Renewable and Sustainable Energy Reviews 132 (2020) 110093

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

# Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk

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A R T I C L E   I N F O

*Keywords:*
Mould growth
Indoor environmental quality
Energy efficiency
Construction detail
Building envelope
Air change rate
Critical moisture level
Building occupants health
Literature review

A B S T R A C T

Today, buildings still account for almost half of the global energy consumption and carbon emission. This highlights the necessity to increase energy efficiency requirements worldwide in a common effort to reduce the construction sector's impacts on the environment. The current energy policies are driving toward a design that relies on airtight and highly insulated envelopes. As a consequence, energy efficient houses are found to have insufficient indoor air change rates, impacting on the indoor air quality and resulting in higher latent loads. The increased indoor humidity, coupled with the rising trend to use bio-based construction materials, can easily support mould growth and facilitate indoor organic proliferation. It has been estimated that the proportion of buildings damaged by mould is 45% in Europe, 40% in the USA, 30% in Canada and 50% in Australia, highlighting the extent of this issue. Beyond the economic loss due to the remediation works needed to rectify a buildings degradation due to fungi, mould also has significant adverse health effects on the building occupants. Data show that the occurrence of asthmatic symptoms is higher in new energy efficient buildings with low ventilation rate. This paper investigates the effects of building sustainably on the indoor environment in relation to the risk of mould growth. Favourable conditions for growth, causes of growth, effects on health as well as possible solutions are addressed. The conclusions are a step forward toward a more precise and detailed comprehension of mould growth to support policymakers and promote sustainable housing standards.

## 1. The dark side of building sustainability standards

The energy crisis and the increasing environmental awareness have led to global concern when it comes to issues on urbanisation, use of fossil fuel, depletion of resources and carbon emissions in the atmosphere. The total global primary energy consumption shows an annual increase of 2%, and it is expected to increase by 32%–2035 [1]. The construction sector still accounts for 40% of this energy consumption [2], which indicates the necessity to increase the building energy efficiency, regularly updating the energy policy, and pushing for more sustainable solutions [3]. The current international efforts aimed at minimizing a buildings' impacts on the environment clearly underpins the Sustainable Development Goal (SDG) 13- Climate Action promoted by the United States Member Sustainability Agenda. However, the increasing requirements for energy efficiency are pushing for technological solutions and design approaches that, if not consciously and correctly applied, may actually have a negative influence on the indoor environment. Thus, in an effort reduce overall energy consumption in buildings, the long-term health implications are often overlooked [4], hindering another important sustainability goal: the SDG 3- Good Health and Wellbeing.

Between home and office, humans spend up to 90% of their time indoors [5], highlighting the importance of indoor air quality (IAQ) for achieving the set SDG 3. IAQ is determined by the interactions between physical, chemical and biological parameters. The physical factors are all those parameters that refer to the physical environment, such as temperature, humidity, ventilation, lighting and noise. Chemical factors relate to the concentration of substances in the air; while biological ones include the presence of bacteria, mites, moulds, pollen and dust [6–8]. Energy efficient buildings are usually measured only on the first two groups, leaving to mechanical systems or the occupants with the burden of dealing with the third one. However, because of this, these types of buildings may have higher indoor concentrations of air pollutants and increased occurrence of mould growth and condensation [9] compared to older constructions.

It has been shown that indoor organic pollutants can significantly decrease the service life of building materials and components [10] due

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https://doi.org/10.1016/j.rser.2020.110093
Received 19 January 2020; Received in revised form 4 July 2020; Accepted 13 July 2020
Available online 27 July 2020
1364-0321/

**Nomenclature**

| | |
|---|---|
| $a_w$ | water activity |
| IAQ | ndoor air quality |
| RH | relative humidity |
| SDG | Sustainable Development Goal |
| pp | species (all the species of the genus) |
| T | temperature |
| TOW | time of wetness |

to the process of biodeterioration [11], resulting in considerable economic loss [12,13]. Yet their impacts span beyond the materials durability, as their impacts on health are consistent with the ones caused by other pollutants, such as tobacco [14]. Mould growth is significantly influenced by inappropriate design strategies and bad operation and maintenance programs that may lead to insufficient indoor ventilation and higher moisture loads [15–17].

This review challenges the concept of sustainable buildings, offering an alternative perspective on the unintended effects of energy efficiency and airtightness. Mould growth phenomenon is analysed in regard to the possible causes and optimal conditions for growth; the health consequences for humans and the strategies that can be adopted to minimize the risk.

## 2. Methodology

The purpose of this paper is to discuss the indoor mould growth phenomenon and its correlations with the current building practice. The main objective is to analyze the knowledge about indoor mould types, causes, and current minimization strategies to identify existing research gaps and potential future directions. The paper addresses the following objectives:

- Analyze the indoor pollutants, identify the dominant species in different locations and/or building applications and study the potential health consequences for building occupants;

- Investigate the possible causes and favourable conditions for indoor mould growth, and evaluate the role of energy efficiency standards in offering such conditions;

- Offer a snapshot of the possible risk mitigation strategies and analyze the current construction policy framework in regard to mould growth prevention and moisture-safety design;

- Identify possible future directions and knowledge advancements needed to support designers and policy-makers to address the issue of indoor mould growth and, consequently, to reduce its incidence.

The research methodology adopted a two-step approach. The first step consisted in a literature search based on keywords to understand the fundamental dimensions of the mould growth issue, while the second step involved a deeper investigation on the specific topics identified.

The literature search included academic outputs, such as scientific papers, conference proceedings and published books, as well as grey-literature, such as technical reports, professional guidelines and governmental documents. This approach allowed us to consider at the same time the scientific and practical implications, as well as acknowledge both the recent knowledge advancement and the current construction practice. The screening process selected the references based on the presence of the main keywords in titles and abstracts of papers indexed in Scopus and Science Direct. The results have been used to find previous references and ensure that all the relevant publications are included in this literature review.

The search relied on the use of keywords related to the different aspects of mould growth, examples can be found in Table 1. Few keywords have also been used as exclusion criteria during the first round of literature research to reduce the number of results not linked to the study (Boolean operators *and not*: food, agriculture, crop, cheese, pathog*, animal, culture).

**Table 1**
Examples of keywords used for the literature review.

| Topic | Keyword 1 | | Keyword 2 |
|---|---|---|---|
| Indoor moulds, growth, growth parameters | Mo?ld*; mildew; organic pollutants | and | Indoor; growth; type; species; indoor environment; buildings; building materials; envelope; experiment; test; laboratory; growth model; biodeterioration; germination; conditions; damp* |
| Health consequences | | | Health; symptom*; exposure risk; illness |
| Mould in energy efficient buildings | | | Sick building syndrome; SBS; moisture damage; hygrothermal |
| Risk mitigation | | | Criteria; risk; management; remediation; condensation; moisture safety |

Fig. 1 shows the year of publication of the most relevant references in each topic group.

