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An Assessment of the Influencing Factors Promoting the Development of Mould in Buildings, A Literature Review

Junpeng Lyu[1,*], Michael Pitt[1], Tim Broyd[1]

[1] Department of The Bartlett School of Sustainable Construction, University College London, London, United Kingdom

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ABSTRACT

There are few literature evaluations that analyse the growing environment of indoor mould, despite its health risks and building management burden. This paper examines the most significant factors influencing indoor mould growth and risk levels through a literature review. It was discovered that relative humidity, temperature, time, and nutrients in the substrate were the most significant factors affecting the growth of moulds and that the development of the majority of mould species depended heavily on the relative humidity and temperature values. The optimal ranges for mould growth in terms of temperature and relative humidity are 30°C to 35°C and 95% to 99%, respectively. In order to prevent the growth of indoor mould, this review suggests that the indoor environment of future buildings should pay particular attention to the control of the thermal and humid environment, as well as the accumulation of nutrients and time within the interior of walls.

1. Introduction

Indoor mould affects structures and human health. Indoor mould may harm furniture, thermal insulation, and wall paint. More significantly, indoor mould development and spread may cause asthma, coughing, and upper respiratory tract problems in occupants. Mould development causes upper respiratory tract symptoms in around 10,000 Brits each year [1]. Woolliscroft said 17% of British households had mould. Indoor mould avoidance is becoming more significant due to its environmental and public health impacts [2].

Indoor mould is commonly ignored. Early on, individuals were less worried about the interior environment, which increased mould infestation. During the first energy crisis, individuals concentrated on energy reduction. Building air tightness was improved to minimise interior heating energy. People overlook sufficient indoor ventilation, which increases indoor humidity and mould development [3]. With the advancement of industrial technology, more single-glazed windows have been replaced by double-glazed ones, which reduces indoor heat loss but increases the indoor-

* *Corresponding author.*
E-mail address: j.lyu@ucl.ac.uk

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outdoor temperature difference, allowing more condensed water on the walls around interior windows to be absorbed. Increased relative humidity on interior walls increases mould formation [4].

Mould growth is affected by numerous variables. The main causes of indoor mould formation are moisture, temperature, and nutrients [5]. Indoor comfort and building material durability may be affected by high humidity. The weather on a given day might impact interior humidity. Condensation is the principal indoor moisture source. Excessive room moisture causes 70% of structure damage [6]. When wet air in the room cools to a particular degree, condensation forms on the object's surface, providing mould development conditions. Temperature is a major element in home mould formation. Biochemical processes in mould development are temperature dependent. Too high or low temperatures impair mould cell structure and enzyme function, hindering metabolic activities. Mould growth will be reduced. If the temperature is optimal for mould development, temperature increases protein and enzyme activity in cells, biochemical reactions quicken, and growth rate increases for most moulds. The substrate temperature affects mould growth temperature. Mould development requires nutrients from the substrate, thus when the temperature and humidity are the same, mould grows on the carpet. Thus, mould growth and sustainable construction need moisture, temperature, and nutrient regulation [7]. The following three elements impact indoor mould development, but tenant behaviour and building ventilation also matter.

To combat indoor mould development, the international standard set building relative humidity limits. This study does not analyse or describe the internal environment; hence mould persists in many contemporary structures. Despite decades of study to prevent mould formation, mould growth likelihood and indoor environmental conditions are still unknown. Recent research demonstrates that numerous variables impact mould formation, including building fabric U-value and HVAC. Indoor environment and other intricate aspects induce mould development, making it difficult to identify the underlying causes and propose the best remedies during design [8]. This study aims to identify the most significant elements that might cause moisture risk and mould development in the indoor environment and analyse their individual and combined contributions to mould risk in buildings. To achieve this aim, four objectives need to be achieved:

(1)Find out the most related factors that can cause moisture risk and mould growth in buildings, based on literature review.

(2) Investigate how these factors can contribute to the growth of moulds indoors.

(3) Discuss the individual risk levels of these factors to the mould growth in buildings, through the collection, analysis and conclusion of data from existing studies.

(4) Assess the overall mould risk levels in the buildings on the basis of different contributing factors.

Indoor mould harms health. Li *et al.* [9] identified meta-analysis linking 500 mould toxins to human illnesses. Results demonstrate that long-term mould exposure causes respiratory disorders include upper respiratory symptoms, respiratory infections, cough, wheeze, dyspnea, bronchitis, and allergic rhinitis. Mold's health effects also rely on inhabitants' immunity. Mould poisons may kill humans with low immunity [10]. Indoor mould growth harms health and the economy [11]. Due to indoor mould, 4.6 million Americans have asthma, and the average cost of treatment is 3.5 billion dollars [11]. The interior decorating, materials, and building structures harmed by mould may be expensive [12]. Repair and demolition costs depend on how extensive the mould damage is. Lightly damaged indoor objects may be fixed by the owner for a minimal fee, while significantly damaged things must be restored by specialists. Professional indoor repair costs up to 7000 pounds, while home-owner mould repair costs over 4500 pounds [13].

1.1 Main factors affecting mould growth

Mould is affected by minimum, optimum, and maximum temperature. Mould grows best at 5-45°C and spores at 5-60°C [14]. Most mould grows best at 5–35°C. As temperature drops, mould development slows [15]. Byssochlamys fulva can live below 85°C for 30 minutes or 87.7°C for 10 minutes, making it more heat-resistant than other moulds [16]. Acidophilia mould can live at frigid temperatures, unlike other moulds. RNA (Ribonucleic Acid) helps mould live and proliferate in low temperatures [17]. The optimal indoor temperature range for mould survival is 5-30°C, which is also the range for humans.

Many studies have shown that relative humidity is critical to mould growth [16]. The substrate and airborne water vapour contribute to relative humidity. Water Active, the Equilibrium Relative Humidity (ERH) divided by 100, is a number between 0 and 1 that measures surface moisture. The experiment conducted by Johansson *et al.,* [18] showed that mould can only develop at 75-80% RH. Johansson *et al.* [19] found that mould requires 85% relative humidity. Architecture study [20] has shown another minimum RH requirement for mould growth: 80%. The lowest critical limit of RH (RHcrit) for mould development is 75% [21]. Depending on the species or growing circumstances, mould may grow below 75% RH. Kubicek and Druzhinina [22] found mould formation begins at 72% or 70% RH. Considering that their mould formation was replicated in storage and roof areas, the indoor method applies to 75% RHcrit.

Mould development depends on exposure time. Mould may develop after prolonged exposure to good circumstances. Due to unfavourable circumstances, brief exposure does not encourage mould development [19]. Temperature and humidity affect mould development. Several studies have shown that mould growth is delayed by fluctuating temperature and humidity [6,21]. Rapid relative humidity changes slow mould growth.

