be components of bio-aerosols. Air contains significant number of microorganisms, acting as a medium for their transmission or dispersal. Though bio- aerosol particles are generally 0.3 to 100 um in diameter; but their respirable size fraction is regarding to be 1 to 10 u m. Bio-aerosols ranging in size from 1.0 to 5.0 u m generally remain in the air, whereas larger particles are deposited on surfaces (1). Microbial flora who produced infected indoor environment is listed as under:

3.3.1. Microbial Agents of Biodegraded Building's Indoor Environments-

Toxins of Gram-positive and Gram- negative bacteria
Fungal toxin
Bacterial cells, spores and fragments
Fungal spores and mycelia
Microbial volatile organic compounds.

3.3.2. Allergens of the Biodegraded Building's Indoor Environment-

House dusts and mites
Cockroaches, rodents and pests
Pets: dog, cat, rabbit, mouse
Fungal and bacterial allergens

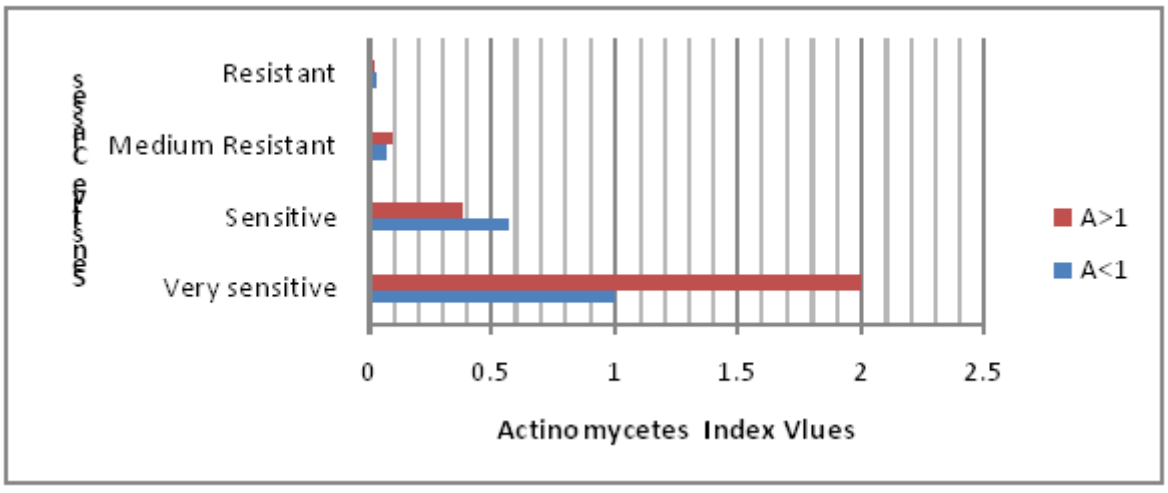

Figure 1: Fungi growth intensity factors k_1 sorted into four sensitivity classes

Therefore, by the simplify use of these factors, which were also classified to be used as material sensitivity groups. The result of this categorization is presented both for actinomycetes growth intensities and maximum actinomycetes index levels in Table 2. These data give the values for the actinomycetes growth intensity parameter (k_1) and for the coefficient of the max. Actinomycetes index factors (A_{max} and k_2) and RH_{min} indicates the minimum level of relative humidity, where actinomycetes growth is possible on specific material

group. All data of Tables (2) determined the best approximation based on different numerical post processing of the experimental results.

Material	25˚C, 97% RH	10˚C, 97% RH	25˚C, 90% RH	10˚C, 90% RH
Pine sapwood	6	5	4	3
Spruce sapwood	5	5	3	2
Fiber board	4	3	1.5	1
Gypsum	2.0	1.7	1	1
Concrete	2.5	2	0.5	0.5

Table 2: Maximum actinomycetes growth index for different material under using steady state conditions

The results of these investigations show that, depending on the hygrothermal boundary conditions and the material, different durations are necessary to enable mould fungi to grow. This implies that the calculation method to be developed for the prediction of mould fungus formation has not only to consider the influence of various substrates of building materials and contaminations but also transient boundary conditions. the hygrothermal conditions existing in the room. Under stationary conditions, the surface temperature can be calculated as follows (9):

JOi = JL i - U Rsi (JL i -JLa) (1)

JOi [°C] Temperature of internal surface

JL i [°C] Temperature of indoor air

JLa [°C] Temperature of outside air

U [W/(m² K)] Heat transition coefficient

Rsi [(m2 K)/W] Inside heat transmission resistance

The morphological characteristics of the fungal colony were schematically predicted in modeling active and inactive fungi separately. In the early stage of calculation (less than 24 h), fungal colonies grew rapidly and seven days after the test started, the result of numerical analysis showed a tendency to increase constantly.

4. Conclusions

The findings obtained in this work can be summarized as follows:

(1) The distinctive features of the new prediction method as against the previous standard methods to the growth of mould fungus in building materials and an elaborated indication of growth conditions. In this mathematical fungal growth model, the spore germination times and grow thrates can be specified for three different substrate categories independence on temperature and relative humidity. These indications refer to all fungus species occurring in buildings, as it is known according to the current state of knowledge, with always the lowest spore germination times and the highest growth rates being considered. That allows to determine the minimum time needed by mould fungi to germinate, for different building materials and degrees of contamination.

(2) To assess building constructions at any climatic boundary conditions, the transient courses of temperature and relative humidity can be calculated as input parameters for the biohygrothermal model by means of the hygrothermal calculation program. Different spore germination times

arise, however, with different substrate categories by means of which the critical moisture contents are set. For reasons of safety it is therefore recommended for biohygrothermal calculations to always choose that group which is more favourable for fungoid growth.

(3) The morphological characteristics of fungal colony formation could be reproduced on the basis of reaction diffusion expression in modeling active and inactive fungi separately.

(4) As the next step of this research, model parameters must be identified on the basis of detailed experimental data, and it is also necessary to couple numerical analysis with other parameters, for example characteristics of building materials and pH, in the proposed mathematical model.

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