The earliest documents concerning indoor mould growth and health implications were published around 1970, however, the research became very active from the late ‘80s. Ever since, the trend never ceased, underlining both the importance of this research and its complexity. The sick building syndrome and the correlations between building energy efficiency and health concerns witnessed an increased number of publications from 2000, probably correlated with increased awareness about sustainability and the contribution of the construction sector to global warming. For the same reason, from 2010 it is possible to see a clear emerging research stream that correlates climate change and indoor air quality, including mould growth. Research on the effects of thermal bridges on the risk of mould growth started in the early ‘90s, however, it intensifies after 2010, with the recent advancements in hygrothermal modeling and the development of software for the 2D hygrothermal calculation.

Fig. 1 shows that there is growing concern about mould growth, buildings, and health, which is highlighted by the increasing number of research streams on different aspects of mould that developed through the years. The diversification of the research focuses is supported by new identified research gaps, knowledge and technical advancements that make it possible to develop different approaches (such as the refinement of hygrothermal tools), development of new construction techniques, and increasing awareness about the health hazards related to mould growth. Thus, a better understanding of the phenomenon and, consequently, the development of new mitigation strategies are identified as compelling research needs.

## 3. Unhealthy indoor environments: organic pollutants

The biological factor mainly associated with unhealthy indoor environments is the presence of microorganisms, such as moulds, mites and bacteria. The microbial community of a building is the specific combination of the micro-organisms that characterized it, and it is determined by the exchange between the indoor and outdoor air, the building occupancy patterns [18], and the accumulated organic compounds [19,20].

### 3.1. Indoor moulds and where to find them

Mould is the colloquial term used for indoor fungi. Fungi are among the more feared indoor organic pollutants, as by nature of their being, a fungi infestation is detectable visually and very aesthetically displeasing.

Fungal spores are naturally found outdoor and they can easily be transferred inside, where they settle on rough surfaces or amongst accumulated house dust. These organisms are extremely resilient and

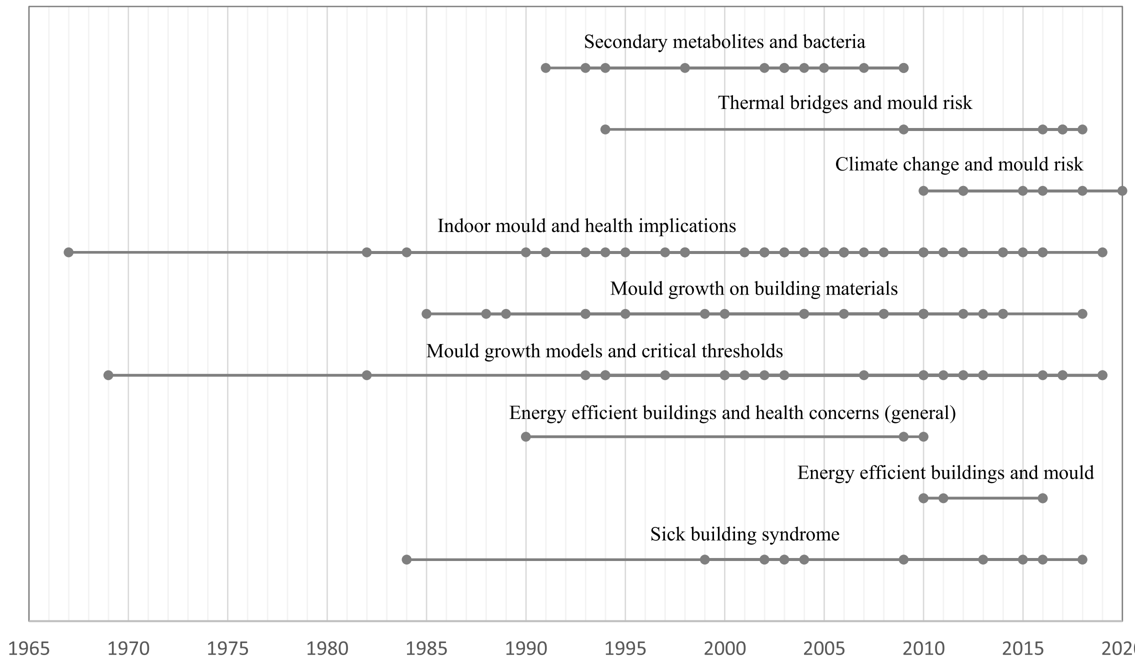


**Fig. 1.** Year of publication of the relevant reference grouped by topic.

they adapted to survive in un-optimal situations [21], waiting for favourable conditions to germinate and spread [22]. Fungi can release several spores, each capable to reproduce one full entity; thus, fungal infestation is often characterized by a fast and extended diffusion that is difficult to remove.

Fungi classification is based on genus, which identify the type, and the strain, which indicate the specific species or genetic variant. The literature agrees in defining as the most common indoor moulds the *Penicillium* spp., *Aspergillus* spp., *Chaetomium* spp., and *Cladosporium* spp. strains [23–25], with the additional species *Alternaria alternata* and *Ulocladium chartarum* [26]. However, there is a high variety of specific strains isolated in different studies, as shown in Table 2.

The majority of the studies isolated *Penicillium chrysogenum*, which is equally found across several climates. However, *Aspergillus versicolor* is the most abundant and dangerous, due to its potential of causing various insidious infections [30]. A specific investigation on newly built houses in Japan detected the presence of *A. versicolor*, among the other species, indicating a possible correlation with the insurgence of sick building syndrome [43].

Even the fungi that are usually found on external building facades, such as *Cladosporium* spp. [51,52] and *Aureobasidium pullulans* [53–55], can be found amongst indoor house dust, underlining the importance of spore transfer from outdoor to indoor air.

Fungi metabolise a wide variety of carbohydrates, such as cellulose, starch and lignin. Common building materials often contain these elements, thus providing fungi with a nutrient-rich environment for optimum fungal growth [13,15]. Additionally, new architecture eco-trends often favour the use of organic-based materials that may aggravate any potential fungal infestation by allowing a fast expansion [56]. For example, timber is highly sensitive to *A. versicolor* [23] *A. alternata, Cladosporium* spp.*, Penicillium* spp. [57], *Coniophora puteana*, also known as wet rot, and *Serpula lacrymans*, or dry rot [58]. Sustainability standards tend to largely promote timber, based on its minimized embodied energy impacts and sustainable life cycle [59]. However, the consequences may be disastrous when improperly used in high humid environments [60,61], with early biodeterioration and alteration of its structural properties [58].

### *3.2. Bacteria and house mites*

House mites and bacteria are the invisible threats that populate buildings. They are both microorganisms that live and proliferate inside damp homes, and a common catalyst for an unhealthy indoors.

Mites' nutrition is composed of human skin scales and water absorbed directly from the air [62], both elements that are naturally and abundantly present inside buildings. Mites can survive in relatively dry environment, with relative humidity as lows as 50% [62], but they proliferate at a higher moisture content, showing a similar water requirement to mould [14].