Mould development depends on substrate nutrients including vitamins, amino acids, carbohydrates, etc. [20]. Mould species determine carbohydrate, mineral, and organic nutrition requirements. Mould may develop on any material, although its growth relies on the base course's dampness. Passanen and others found that mould can develop on nutrient-rich substrates even in low air humidity [23]. Research shows that Aspergillus and Penicillium growth relies more on substrate glucose [20]. However, Vereecken [24] revealed that Mortierella refers its development to the substrate's cellulose more, demonstrating that indoor mould growth depends on cellulose fibres as well as carbohydrates. Architecture is heavily used cellulosic materials, which let mould grow with nutrients.

Dust and fatty substances can increase indoor mould development. Further research shows that surface qualities are important for mould development [5], notably on wall papers and paint, which may give nutrients for mould growth [25]. Indoor dust and shower "residue" may nourish mould development.

1.2 Other factors for mould development

In addition to temperature, relative humidity, and nutrition, oxygen, light, and pH affect mould growth. According to He *et al.,* [26] indoor oxygen levels in buildings are too high to effect mould growth (2%). Meanwhile, the illumination limitation needed to grow spores for many mould species has not been assessed [27]. Most mould grows best at pH 6–7 [28]. The mould's ability to adapt to environmental pH explains its presence in some building materials with pH values above 10 (e.g., concrete and lime) [29], indicating the pH condition's non-deterministic effect on mould development.

2. Methodology
2.1 VTT Model

Viitanen *et al.* [20] created the VTT model while studying mould development in the lab. The model determines the link between germination time, sapwood mould development, and degradation under specified temperature and relative humidity. Because it is difficult to analyse and model the interplay of material moisture content, surface humidity, time, temperature, and mould formation in buildings, corresponding research was done in the lab. The VTT model developed mould index (Figure 1) to measure mould coverage on building materials.

Index	Growth rate	Description		
0	No mould growth	Spores not activated		
1	Small amounts of mould on surface	Initial stages of growth	Microscopic level	
2	<10% coverage of mould on surface			
3	10-30% coverage of mould on surface, **or < 50% coverage of mould (microscope)**	New spores produced		Visually detectable
4	30-70% coverage of mould on surface, **or > 50% coverage of mould (microscope)**	Moderate growth		
5	>70% coverage of mould on surface	Plenty of growth		
6	Very heavy, dense mould growth covers nearly 100% of the surface	Coverage around 100%		

Fig. 1. Mould index classification

Development of the VTT model has continued. The updated VTT model is used for cellular concrete, polyester wool, expanded polystyrene (EPS), glass wool, polyurethane thermal insulation (PUR, with paper and polished surfaces), aerated concrete, and spruce board. The original and revised VTT models were compared in Figure 2. It shows the connection between mould index and time under constant relative humidity and compares two relative humidity values. Relative humidity raises mould index with time.

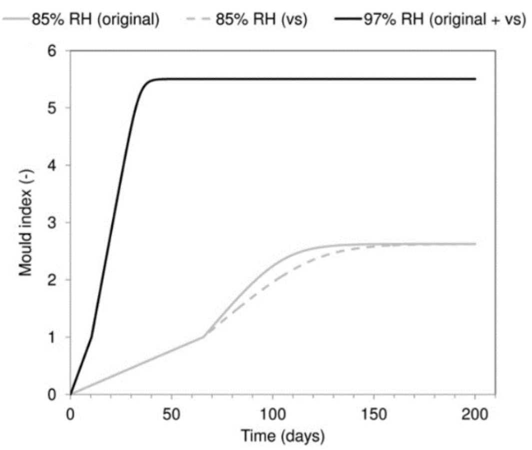

Fig. 1. Comparison between the original and updated VTT models

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2.2 Isopleth Model
2.2.1 Ayerst's isopleth model

Ayerst [30] investigated how indoor temperature, relative humidity, spore germination, and mould development rate relate. The isopleth model yielded and presented the data [30]. The time it takes mould spores to germinate at various temperatures and relative humidity may be used to create an isopleth model. Spore germination and mycelial growth under hydrothermal conditions may be compared. Isopleth models characterise spore germination and growth rates under temperature and relative humidity.

Ayerst's model considered mould species, unlike the VTT model. Different mould species have isopleth curves showing how relative humidity and temperature affect germination and growth. Ayerst's model compared mould species and drew diagrams of their curves. The lowest mould isopleth (LIM) curve was introduced to indicate a crucial stage of no spore germination or growth (Figure 3).

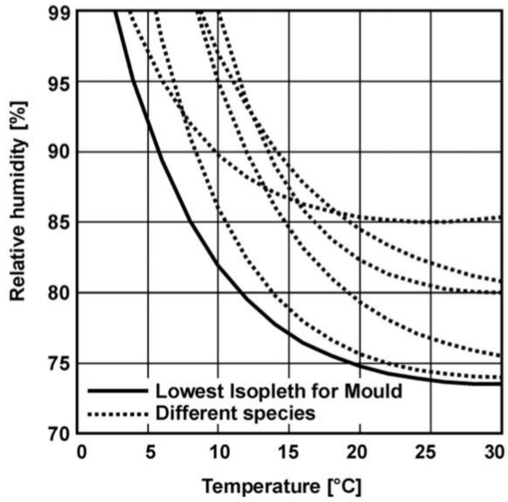

Fig. 2. Isopleth curves for different mould species in Ayerst's isopleth model

Isopleth curves show spore germination relative humidity at each temperature. Spores germinate after a time lag, however germination may occur instantly if environmental conditions are met. However, Ayerst [30] examined how water activity (relative humidity) and interior temperature affected mould species' average spore germination time and growth. These species' findings were shown as isopleth curves, such as Aspergillus chevalieri and repens in Figure 4. Instead of showing isopleth curves, Ayerst used symbols to depict spore germination time, combining the two dependent variables into one figure. The symbols are described in Figure 5.