Indeed, mould is often an indicator of the presence of mites and actinobacteria [23], and evidences show that the occurrence of bacteria increases with increasing concentration of mould [63]. However, bacteria prefer a slightly more humid environment compared to fungi [64], and their presence is often confined to damp buildings [64], especially on the surface of water damaged materials [65]. The species that are commonly found include *Streptomyces, Nocardia, Amycolatopsis, Saccharoplyspora* and *Pseudonocardia* [66], but, in one study, it has been possible to isolate up to 58 different genera in one sample [66]. Bacteria requires higher water availability compared to mould [67], but considering that both mites and bacteria are not detectable with visual inspection, mould is commonly used as a benchmark and precursor for other possible infestations.

Bacteria are highly pathogenic [68], and they are associated with hypersensitivity pneumonitis [69], allergic alveolitis, asthma [70]. The impacts of bacterial infestation on human health is much more severe than the ones caused by mites, which can induce allergic reactions in sensitive subjects [14].

## 4. Health consequences

The high risk associated with the presence of fungal growth on building materials is further emphasised by the fact that humans spend a significant amount of time indoors, sometimes estimated to be as high as 90% [5]. Consequently, when looking at figures such as these, the need for a healthy and liveable space becomes an essential requirement that can not be negotiated.

The presence of mould is associated with a number of different

**Table 2**
Indoor moulds: type of indoor mould isolated in different studies. The table shows the location, the dominant species for the most common mould (if found), the additional fungal strains and the references.

| Location | Dominant species belonging to *Penicillium, Aspergillus, Chaetomium, Stachybotrys*, and *Cladosporium* | Additional isolated fungi | Ref |
|---|---|---|---|
| Sub-artic | *A. ochraceus, A. glaucus* | *Phoma violacea, Ulocladium atrum* | [27,28] |
| European cold climate | *A. ustus, A. versicolor, C. sphaerospermum, C. globosum, P. chrysogenum, S. chartarum* | *Trichoderma harzianum, Chaetomium globosum* | [29–33] |
| European temperate climate | *A. versicolor, A. fumigatus, A. niger, C. sphaerospermum, P. chrysogenum, P. olsonii, P. expansum, S. chartarum* | *Aurebadisium pullulans, Rhizopus* spp., *Trichoderma atroviride* | [34–40] |
| Australia | *A. niger, C. cladosporioides* | *Fusarium* spp., *Botrytis* spp., *Rhizopus* spp., *Epicoccum* sp. | [41,42] |
| Japan | No particular dominant specie isolated | *Aurebadisium* spp., *Eurotium* spp., *Rhodotorula* spp. | [43] |
| India | No particular dominant specie isolated | *Rhizopus* spp., *Curvularia* spp., *Fusarium* spp., *Drechslera* spp., *Helminthosporium solani* | [42] |
| Middle East | *A. flavus, A. fumigatus, A. penicilloides, A. repens, P. glabrum* | *Acremonium* spp., *Botryodiplodia* spp., *Circenella* spp., *Myrothecium* spp., *Syncepalastrum* spp., *Cercospora, Drechslera* spp., *Embellisia, Fusarium* spp., *Rhizopus* spp.,*Torula, Scytalidium* spp., *Curvularia* spp. | [44–46] |
| North America | *P. chrysogenum, P. crustosum, P. aurantiogriseum* | *Bipolaris* | [47–49] |
| Uganda | No particular dominant specie isolated | *Mycosphoerella yeasts, Fusarium* spp., *Cochliobolus* spp. | [50] |

health symptoms. For example, mould has been shown to affect the more general psychological well-being of the building occupants, with a direct negative knock on effect when it comes to indicators such as productivity at work [71]. These effects can be mild, such as sense of fatigue and reduction of the capacity to concentrate, but they can escalate to severe cases of cognitive impairment [72].

Further, the health implications of mould span beyond mould's visible presence. Mould growth is not limited to the indoor surface; it can easily geminate and expand inside building envelopes, mainly through condensation within a building form. In this case, mould's invisibility makes the issue even more dangerous, as building occupants can't detect its presence.

Furthermore, mould toxicity can persist even after remediation and when the mycelium is eliminated. Indeed, some moulds can release mycotoxin [73,74] and secondary microbial volatile organic compounds (MVOC) [75]during their growth, which are known to have negative health impacts independently from the primary fungal mass [57].

Recent investigations proved chemical surface cleaning is useless when it comes to completely eradicating both mould and the produced mycotoxins [76]. Extensive environmental remediations and replacement of infected materials is the only strategy that can be adopted to prevent further health issues when mould is already grown [77].

Table 3 summarizes the possible adverse heath symptoms that have been associated with the presence of indoor moulds or damp environments. Evidences show that there is an existing correlation between respiratory health effects and damp-related factors, such as visible dampness, reported mould and measured microbiological presence.

**Table 3**
Possible health outcome associated with exposure to mould, damp environments or agents associated to dampness.

| Health effect | Ref |
|---|---|
| Comprehensive review study | [57,72,78–80] |
| Asthma | [14,81–89] |
| Allergic rhinitis and sinusitis | [30,88,90,91] |
| Allergic alveolitis | [92–96] |
| Infections (aspergillosis, aspergilloma) | [97–100] |
| Other symptoms (sense of fatigue, reduction of concentration, sore throat, nose and eyes irritation, rhinorrhea) | [71,72,101, 102] |
| Rheumatic diseases | [103–106] |
| Symptoms related to the sick building syndrome | [7,102, 107–110] |

### 4.1. Hypersensitivities, allergies and infections

The adverse health effects caused by mould usually require a significant amount of exposure time [111]; however, it has been estimated that more than 10% of the population is already sensitized to mould and house mite allergens [80]. The sensitization suggests that subsequent exposures, even if they are short, could lead directly to allergic symptoms.

The most common symptom is asthma [78,79] among adults [81], children [82–84] and infants [85]. *A. alternata* is the fungal strain that is most associated with these allergic reactions [14]. Considering that it is also one of the most commonly found indoor strains, the extension of the risk can reach critical levels in sensitive subjects. It has been estimated that dampness-related agents and mould can be associated with 30–50% increases in asthma [79], which in the US, for example, would mean that 21% of the confirmed cases of asthma can be attributable to indoor mould [86].

Other forms of allergies that can be developed after long exposure to mould are hypersensitivity pneumonitis and allergic alveolitis [92,112], allergic rhinitis and sinusitis [30,90]. Allergic alveolitis is particularly severe in Japan, where it has been noticed a recurrence of the symptoms, with more than 60 confirmed cases per year caused by the mould *Trichosporon cutaneum* during summer [93,94]. A similar pattern occurs also in Korea [95] and in southern Africa [96].

Milder symptoms, such as rhinorrhea, nasal congestion, sore throat and irritation of nose and eyes are more common [101]; however, as they are similar to common fever and cold symptoms, they are usually underestimated and misdiagnosed.

Vulnerable subjects may also develop severe respiratory infections, especially if exposed to *Fusarium* spp. and *Aspergillus* spp [97,98]. Aspergillosis may cause a secondary allergic reaction, resulting in wheeze, pulmonary infiltrates and eventually fibrosis [99], symptoms commonly associated also with aspergilloma [100], where Aspergillus hyphae cause a tumor in the lung cavities.

The direct link between mould and the above-mentioned diseases is an issue of note when one considers places where building occupants have an already impaired immune system, such as hospitals or houses with immunosuppressed subjects. Also of note are age care centres, as the elderly are also very sensitive to mould, both when it comes to risk of infection but also in terms of an exacerbation of rheumatic diseases, as fungal spores [103,104] and mycotoxins [105] can aggravate chronic inflammations in muscles and joints [106].

Thus, the presence of mould can have significant negative impacts and lead to serious health hazards for building occupants. This risk can be minimized if accounted for during the early architectural design stage.

### 4.2. Mould-related health issues in energy efficient buildings

Although the incidence of mould is higher in older buildings, mould infestation can happen also within a few years of construction, if the right conditions are met [113]. Newly built and sustainable buildings are often associated with superior indoor comfort; however, this is not always the case [114].

Some studies investigate the increased occurrence of adverse health symptoms, such as asthma, rhinitis and hay-fever, in newly built energy efficient buildings, identifying mould as one of the primary causes [87]. A cross-sectional study performed in China on more than 7000 children correlated newly-built homes with rising cases of asthma and allergies, finding that the use of air conditioners accounted for 7–17% of the rhinitis and eczema cases [88]. Similar results on linking central air-conditioning systems with an increased insurgence of asthma were also found in Germany [91]and in the UK [89]. The reason is notionally linked to the re-circulation of indoor air with very limited exchange with outdoor fresh air, which may lead to high concentration of indoor fungal spores, chemical and physical contaminates [89].

Additionally, newly built houses have been correlated to sick building syndrome (SBS), which is a constellation of symptoms ranging from irritation of the eyes, nose, throat, headache, and general fatigue [107]. Although lethargy and headache are found to be the most common symptoms [109], 9% of the cases can result in respiratory difficulties [102]. SBS is usually caused by indoor pollution, inadequate temperature and humidity [110], and presence of mould, such as *Aspergillus* spp. [43] and *Cladosporium* spp., *Penicillium* spp. and *Stachybotrys* [115]. However, not always it is possible to find a specific cause or factor, but rather depends on all these parameters [108].

## 5. Indoor mould growth

To understand and analyze the current design guidelines and provisions adopted to prevent mould growth in buildings, it is important to define the current knowledge framework about the phenomenon.

The lifecycle of mould can be distinguished in two phases: germination and growth. The moment when it is possible to see, through a microscope, that some germination has taken place, the mould has technically entered the *onset of mould growth* [116].

Studies have shown how the onset and growth of mould is influenced by environmental conditions – mainly water activity and temperature - and the type of substrate the mould is grown on. The best conditions for germination can be different from the best conditions of growth, and both can vary depending on the mould type and species [58].

### 5.1. Environmental parameters

Due to the large amount of parameters involved, it's impossible to determine univocal conditions for the onset of mould growth, and a critical range of values pertaining to different parameters must be considered; including water activity, temperature, and substrate type.

Furthermore, considering that mould germination and growth is a phenomenon that develops over time, it is fundamental to the analyze the transient conditions experienced: greatly favourable conditions achieved for a short amount of time, for example, might be less harmful compared to slightly favourable conditions maintained for a long period of time [21,117].

#### 5.1.1. Water activity

The Water activity $a_w$ is the parameter that defines the water availability on a substrate. This parameter is defined as the ratio of vapour pressure in the substrate divided by that of pure water at the same temperature, and it ranges from $0.0a_w$ (completely dry) to $1.0a_w$ (pure water).

Water activity is the most important parameter amongst all relevant ones as all species of fungi require high level of humidity to initiate the germination.

Tests undertaken under different conditions of temperature and water activity show that each type of fungus germinates under different conditions of aw. Generally, the minimum aw for growth ranges between 0.78 and 0.8 at 10 °C, and 0.9 at 5 °C [29]. Clearly, higher aw determines higher growth rates, with the optimal levels above 0.97 for all fungal strains [118]. At indoor temperature ranges between 15 °C and 25 °C, *A. repens* requires the minimum aw to grow, only 0.76 [24], while *A. versicolor* needs water activity levels between 0.79 [24] and 0.98 [119].

The water activity value is also used as a parameter to define three group of indoor moulds, based on the $a_w$ found in laboratory tests on agar substrate (rich of nutrients) [24], as shown in Table 4.

Primary colonisers: can grow with a water activity below 0.8. This category includes some species of *Penicillium* spp., *Aspergillus* spp. and *Eurotium chartarum*; Secondary colonizers: require average aw between 0.8 and 0.9. This category includes Cladosporium, Alternaria spp. and Ulocladium spp.; Tertiary colonisers: require high level of aw (generally above 0.9). This category includes bacteria, actinomycetes, *Stachybotrys chartarum, Chaetomium* spp., *Trichoderma* spp. and *A. pullulans*.

With an increasing level of water activity, the primary and secondary colonisers are the first one to appear. Among these, *Alternaria* spp. is one of the most common. It is generally classified as a secondary colonizer due to its medium requirements of water [122]. It can grow on most building materials, as well as carpets, wallpaper and synthetic materials. This fungus's ability to grown basically anywhere and in mild humidity conditions is particularly worrisome when you also consider its ability to induce strong allergic reactions [14].

Lastly, third colonisers are correlated to environmental conditions where the $a_w$ reaches 0.9 or more, meaning an actual presence of water due to leakage or condensation, as air relative humidity on its own is not enough to achieve these favourable conditions for growth.

This classification must be considered indicative as it may vary depending on other factors: for instance, a nutrient rich substrate may enable mould germination and growth with lower values of $a_w$, thus shifting the subdivision between primary, secondary and tertiary colonisers.

#### 5.1.2. Temperature and relative humidity

Temperature is another important factor when it comes to mould germination and growth. In terms of speed of growth, lower temperatures are associated with lower growth rates [58]. However, with higher levels of water activity, mould can grow with temperature as low as −5 °C [123]. Furthermore, considering that lower surface temperature is

**Table 4**
Classification of indoor moulds based on the water activity required to grow [24, 120,121].

| Type of colonizer | Mould species |
|---|---|
| Primary Colonisers | *Alternaria citri, Aspergillus (Eurotium) amstelodami, Aspergillus candidus, Aspergillus (Eurotium) glaucus, Aspergillus niger, Aspergillus penicillioides, Aspergillus (Eurotium) repens, Aspergillus restrictus, Aspergillus versicolor, Paecilomyces variotii, Penicillium aurantiogriseum, Penicillium brevicompactum, Penicillium chrysogenum, Penicillium commune, Penicillium expansum, Penicillium griseofulvum, Wallemia sebi* |
| Secondary Colonisers | *Alternaria alternate, Fusairum moniliforme, Ulocladium chartarum, Ulocladium consortiale, Aspergillus flavus, Aspergillus versicolora, Cladosporium cladosporioides, Cladosporium herbarum, Cladosporium sphaerospermum, Mucor circinelloides, Rhizopus oryzae* |
| Tertiary Colonisers | *M. plumbeus, Ph. Herbarum, St. atra, S. brinkmannii* <br> *Aspergillus fumigatus, Epicoccum* spp., *Exophiala* spp., *Mucor plumbeus, Phoma herbarum* <br> *Phialophora* spp., *Rhizopus* spp., *Stachybotrys chartarum (S. atra), Trichoderma* spp., *Ulocladium consortiale, Rhodotorula* spp., *Sporobolomyces* spp. <br> Actinobacteria (or Actinomycetes) |

more likely to cause condensation and thus increase the water activity, it becomes clear that temperature alone can not be used to univocally characterize mould growth.