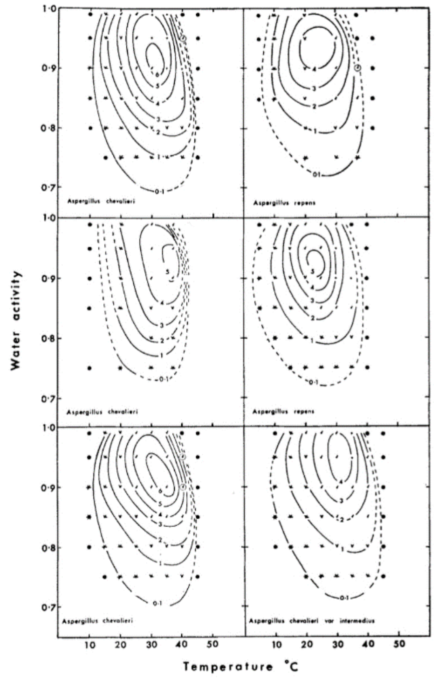

Fig. 3. Spore germination times and rates of growth (mm/day) of Aspergillus chevalieri and Aspargillus repens under various water activity and temperature conditions

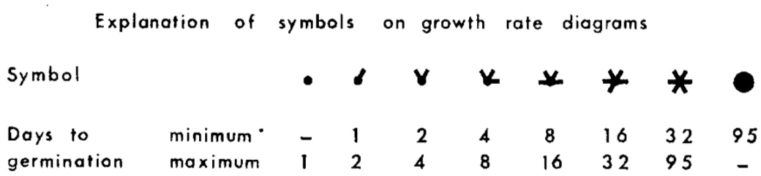

Fig. 4. Explanation of Symbols used on growth rate diagrams

Interpolation displayed the temperature and relative humidity conditions for equal growth rates of 0.1, 1.0, 2.0, 3.0, etc. mm/day in Figure 4. The broken lines indicate extrapolated values. The graphic shows that less time for mould germination leads to quicker development under the same circumstances. The mould that takes longer to germinate grows slower. Depending on the study, even the same species might react differently. Spore germination strongly correlates with growth rate. Figure 4 further shows a consistent result that the highest grow rate is generally at temperatures around their peaks.

These findings allowed Figure 4 to show how water activity or temperature affected spore germination time or growth rate for various mould species. Fig. 6 shows the association between water activity and mould growth rate for Aspergillus chevalieri at 20°C.

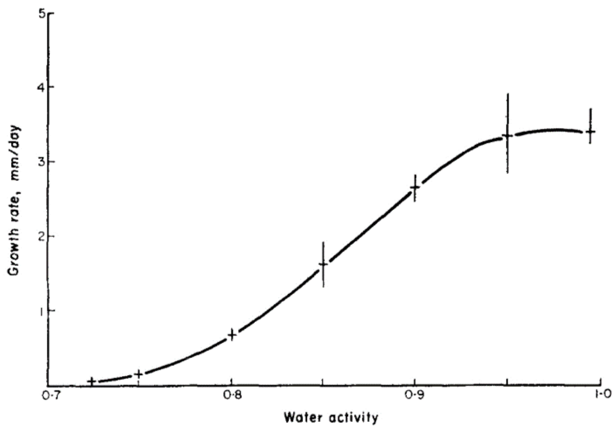

Fig. 5. Relationship between water activity and average growth rate of Aspergillus chevalieri at 20°C

2.2.2 Sedlbauer's model

Due to the abundant species of mould and materials, it is significant to determine an individual isopleth system for each species and substrate of mould. As a result, the mould species and materials found in buildings was subdivided into a set of classes by Sedlbauer *et al.* [31] Sedlbauer *et al.* [31] defined three hazardous classes in the first research, based on the health risk of the different species of mould (Figure 7).

- *Class A*: mould species which are highly pathogen and consequently not allowed to occur in buildings.
- *Class B*: mould species which are pathogen when exposed over a longer period or which cause allergic reactions.
- *Class C*: mould species which are not dangerous to health. Though, they may cause economical damage.

Fig. 6. The three hazardous classes on the health risk of different mould species

Subsequently, due to the consideration of building substrate, including possible contaminations were included. The second subdivision was made by Sedlbauer *et al.* [31] in terms of different substrates in buildings, as shown in Figure 8.

Substrate category 0	Optimal culture medium
Substrate category I	Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, material for permanent elastic joints
Substrate category II	Biologically adverse recyclable building materials such as renderings, mineral building material, certain wood as well as insulation material not covered by I
Substrate category III	Building materials that are neither degradable nor contains nutrients

Fig. 7. Sedlbauer's substrate categories

Consequently, distinct categories' isopleth systems were created. Figure 9 shows categories I and II. Separate isopleth graphs showed mould development rate by temperature and relative humidity. The lowest mould growth boundary lines (LIM) were displayed for various substrate types. In contrast to prior models, Sedlbauer's graphs reveal that increased temperature and relative humidity may shorten germination, although humidity affects growth rate more than temperature.

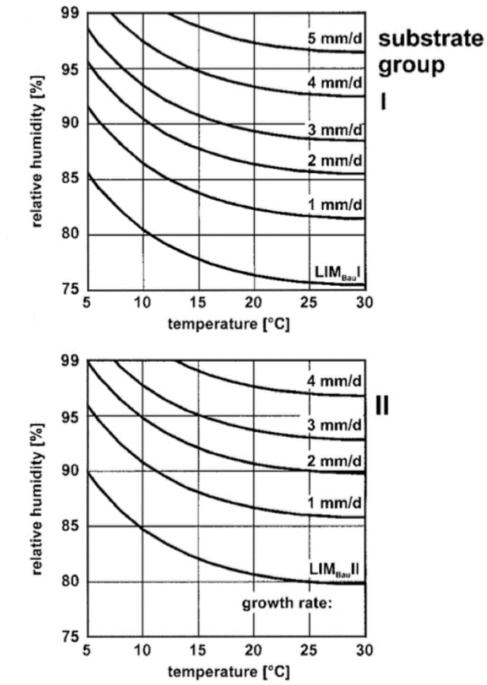

Fig. 8. Sedlbauer’s isopleth system of mould growth rate for substrate class I and II

2.3 The Definition and Classification of Mould Risk Levels

Temperature, relative humidity, time, and substrate nutrients are independent factors in this study, whereas mould index and growth rate are dependent variables. To better comprehend the relative relevance of these independent factors and the overall influence of numerous variates, the mould risk level is created to measure building moisture risk and mould development in terms of the dependent variables.

Thus, the mould danger level is divided into five categories from 0 to 4 based on dependent variable values. The mould danger level is '1' when the mould growth rate is 0mm/day to 2mm/day or the mould index is 0 to 1.5 (Figure 10). Due to inadequate data from the analysed models, the maximal risk level is 4 with a mould growth rate of 6–8 mm/day and a mould index of 4.5–6.

Mould growth rate (mm/day)	MGR=0	0<MGR≤2	2<MGR≤4	4<MGR≤6	6<MGR≤8
Mould index	0=MI	0<MI≤1.5	1.5<MI≤3	3<MI≤4.5	4.5<MI≤6
Mould risk level	0	1	2	3	4
Mould growth rate and mould index can be represented by "MGR" and "MI" respectively					

Fig. 10. Mould risk level classification

2.4 The Data Sources of Dependent Variables
2.4.1 Time

The VTT model in the literature review shows the link between time and mould index in two environmental conditions. The two climatic conditions had 85% and 97% relative humidity and 20°C temperatures. Figure 10 shows that at 85% relative humidity and 30 days of germination, the mould index is 0.5. The mould index may soar to 4.6 at 97% relative humidity. Figure 12 lists all Figure 11 data and mould danger levels.