Although different studies undertaken under different conditions found fungal presence for temperature between −5 °C and 50 °C [124]; generally, indoor mould requires relative humidity above 70% [125] and a temperature range between 20 °C and 30 °C [124,126], with an optimal mean value of 27 °C [127]. However, most of the studies aimed at developing indoor mould growth models are done with a relatively low temperature range, mainly because the tests are performed in research centres located in cold countries. Thus, the results of these models are yet to stand true when it comes to warmer climates [128, 129].

These conditions can be shifted towards lower temperature, for higher values of water activity, and lower values of $a_w$, for higher temperature [118,130]. As such, the most relevant factor to support mould germination and growth is the combination between temperature and humidity, as the two may compensate one another. A general snapshot of the conditions for mould growth is given in Fig. 2.

Mould growth is intrinsically correlated to indoor and outdoor environmental conditions. Indeed, temperature and humidity are two of the most influential parameters that determine the risk and the velocity of growth.

Considering the IPCC climate change projections [131], the risk of indoor mould growth may further increase in the future [132], due to the poor resilience of the current building stock to increasing temperatures. Long-term climate change may influence indoor mould growth in multiple ways: both modifying the environmental conditions that support the growth [132] and increasing the fungal spore production [133, 134]. Indeed, a warmer outdoor weather poses a higher thermal solicitation on the building envelope, increasing the possibility of internal overheating [135], and, thus, creating favourable conditions for mould to germinate and grow. Furthermore, it also affects the fungal activity: evidences positively correlate increased temperature and increased concentration of fungal spores in the air [136,137]. The higher presence of spores in the outdoor air may challenge the buildings' mechanical ventilation systems, which are already designed to manage the air pollutants and the thermal expectation of an old weather [135], failing to meet increased air changes expectations.

Thus, the design choices of today have a great impact on the future building hygrothermal performance [138] and, with evidences that the

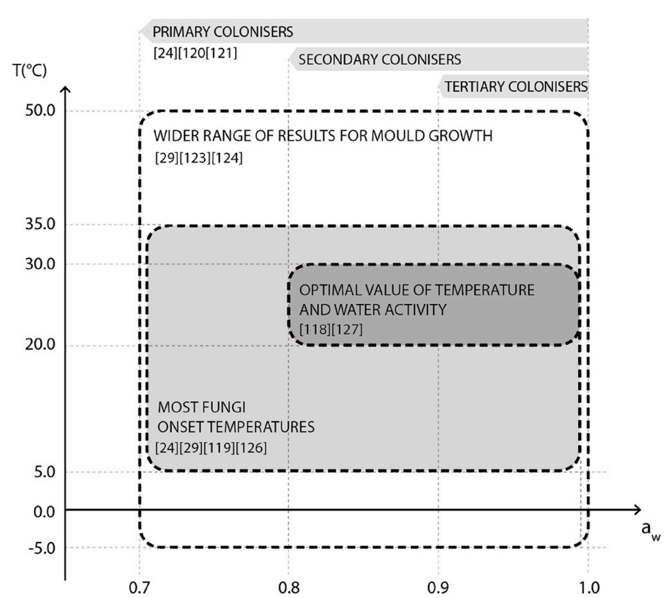


**Fig. 2.** Conditions for mould growth: temperature and water activity ranges for increased probability of growth.

future climate will increase both the risk of mould germination [139] and the velocity of growth [140], also the material selection becomes an essential choice to be carefully considered [141].

*5.1.3. Transient conditions*

A functional building, during its design life, is often subjected to a certain fluctuation of internal conditions. Temperature and water activity are rarely stable in both the external and internal environment. These cycles include the daily variations between day and night conditions, the changing of the seasons and also the variations caused by a change of usage of the building (occupancy and users behaviour).

Due to a changing environment, a building can alternate periods of favourable conditions for mould growth and periods where these conditions are not met. The alternation and duration of these periods play an important role in determining the onset and mould growth rate [21, 117]. A parameter that can be used to express this concept is the Time of Wetness (TOW) [142]. TOW is defined as the ratio between the wet period (RH above 80%) and the total time period considered. Mould growth is observed to start for TOW equal to 0.17, and it increases significantly when TOW is above 0.5.

The need to consider both water availability and temperature together is also emphasised by the results of transient studies, which observe that variations in temperature have a smaller impact on mould growth than variations in relative humidity [143].

*5.1.4. Substrate*

The relationship between mould growth and substrate can be influenced by the substrates various characteristics, such as its material composition, hygroscopic nature, and the substrates surface porosity and treatment.

In terms of material composition, fungi grow easily on materials with a high concentration of organic carbon, such as cellulose or timber [23]. Timber is an interesting example, as timber based materials are particularly sensitive to mould growth also because of their hygroscopic nature; however, despite this, timber is widely used in the built environment due to its widely accepted positive influence on the life cycle perspective of a building [59]. Timber's ability to spawn mould growth varies greatly between different timber species and depending on the part of the tree trunk where the timber is taken from: sapwood, for example, better supports mould growth compared to heartwood [144], because sapwood is the most active part of the tree trunk and thus circulates water and nutrients at a higher rate [145]. The most common fungal strain isolated on wood samples is the *Aureobasidium pullulans* [55].

Plasterboard is also commonly used in construction; the various types are all essentially made of a gypsum paste matrix sandwiched between two layers of cardboards with starch glue. The cardboard is highly hygroscopic, and it absorbs moisture form the air; thus, even low levels of relative humidity can trigger mould growth [146]. *Stachybotrys chartarum, Penicillium* spp.*, Aspergillus pp., Chaetomium* spp. and *Ulocladium* spp. are the fungal strains that find this material optimum for supporting the growth [32,147].

Rough surfaces can retain dust and fungal spores better than smooth ones, so porous and granular materials may positively influence spore settlement. When it comes to materials of this nature used in construction, this highlights certain types of plaster, paints and concrete. These materials constitute the optimal substrate *for Aspergillus* spp., in particular, *A. melleus, A. niger* and *A. ochraceus* [23]. This highlights a potential health risk of such materials as they might encourage a mouldy indoor environment. The *Aspergillus* strain is particularly concerning as it is associated with sever forms of infections [30,112].

When the right conditions are met, even materials not normally associated with mould growth such as aluminium [148] or synthetic polymers can present signs of fungi [149]. Other materials such as rubber and plastic have been shown to experience mould growth, with mould being linked to microcracking and loss of plasticity and other types of deterioration.

Mould growth is considered the main cause of early biodeterioration of building materials, which can significantly reduce the service life of building components [11] with considerable economic impacts. For example, it has been estimated that Germany suffered an economic loss of more than 200 million euros due to mouldy indoors [13], which underlines the significance of mould growth in buildings.

#### 5.1.5. Limitations of the current knowledge

The growth phenomenon of mould is the consequence of complex interactions of several parameters. It involves the organic response of fungi; and by nature the results are highly unpredictable and difficult to describe through mathematical models [16,150].

The current accepted knowledge about mould growth suffers from several limitations, which hinders the ability of policy makers to correctly provide a clear framework for the design of mould-free buildings. These limitations are related to the methodology used in the experiments to define mould growth, and the limited number of tests, specimens and material.

The existing models used for mould growth are based on experimental tests performed in a climate chamber, but, so far, none of the conditions used are found to be reliable when it comes to describing real climatic conditions, thus bringing into question the validity of the current growth models.

Additionally, the research is not yet able to provide a clear and univocal threshold for mould growth due to the research gaps in the testing methodology. All the investigations conducted used different methods for mould inoculation, climate definition and material selection [10], resulting in a fragmented constellation of different conclusions that can not be compared, nor used to create a complementary snapshot of the issue.

### 5.2. The role of energy efficiency standards

Energy efficient buildings can offer favourable conditions for mould growth in terms of increased presence of nutrients and water activity. These two aspects are represented by the building materials used and the ventilation rate achieved.

Sustainable standards largely promote the use of bio-based, and often organic, products, such as timber, straw, and sheep wool among others [59]. These materials are particularly sensitive to mould growth as they offer high concentrations of organic compounds that can be easily digested by fungi [56].

Additionally, sustainable standards often require high level of air tightness to reduce the energy consumption. Sealed envelopes reduce the uncontrolled air movements between the interior and exterior environments, thus minimizing thermal loads. Airtightness is further enforced by mandatory provisions in response to both the increasing level of outdoor air pollutants concentration in cities, and the fire safety measures undertaken in countries where this risk is elevated (e.g. Australia and California). In these cases, the goal is to minimize the uncontrolled ingress of air pollutants or ash, and to recur to mechanical ventilation system to filter the external air and filter out dangerous particles.

However, evidence correlates the increasing value of airtightness with lower air change rates [114]. The highest reduction noted for the period 2006–2009 corresponds to one of the most significant changes in airtightness performance [9]. Sometimes the real ventilation rate can't even fulfill the minimum requirements set by law [84]. The reduction of air leakage minimizes the uncontrolled exchange with the exterior, resulting in a system that greatly relies on the users to either correctly engage with the ventilation system or naturally ventilate the indoor spaces to dissipate the excess of latent loads [151]. However, occupants' behaviour is a parameter that it can't be controlled or predicted, thus all the calculation on the expected performance of a building can be considered inaccurate [152]. Evidence suggest that, for example, window opening behaviour of building users is highly uncertain and overestimated [153], explaining the higher hygric loads found in airtight buildings. Additionally, residential buildings often have only heating and cooling device with no humidity control, further contributing to the issue. However, energy efficient homes show higher dehumidification needs also when a mechanical ventilation system is installed [154,155], probably due to the underuse of the system. This opens the questions about the potential discomfort of users [156] and potential poor indoor health, in regard to organic air pollutants and mould growth.

## 6. Strategies to mitigate the risk

Interpreting sustainability as being only energy efficiency led to promote the design of sealed indoor environments that are completely separated from the outdoors. However, this approach reduces the architectural design resiliency in regard to these uncertainties, as there is no possibility to mitigate eventual additional loads that were not considered during the design stage. Energy efficiency standards strongly rely on strategies, technologies and provisions that must be carefully evaluated during the early design stage.

Considering that the presence of fungal spores and organic pollutants in the air as inevitable, the strategies that can be used to reduce the risk of mould growth should aim at minimizing the factors that support the phenomenon. These factors can be divided into three groups: design, occupational and policy factors. Design factors include all the choices that can be made during the design process, from basic architectural strategies to the materials selection and the design of mechanical services; all these aspects can be controlled by adopting a mould risk-conscious design approach. Occupational factors relate to all those occupants' behaviours that might increase the internal moisture content, creating optimal conditions for fungal spores to germinate. These aspects require a cultural shift, which may be promoted by education and awareness about the risk and the human impacts on mould growth. The last type of factors refers to the current policies, which enormously simplify the mould growth risk, often relying on a number of experience based provisions that might not be suitable for new energy efficient buildings.

Table 5: Mould mitigation strategies divide by groups: design, occupational and policy factors (further explanation is given in the following sections of the paper).

### 6.1. 6.1. adopting a mould risk-conscious design approach

Minimizing the design factors that support mould infestation implies the control and management of the parameters that influence mould growth: presence of nutrients and presence of water. The availability of nutrients is linked to the substrate where fungal spores are deposited, thus the selection of materials and finishing is essential to determine nutrient availability. The presence of water is influenced by both the architectural design as well the ventilation rate.

#### 6.1.1. Materials

In the architectural process, the choice of materials is usually driven by multiple aspects, such as architectural intent, energy efficiency and thermal behaviour, availability of the product, codes requirements and cost.

As seen, sustainability standards often promote the use of bio-based and natural materials that can offer optimal medium for mould growth [56], as they contain high levels of organic compounds that are easily digested by fungi.

At the same time, economic factors can also negatively influence the risk of mould infestation, as value management in construction often leads to an extensive use of various types of chipboards and particleboards. The issues surrounding the use of these products is not related to the material itself, but to the conditions of use: for instance, a material

**Table 5**
Indicates the possible mould mitigation strategies that can be adopted to reduce the moudl occurrence.

| | | Mitigation strategy | Supporting references |
|---|---|---|---|
| Design | Materials | Use of low-hygroscopic materials in rooms with high moisture loads | [157] |
| | | Careful material selection based on the location | [158] |
| | | Avoid or reduce the use of plasterboard and gypsum-based materials | [157] |
| | | Replace carpets with vinyl or ceramic tiles and use rugs | [157,159] |
| | | Use materials that can withstand repeated wetting in wet-rooms, below grade wall and floor insulation | [158] |
| | Ventilation rates and systems | Increase air change or ventilation rate | [84,158, 160–162, 164,165] |
| | | Introduce continuous mechanical ventilation (outlet) | [158,166] |
| | | Installation of dehumidification systems | |
| | Envelope design | Reduce thermal bridges and use of continuous insulation | [135,158, 167,168] |
| | | Use of continuous air barrier to prevent air infiltrations | [158] |
| | | In cavity walls add additional weep-holes to support drying process | [167] |
| | | Use of well-ventilated air gap with vertical or perforated batten to increase drainage capacity | [169] |
| Occupational/ management | Repair & maintenance | Increase frequency of maintenance inspections | [166,167, 170] |
| | | Introduce periodical audit of indoor moisture generation rate | [166] |
| | | Introduce monitoring system (indoor air quality and surface conditions) | [166] |
| | | Immediate replacement of materials damaged by moisture | [166] |
| | | Periodical cleaning and disinfection of HVAC systems and interior surfaces | [57] |
| | | Increase frequency of HVAC inspections | [163–166] |
| | | Immediate reporting of failures, damages or changes in the conditions of interior surfaces | |
| | | Develop consistent guideline for building occupants | [129] |
| Policy | | Increase opportunity to exchange knowledge and experience between the different stakeholder | [158] |
| | | Develop thorough criteria for mould-free homes | [166] |
| | | Improve the building code for new residential constructions in regard to ventilation and moisture control | [166] |
| | | Develop product control and labelling systems for building materials | [166] |
| | | Establish clear and regulated workflow for design, construction, management and reporting | [171] |

can work perfectly within a certain range of temperature and humidity, but under other conditions might offer a fertile ground for mould germination and growth. Indeed, materials should be carefully selected regarding their conditions of use, including the location [158]. Places with cyclical and recurrent high moisture loads, such as kitchens and bathrooms, should be clad with low-hygroscopic materials able to withstand repeated wetting [158], to reduce the water absorbed by the surface and available for fungal spores to germinate [157].