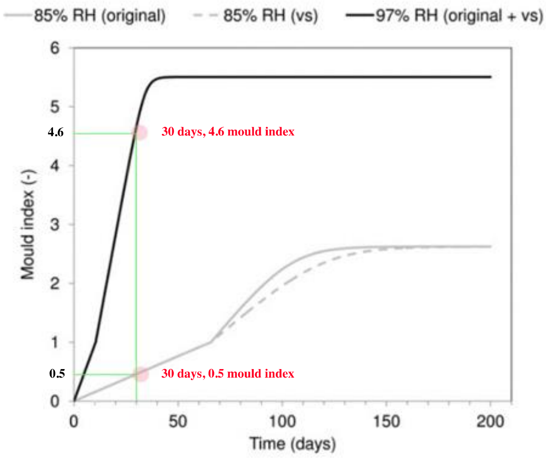

Fig. 9. Example of extracting data from VTT models at temperature of 20 °C

Time (days)	0	10	20	30	40	50	60	67	70	80	90	100	110	120	130	140	150	160	170	180	190	200
Mould index (T=20°C, RH=85%)	0	0.15	0.30	0.50	0.60	0.75	0.90	1.01	1.30	1.65	1.93	2.20	2.30	2.38	2.44	2.49	2.53	2.56	2.58	2.60	2.60	2.60
Mould risk level (T=20°C, RH=85%)	0	0.10	0.20	0.33	0.40	0.50	0.60	0.67	0.87	1.10	1.29	1.47	1.53	1.59	1.63	1.66	1.69	1.71	1.72	1.73	1.73	1.73
Mould index (T=20°C, RH=97%)	0	0.90	2.70	4.60	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
Mould risk level (T=20°C, RH=97%)	0	0.60	1.80	3.07	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67

Fig. 12. The relationship between time and mould index based on the available models

2.4.2 Temperature and relative humidity

Ayerst's isopleth models for numerous mould species show how temperature and relative humidity affect mould development rates. Aspergillus Chevalieri grows 2mm/day at 20°C and 85% relative humidity (Figure 13, red point). Figure 14 lists its mould growth rates at varied temperatures and relative humidity. Due to the large species differences, the average mould growth rates of 10 species are estimated under varied temperature and relative humidity circumstances.

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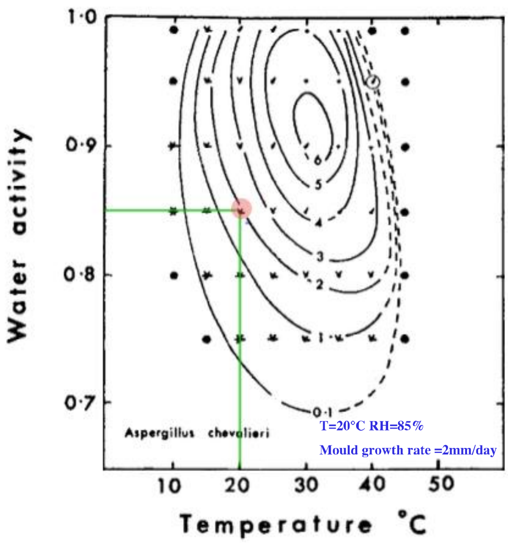

Fig. 10. Example of extracting data from isopleth model of Aspergillus Chevalieri

Aspergilius chevalieri		
Temperature (°C)	Relative humidity (%)	Mould growth rate (mm/day)
10	99	0.1
	95	0.1
	90	0.1
	85	0.1
	80	0.1
15	99	2.2
	95	1.9
	90	1.5
	85	0.8
	80	0.2
	75	0.1
20	99	3.9
	95	3.5
	90	3
	85	2
	80	0.9
	75	0.3
25	99	4.5
	95	5.2
	90	4.8
	85	3.2
	80	1.5
	75	0.7
30	99	6
	95	5.7
	90	6.1
	85	4.2
	80	2.1
	75	0.9
35	99	3
	95	5
	90	5.5
	85	4
	80	2.5
	75	1
40	99	0.1
	90	3
	85	3.2
	80	2.3
	75	0.9
45	99	0.1
	95	0.1
	90	0.1
	85	0.1
	80	0.1
	75	0.1

Fig. 14. The relationship among temperature, relative humidity and mould growth rates based on the available models

2.4.3 Substrate

Sedlbauer's isopleth model classifies substrates as class 0, I, II, and III. The best biologic culture media is substrate class 0, whereas substrate class III has no nutrients for mould development. Both categories are impractical and will not be investigated in this dissertation. Thus, only substrate classes

I and II are studied for the link between substrate nutrients and mould growth rates. For analysing substrate boundary environmental conditions, LIM curves are also studied.

Sedlbauer's isopleth model gives LIM values and mould growth rates at different temperatures and relative humidity. The left graph in Figure 15 shows two crossing locations (the red point) on the LIM I curve of the two green lines denoting 80.5% relative humidity and 10°C temperature for substrate class I and class II. The right graph of Figure 15 shows that the LIM II curve requires 84.8% relative humidity at 10°C for substrate class II. Figure 16 lists all extracted data.

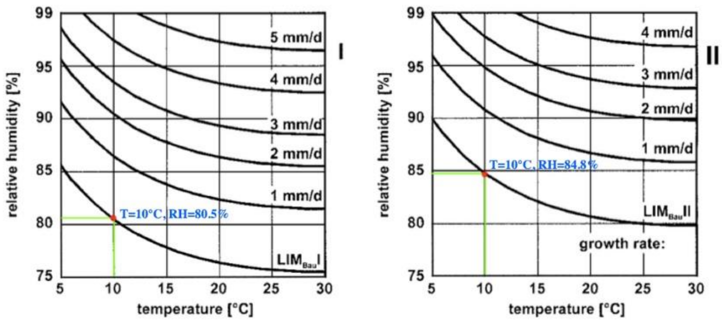

Fig. 11. Example of extracting data from Sedlbauer’s isopleth model with Substrate Class I and II