In the same way, all the sensitive locations should be carefully considered. For example, plasterboards and gypsum-based materials, as well as carpet, are perfect substrates for mould to grow [146], but they are broadly used as interior cladding materials. In order to reduce the risk of mould growth, these materials should be avoided and replaced with less hygroscopic and easier to clean ones, such as vinyl or ceramic tiles and rugs [157,159]. A possible implementation regarding materials and mould could be the development of products control and labelling systems that contain all the relevant information for designers to inform the design phase [166]. Another example on the misuse or misplacement of materials can be the use of organic insulation panels as fire retardants close to mechanical ventilation system. Although the material performs perfectly well in regard to both fire and thermal performance, when in contact with water, it might have consequences beyond the biodeterioration of the panels: an hospital, for example, reported a serious spread of aspergillus infection in cancer patients due to a fungal infestation of the fire retardants used [172]. The presence of water is not only due to leakage, but it might also be due to condensation issues on the ducts surface. Thus, the risk is not a rare, one off occurrence that can be overlooked.

### 6.1.2. Ventilation rates

Efficient buildings rely on mechanical ventilation to guarantee an adequate fresh air supply, which assist in reducing the spore concentrations and the indoor moisture load. However, ventilation is usually designed to respond to hygienic and thermal requirements but with little consideration for moisture management. A possible strategy to minimize the risk of mould growth is the introduction of hygric loads control into the building management system to account for a hygrothermal-based ventilation system. If correctly designed, this system should override other requirements to prioritise the reduction of the indoor relative humidity when critical levels are achieved. A correct ventilation strategy that could support the provision and control of healthy indoor hygrothermal environments is among the most suitable forms of mould-growth prevention [20,170]. This strategy should be correctly designed and tailored for the specific case in analysis: indeed, occupancy patterns, construction characteristics and building specific features influence the amount of fresh air needed to assure adequate ventilation. Thus, the case specificities and the lack of agreed thresholds in regard to indoor air pollutant concentrations makes impossible the definition of a unique minimum air change rate [158] to avoid mould growth. Nonetheless, it is possible to identify minimum recurring values often associated with health improvements, although studies on ventilation rate often fail to describe how the air change value was measured or tested [173].

Air change rates higher than 0.5 ACH (air change per hour) are associated with a significant reduction of risk of mould growth [160] and health hazards [165,174], while it needs to be greater than 0.8 ACH to avoid increments of house dust mites [160]. Additionally, ventilation rates below 10 l/s per person are correlated to a higher prevalence of adverse health outcomes or worse perceived indoor air quality [164], and an increment in the ventilation rate up to 25 l/s per person can reduce the prevalence of symptoms up to 29% [161]. Indeed, associations between ventilation rates above 15 l/s per person and improved human health are well established and recognized [84,162]. Thus, it is possible to identify ACH 0.8 and ventilation rate 15 l/s as minimum thresholds to guarantee healthy indoor environments, considered as the sum of controlled and uncontrolled air exchanges.

Mechanical or hybrid ventilation systems should be preferred to the sole natural ventilation, as they provide better control of the air rates, dehumidification possibilities, heat recovery and air filtration. Indeed, the average size of bioaerosol particles that transport bacteria and fungi range between 5.5 and 5.9 μm (diameter) [175], and they can be removed efficiently by most residential ventilation systems [158].

The success of mechanical ventilation in controlling the indoor pollutant concentration relies on the correct design, installation and maintenance of the systems. The system should be designed to respond to real data monitored about the indoor and outdoor temperature, humidity, and pollutants concentrations [166], in order to calibrate the ventilation rate to the building's real needs. Furthermore, a complete and detailed maintenance program should be discussed with the building owners and put in place to guarantee the long-term provisions of the adequate ventilation rates; the maintenance service should include a periodical audit of the indoor moisture generation rate [166], cleaning and disinfection services, as well as more frequent inspections aimed at the early detection of failures and malfunctioning [163].

#### 6.1.3. Envelope design

Fungi needs water to grow and proliferate. Normally, in buildings, the availability of water is determined by the surface hygric conditions, which depends on the indoor relative humidity as well as the water uptake and hygroscopic behaviour of the material on which it happens. Rain-driven wetting of the envelope and slow drying processes negatively influence the mould growth risk, especially if the envelope is not well ventilated and the moisture trapped inside [176]. Thus, ventilated rainscreen with vertical or perforated batten [169] should be preferred to increase the envelope's drying capacity. The same principle applies to brick cavities walls, where the slow drying process [177] increases the risk of mould growth, especially when coupled with poor workmanship, as mortar bridges are found to have a dominant impact on the indoor growth phenomenon [178]. To mitigate this issue it is possible to design additional weep-holes to assure correct drainage [157].

However, one of the major causes of mould growth is the presence of thermal bridges and air leakages, which often leads to highly humid and localized microclimates, leading to mould germination [179]. Indeed, it is essential to conduct a detailed hygrothermal analysis when assessing the impacts of thermal bridges, as the only thermal profile is not a good predictor for mould growth risk [180,181].

Continuous external thermal insulation [158] is not the only strategy that can be used to reduce thermal bridges, but it is one of the most cost-effective, as few centimeters can significantly reduce the associated mould growth risk [182]. Unfortunately, the prevention of thermal bridges can be done only during the design stage on a case-by-case basis, as predetermined catalogue of solutions may not be effective, due to the limited-number of cases that it is possible to include [168], and sometimes increasing the overall thermal resistance may be insufficient to minimize the risk of biodeterioration [183]. The promotion of a risk conscious-design approach is the only strategy that can be employed to minimize the occurrence of mould due to thermal bridges.

### 6.2. Management of the indoor environment

Design is only one aspect of a multifaceted issue that leads to the creation of favourable conditions for mould growth, with occupational factors being probably the most influent. Building's occupants determine the final moisture load through habits and management of the indoor environment.

Fungal spores can stay in house dust compounds, waiting to settle on adequate surface and germinate. At the same time, dust is mainly composed of human skin scales, the mites' primary nutrient. Therefore, accumulated house dust can support indoor organic pollution and significantly contribute to the creation of unhealthy environments. Regular cleaning, especially of rough surfaces capable to retain dust particles, such as carpets, assists in minimizing the risk by reducing both the spore concentration and the availability of nutrients [57]. Frequent and regular cleaning, disinfection and inspections should also be planned to decrease the risk of mould growth [167]. Indeed, frequent maintenance inspections may detect hidden moisture-related damages and prevent the fungal spore germination [170] by immediate replacement of damaged materials [166].