		Temperature (°C)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Substrate I	LIM I	Relative humidity (%)	85.8	84.3	83.5	82.5	81.5	80.5	79.9	79.2	78.8	78.3	78	77.5	77.3	77	76.8	76.5	76.3	76.2	76.15	76	75.95	75.9	75.85	75.81	75.79	75.77
	1mm/day		91.5	90.2	89.3	88.4	87.5	86.5	85.8	85.2	84.8	84.3	83.8	83.4	83	82.8	82.6	82.3	82.1	82	81.95	81.9	81.85	81.8	81.75	81.7	81.65	81.6
	2mm/day		95.8	94.3	93.2	92.3	91.4	90.5	89.9	89.2	88.7	88.3	87.8	87.4	87	86.9	86.7	86.4	86.2	86	85.95	85.9	85.85	85.8	85.75	85.7	85.65	85.6
	3mm/day		98.5	97.2	96.3	95.3	94.6	93.5	92.9	92.1	91.5	91.1	90.8	90.3	90	89.8	89.6	89.3	89.1	89.05	89	88.95	88.9	88.85	88.8	88.75	88.7	88.65
	4mm/day		/	/	/	99	98.2	97.3	96.9	96.2	95.8	95.2	94.9	94.4	94.1	93.9	93.7	93.3	93.1	93	92.95	92.9	92.85	92.8	92.75	92.7	92.65	92.6
	5mm/day		/	/	/	/	/	/	/	/	99	98.9	98.7	98.3	98	97.8	97.5	97.2	97.1	97	96.95	96.9	96.85	96.8	96.75	96.7	96.65	96.6
Substrate II	LIM II		90	88.5	87.8	86.8	85.9	84.8	84.1	83.5	83	82.5	82.1	81.8	81.4	81.2	81	80.85	80.7	80.4	80.15	80.05	80	79.98	79.96	79.94	79.92	79.9
	1mm/day		96	94.7	94	93	92	91.1	90.2	89.5	89.1	88.6	88.2	87.9	87.5	87.2	87.1	86.9	86.7	86.5	86.2	86.1	86.08	86.06	86.04	86.03	86.02	86.01
	2mm/day		99	98.6	97.9	96.8	96	94.9	94.2	93.8	93.2	92.9	92.4	92	91.7	91.3	91.1	90.9	90.7	90.5	90.3	90.1	90.05	90	89.97	89.94	89.92	89.9
	3mm/day		/	/	/	99	98.4	98	97.2	96.5	96.1	95.5	95.1	94.8	94.5	94.2	94.1	94	93.9	93.8	93.7	93.6	93.5	93.45	93.4	93.35	93.3	93.25
	4mm/day		/	/	/	/	/	/	/	/	/	99	98.8	98.7	98.6	98.5	98.3	98.15	98	97.85	97.7	97.55	97.4	97.3	97.2	97.1	97.05	97

Fig. 16. The comparison between substrate class I and II based on the mould growth rates under various temperature and relative humidity conditions

3. Results

3.1 The Mould Risk Levels of Temperature and Relative Humdity

Indoor temperature and relative humidity affect mould development in structures. This dissertation also considers Ayerst's isopleth model distinctions amongst mould species. Thus, the average growth rates of 10 mould species are used instead of individual kinds under different temperature and relative humidity circumstances. Figure 17 summarises mean growth rates under various scenarios.

Mould growth rate (mm/day)	Relative humidity (%)					
Temperature (°C)	75	80	85	90	95	99
5	0.10	0.13	0.21	0.28	0.35	0.42
10	0.10	0.28	0.66	0.68	0.77	1.09
15	0.23	0.53	0.68	0.78	2.13	2.68
20	0.23	0.57	1.08	1.91	2.47	3.01
25	0.42	0.60	1.45	2.76	4.40	5.71
30	0.45	2.13	2.65	4.13	5.61	7.46
35	0.32	2.26	2.97	4.98	6.46	7.79
40	0.12	0.64	1.79	3.72	4.31	5.98
45	0.10	0.10	0.28	1.51	2.09	3.13

Fig. 17. The average mould growth rates of 10 mould species under different environmental conditions

The literature review's Ayerst's isopleth model recommends a minimum temperature of 5°C and relative humidity of 75% for mould growth. Thus, Figure 17's temperature and relative humidity differ by 5°C and 5% from the two minimum. Note that moulds nearly cease developing at 100% relative humidity, hence the maximum value is 99%. The influence of indoor relative humidity is enormous, since increased humidity speeds up mould formation. At 35°C, where moulds are most active, 99% relative humidity grows roughly 25 times quicker than 75%.

Since temperature and relative humidity may impact mould growth simultaneously, one component must be regulated to analyse how the other influences mould growth. Figures 18 and 21 are produced from Figure 17 to show temperature and relative humidity separately. Each graph shows the link between relative humidity (or temperature) and mould development rate at one fixed temperature.

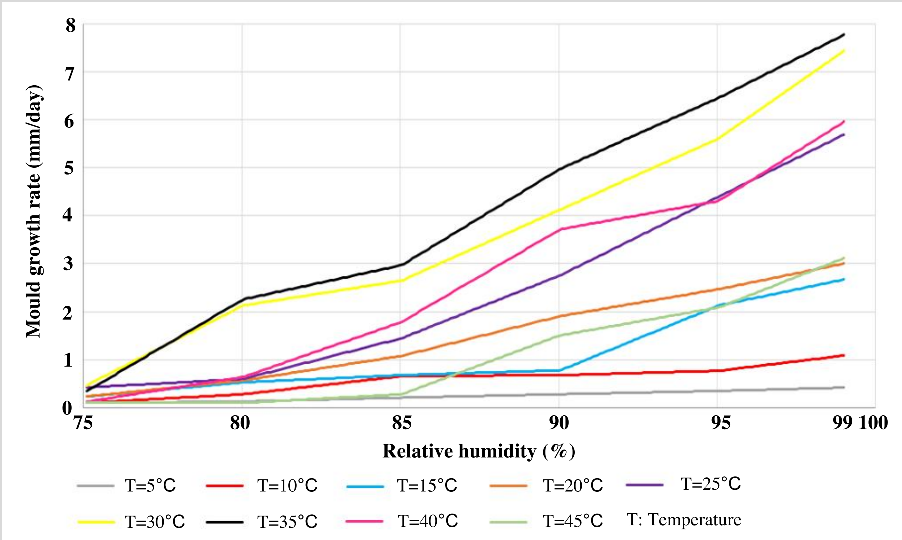

Fig. 18. Variation of mould growth rates with relative humidity at constant temperature values

Figure 18 shows that moulds grow similarly at various temperatures and increase with relative humidity. Growth rates rise quicker at temperatures between 25℃ and 40℃ compared to other temperatures. At 25℃ and 40℃ temperatures, mould growth rates range from 4 to 6mm/day with ideal relative humidity of 99%, reaching above 7mm/day at 30℃ and 35℃. The ideal temperature for mould development is 35℃, with the highest growth rates across all relative humidity levels. Mould formation is slowest at temperatures between 5℃ and 10℃, with growth rates ranging from 0 to 1mm/day. Beisdes, other temperatures may cause 2–4mm/day growth.

Figure 19 and Figure 20 classify and summarise the mould risk level of temperature under ideal relative humidity according to Figure 18. Mould growth rates may approach danger level ‘4’ (6-8mm/day) from 30℃ to 35℃, with ideal relative humidity of 99%.

Temperature (°C)	T<5	5⩽T<15	15⩽T<25 or 40 <T⩽45	25⩽T<30 or 35<T⩽40	30⩽T⩽35
Mould risk level	0	1	2	3	4

Fig. 19. Mould risk levels of temperature under the optimal relative humidity

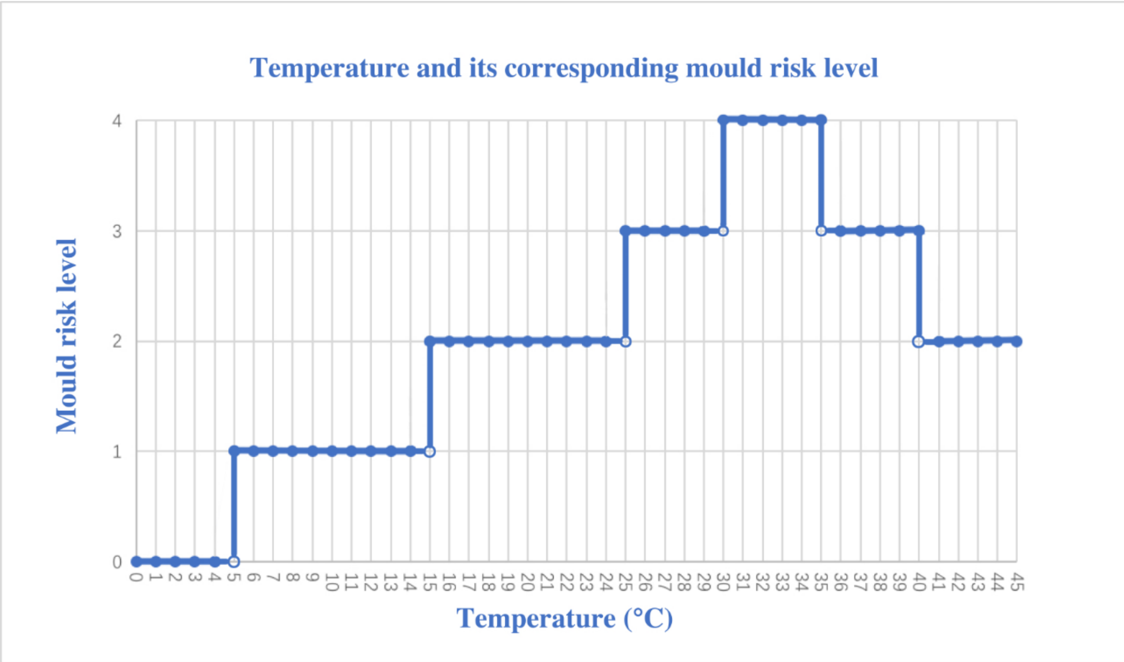

Fig. 20. Mould risk levels of temperature under the optimal relative humidity

Similar to Figure 21, temperature affects mould development rate under various relative humidity situations. Moulds grow consistently independent of relative humidity. Under all circumstances, growth rates peak at about 35℃ and subsequently fall till 45℃. Unsurprisingly, the highest relative humidity of 99% has the greatest mould development rates, reaching 8mm/day, while the lowest value of 75% has the slowest, consistently under 1mm/day. Thus, keeping relative humidity below 75% prevents mould growth. The maximum mould growth rate decreases by 1.5mm/day when relative humidity drops from 99% to 95% and 95% to 90%. Also, peak growth rates are 2–3mm/day at 80%–85% relative humidity.

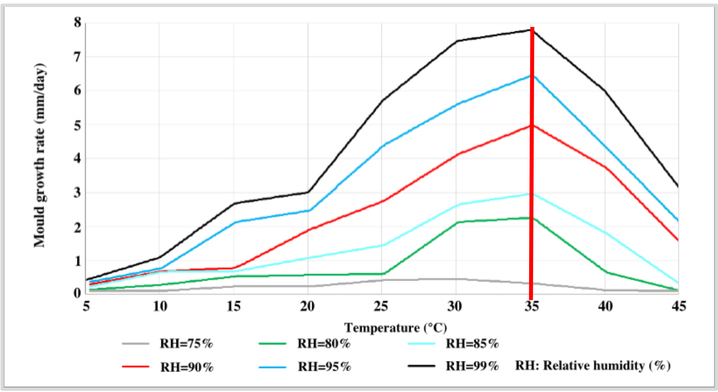

Fig. 21. Variation of mould growth rates with temperature at constant relative humidity values

Figures 22 and 23 classify and summarise the mould risk level of relative humidity under the ideal temperature according to Methodology Part 3.3.1 and Figure 4-5. At an ideal temperature of 35℃, mould growth rates may reach danger level ‘2’ (2 to 4mm/day) at 80% and 85% relative humidity.

Relative humidity (%)	RH<75 or RH=100	75≤RH<80	80≤RH<90	90≤RH<95	95≤RH≤99
Mould risk level	0	1	2	3	4

Fig. 22. Mould risk levels of relative humidity under the optimal temperature

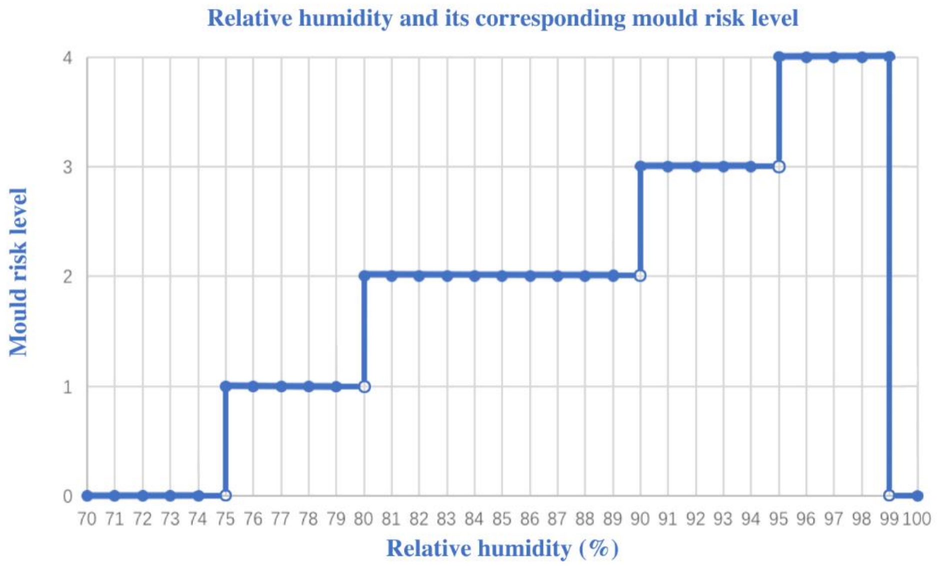

Fig. 23. Mould risk levels of relative humidity under the optimal temperature

3.2 The Mould Risk Levels of Nutrients in Different Substrates

Besides temperature and relative humidity, substrate nutrients affect mould growth. Substrates are split into four groups, however only substrate classes I and II are examined here since they promote indoor mould development. Figure 24 may be plotted using Figure 16 data. It clearly shows the differences between substrate I and II mould growth, notably their LIM curves, which indicate the boundary requirements for spore germination. Each curve relates to a fixed number of mould growth rates, therefore each temperature (or relative humidity) value must match a unique growth rate.

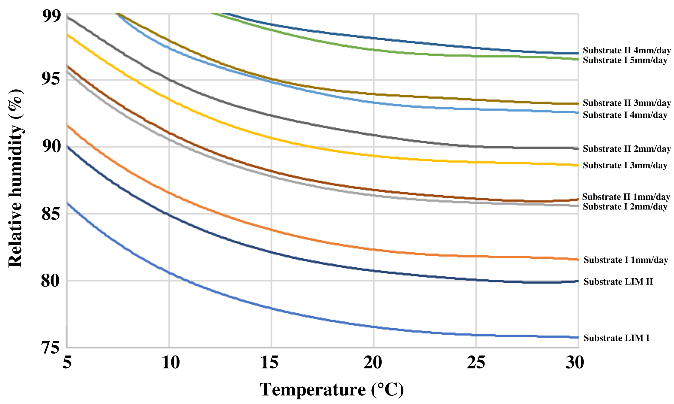

Fig. 24. The comparison between substrate class I and II

Figure 24 shows that substrate I curves are always below substrate II curves. In the LIM lines, mould spores in substrate category I germinate at 85.8% relative humidity at 5℃, whereas those in substrate II need 90% relative humidity. Mould growth in substrate II requires a minimum temperature of 9℃ at 85.8% relative humidity, whereas mould growth in substrate I requires just 5℃. When substrate I and II moulds develop at the same pace, other curves follow suit. Thus, substrate II moulds always develop at greater temperatures or relative humidity than substrate I moulds. In addition, substrate class I allows mould development from 76% to 99% relative humidity, whereas substrate class II allows it from 80% to 99%. That implies moulds may form in a wider range of relative humidity in substrate I, making it more likely to develop moulds than substrate II. It is remarkable that substrate category I moulds may develop at 5mm/day whereas substrate II moulds grow at 4mm/day under comparable circumstances. Thus, substrate class I is more favourable to mould development again because its mould growth rate is predicted to be quicker than that of substrate class II under the same environmental circumstances. Thus, substrate classifications have varying mould danger thresholds. The maximum risk level is ‘3’ for substrate class 0 because it has the best culture medium, whereas substrate class III should be ‘0’ since it has no nutrients for mould development. Since substrate I is better for mould development, substrate I and II have risk ratings of ‘2’ and ‘1’ (Figure 25).

Substrate category	III	II	I	0
Mould risk level	0	1	2	3

Fig. 25. Mould risk levels of substrate categories

3.3 The Relationship between Mould Risk Level and Time

According to the VTT model in the literature study, mould coverage on building materials may be described as six mould indices from 0 to 6, signifying mould growth rate from zero to maximum. Methodology may convert mould index to mould danger level. Thus, the mould risk level may be used as an independent variable to assess the relative contributions of various causes to mould development.

Mould danger level and duration may be summarised using constant environment conditions (Figure 26). Mould risk increases with time at 20°C and 85% relative humidity until 140 days of germination. The mould danger level then peaks at 1.8. The growing mould index further accelerates mould risk over the 67 to 110-day timeframe.

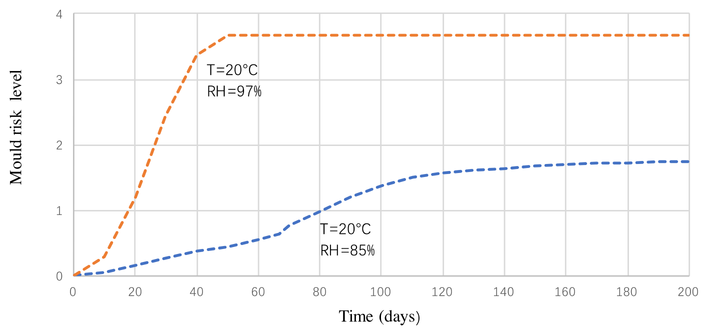

Fig. 26. The relationship between time and mould risk level under constant temperature T and relative humidity RH

The red line shows a considerable difference from the blue line when the relative humidity is increased to 97% at 20°C. Its mould danger level is usually greater than the blue line and may exceed 1.8. Mould risk develops rapidly until 50 days of germination. The mould germinates, grows, and reaches its maximum in less time. In conclusion, mould risk grows until a relative humidity-dependent maximum, then stays the same. Relative humidity also accelerates danger level rise. Therefore, relative humidity may significantly affect mould risk or index. Increased relative humidity may considerably aid mould growth without other factors.

3.4 The Assessment of Indoor Mould Risk Level Contributed by Different Factors

Figure 27 shows an indoor mould risk assessment flow chart. Three stages are used to assess interior mould risk from various variables. The first phase considers temperature and relative humidity, while the second and third address germination time and substrates individually. This study ignores secondary mould development variables like light and oxygen. The three stages are outlined below.

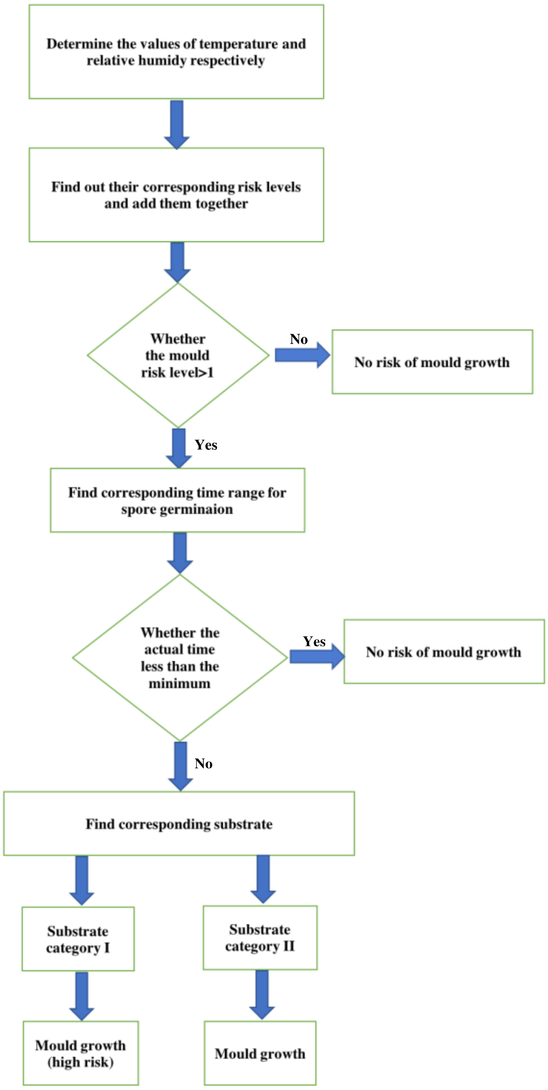

Fig. 27. The flow chart of the indoor mould risk assessment

First step Determine the combined risk level of temperature & relative humidity

a

Different factors	Range of each factor	Mould risk level
Temperature (°C)	T<5	0
	5≤T<15	1
	15≤T<25 or 40<T≤45	2
	25≤T<30 or 35<T≤40	3
	30≤T≤35	4
Relative humidity (%)	RH< 75 or RH=100	0
	75≤RH<80	1
	80≤RH<90	2
	90≤RH<95	3
	95≤RH≤99	4

b

8	High risk
7	
6	Medium risk
5	Low risk
4	
3	
2	
1	No risk
0	

Fig. 28. 'a' mould risk levels of temperature and relative humidity

'b' mould risk level classification for combined effects of different factors

The 'a' in Figure 28 gives temperature and relative humidity mould danger levels. After that, their risk levels are merged to create a composite risk level indicating temperature and relative humidity ('b' in Figure 28). The amount from '2' to '5' is 'low risk', '6' is 'medium risk', and '7' and '8' are 'high risk'. The danger levels are '4' and '2' when the interior temperature and relative humidity are 30 °C and 80%, respectively. Sum of two risk categories is '6', which is 'medium risk' according to Figure 28 'b'. Note that mould incidence is zero when the mould risk level of any temperature or relative humidity is '0' on the 'a' in Figure 28. Figure 28 'b' demonstrates that there is no danger when the sum of the risk levels of temperature and relative humidity is '1' since temperature or relative humidity must be '0'.

Time for germination (days)	Relative humidity (%)					
Temperature(°C)	75	80	85	90	95	99
5	>95	>95	>95	>95	>95	>95
10	>95	>95	>95	>95	32~95	32~95
15	32~95	16~32	16~32	16~32	8~16	4~8
20	16~32	8~16	4~8	2~4	2~4	1~2
25	8~16	4~8	2~4	1~2	1~2	1~2
30	4~8	2~4	1~2	1~2	1~2	0~1
35	4~8	2~4	1~2	0~1	0~1	0~1
40	4~8	2~4	1~2	0~1	0~1	0~1
45	8~16	4~8	2~4	1~2	1~2	0~1

Fig. 29. The range of germination time required by moulds under different environmental conditions

Second step Identify the germination time in different environmental conditions

After calculating mould risk of temperature and relative humidity, germination time is considered. Figure 29 shows the germination time range to determine mould danger. Mould development should not occur if spores do not achieve germination under the proper environmental conditions. Mould germination at 30°C and 80% relative humidity takes 2–4 days. That indicates spores can germinate for at least 2 days, whereas a room with the same circumstances for 1 day has no mould development danger. Thus, even if the temperature and relative humidity are right, mould cannot grow if the spore germination time is wrong.

Third step Assesse the mould risk level based on different substrates

Substrate nutrients should be considered when temperature, relative humidity, and germination period are suitable for mould development. According to substrate study, both substrate class I and II enable mould growth, however substrate I is more favourable (Figure 25). Thus, substrate I has a larger mould risk than substrate II. Mould cannot develop in substrate III because it lacks nutrients.

The three procedures above may be used to estimate indoor mould danger. Figure 28 ‘a’ shows that mould risk levels of ‘3’ and ‘2’ apply to 25°C and 80% indoor temperatures and relative humidity. Thus, the total of temperature and relative humidity danger levels is ‘5’, which is ‘low risk’ from Figure 28 ‘b’. Based on given temperature and relative humidity, Figure 29 gives the germination time range of 4 to 8 days. If environmental conditions cannot be maintained for 4 days, there is no danger. The third stage should be taken if the environmental conditions can be maintained for more than 4 days and mould spores can develop. Both substrate category I and II support mould growth, but the former (including indoor wall paper, plaster cardboard or indoor building materials made of biologically degradable raw material) is more risky than the latter.

4. Conclusion

This paper examines the components' relative contributions to moisture risk and mould development in buildings and estimate their overall influence using mould risk levels. A lot of literature has been studied to find mould growth variables and mould prediction models that analyse their link with mould formation. Many studies have examined how water activity (relative humidity), temperature, time, and nutrients affect substrates. Secondary elements like oxygen and light are ignored owing to a lack of study. With regard to mould prediction models, the VTT model is researched to determine the link between time and mould growth index, while the Ayerst's isopleth model focuses on temperature and relative humidity. Sedlbauer's isopleth model analyses substrate effects on mould development. The findings show that relative humidity and temperature are critical determinants in indoor mould growth. Additionally, mould species variations and development characteristics have been studied.

According to study, mould may thrive inside at 5°C to 45°C and 75% to 99% relative humidity (if other conditions are ignored). In addition, the best temperature and relative humidity for mould development and danger are 35°C and 99%. Both temperature and relative humidity have five mould danger categories, from ‘0’ to ‘4’ (‘no risk’ to ‘highest risk’). Spores also germinate differently at varying temperatures and humidity. Mould growth might germinate in one day or 95 days. Category I substrates are better for mould development than category II.

First, the individual danger levels of temperature and relative humidity are established, then the two values are compounded to produce the combined effect of temperature and relative humidity on mould formation. The second and third steps emphasise that spore germination time and substrate category affect mould risk in structures.

Indoor mould risk assessment should be more particular and studied, such as by considering building functioning areas. First, measure and experiment in different interior environments to obtain data. Instead of laboratory-simulated indoor data, buildings should be studied inside to get environmental data. That improves outcomes and helps minimise mould development in the building. Researchers may also summarise mould risk reduction techniques and employ them in trials since inhabitants' behaviours might impact mould growth inside.

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Conflicts of Interest
The authors declare no conflicts of interest.

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