Considering favourable conditions for mould growth, indoor RH should not exceed 70% for prolonged and cyclical periods. Human habits can influence the indoor moisture load: cooking, bathing, excessive numbers of indoor plants that require frequent watering, pet urine, clothes dryers vented indoors or clothes hanged inside to dry are all activities that highly generate moisture.

Minimizing the activities that increase the indoor moisture loads and engaging in those that reduce it, such as ventilating indoor spaces, is also a responsibility of the building occupants. However, rising the awareness and promoting mould risk-conscious behaviour through social education is an essential requirement [129].

### 6.3. Improvement of the current policy framework

Currently, the major building codes incorporate guidelines to avoid mould growth in the form of design criteria, prescriptive provisions and method for the assessment of the risk [17]. However, each code proposes, with different degree, an excessively simplified vision of the problem of mould growth [13], often providing inconsistent threshold values for relative humidity and temperature or missing to give univocal results free from interpretation.

Considering the current regulatory framework in Australia, United Kingdom and United States, the inconsistencies between the approach become clear, as shown in Table 6.

Not only the relative humidity threshold varies of 10% between different standards, but the calculation method and the values considered are not consistent. Indeed, ASHRAE 160 [184] refers to the 30-day running average, while the others codes to a not better specified mean RH. The lack of a unified and agreed framework for mould avoidance is reflected also in the approach of the different standards (Table 7 ).

Despite the differences, all the building standards approach mould growth as a deterministic phenomenon, providing critical conditions that should not be met to reduce its occurrence. The critical conditions are either thresholds or more general guidelines, often even not better specified for the particular context in which the code is used [129].

**Table 6**
Overview of different RH thresholds indicated by different international standards.

| United States | EU members | United Kingdom | Australia |
|---|---|---|---|
| ASHRAE 160P - 2008 [184] | ISO 13788:2012 [185] | BS 5250:2002 [186] | Condensation in Buildings [129] |
| RH < 80% | RH <80% | RH <70% | RH <70% |
| 30-day running average surface RH should be always below 80%, when temperature is between 5 °C and 40 °C | monthly mean RH should not exceed the critical value, set as 80% in lack of more specific information | mean room RH should be below 70%, the value can be exceeded for short period | average RH should be below 70%, and temperature between 4 °C and 40 °C |

**Table 7**
Overview of different international standards regarding mould avoidance.

| | ASHRAE 160P - 2008 [184] | ISO 13788:2012 [185] | BS 5250:2002 [186] | Condensation in Buildings [129] |
|---|---|---|---|---|
| **Type of document** | International standard | International standard | National Building Code | Good practice guide |
| **Building typologies included** | All building typologies/New built/Renovations | All building typologies/New built/Renovations | All building typologies/New built/ Renovations | All building typologies/New built/ Renovations |
| **Indications and thresholds type** | indicative | indicative | prescriptive | none |
| **High level recommendations** | none | None | included | included |
| **Reference to the assessment method** | yes | Yes | Refers to other code (ISO 13788 + EN15026) | Refers to another code (ASHRAE 160) |
| **Recipients** | Designers | Designers | Designer, construction companies, building owners and occupants | Designer, construction companies, building owners and occupants |

Considering the complexity of mould growth, the number of parameters involved in the biological process and the importance of the transient interactions among them, it is clear that none of these approaches provides a valid strategy to reduce mould growth. Furthermore, many national building codes have requirements and specifications for health and safety, designed to protects the occupants from health hazards; however, these regulations have a strong focus on structural, electrical and fire safety issues [187].

The same issue can be identified in green building standards, where some issues are raised in regard to mould growth and indoor air quality. The WELL standard is pioneering the discussion, incorporating results and findings of the ongoing research on the topic [187], but, generally, the lack of specific and agreed frameworks for mould growth risk assessment hinders the development of more specific guidelines.

Part of the issue is determined by the lack of detailed supporting data, research and information. The Australian guidelines (handbook) clearly state that the current knowledge is limited when it comes to cool climates, and that there is less research validated data available for warm regions [129]. Despite the advancements made in the field to understand the phenomenon and represent it with adequate computational models, there is urgent need to update the policy frameworks and incorporate clearer guidelines and indications to prevent mould growth.

The codes report some calculation methods and provisions, but they don't provide an interpretation of the results, nor an explanation on the phenomenon. Generally, there is also little feedback from the construction industry, which is reluctant to share insights from actual projects and case studies, interrupting the feedback cycle that could inform the building codes.

Potential improvements on the policy framework could include the following strategies:

- Establish clear and regulated workflow for design, construction, management and reporting [171], and increase the clarity of the assessment and the interpretation of the outcomes also through the regulation of a feedback framework from designers and developers to inform the next generation of hygrothermal standards based on real case studies [158].
- Eliminate existing codes and provisions that are too simplified, such as the steady-state methods: although it is widely known that mould growth is a transient phenomenon and that steady state assessments (such as Glaser) are not capable to fully express it, some building codes still include them as viable solutions. This clearly fails to provide an appropriate assessment method for designers, as well as to educate and raise awareness about the phenomenon.
- Introduce hygrothermal regulations: most of the provisions are included in guidelines and standards that are not part of the regulatory building codes. Switching from the current informative nature of these provisions to a normative form is an essential step to undertake in order to assist designers and decrease the mould growth risk.
- Improve the building code in regard to minimum ventilation strategies and moisture control strategies by developing thorough criteria for mould-free homes [166].
- Contribute to regulate the testing framework: the available research that focuses in defining the favourable conditions for mould growth is currently based on investigations performed without following a precise and regulated testing method, resulting in a fragmented body of knowledge. The introduction of a clear and standardized testing procedure and set-up would assist in developing a consistent research methodology that could better inform the policy framework.

## 7. Future directions

The correlations between energy efficient buildings, ventilation, mould growth and health call for the development of new knowledge and tools that could promote healthier indoor environments. A multidisciplinary research approach is needed to advance the understanding and improve the building design and maintenance practices by integrating the expertise, knowledge and methods from different fields. Indeed, this issue requires a comprehensive and holistic research program that could bridge construction, design and health, while informing policy and human behavior. The literature review identifies five future directions and priorities that must be addressed (Table 8).

The characterization of the correlations between health, buildings and occupants is still a significant research gap in the field. Indeed, despite the existing strong evidences, the lack of a common research framework and methodology makes it difficult to compare, benchmark and analyze the different studies. Indeed, the different methodologies undertaken in different studies constitute a limit to the development of clear mitigation strategies as the results and conclusions obtained do not constitute a complete and complementary body of knowledge. Furthermore, additional research must be done to understand the mould growth phenomenon under more realistic conditions. Indeed, at the

**Table 8**
Relevant research gaps and indication of possible future directions to advance the field.

| Gap | | Future directions |
|---|---|---|
| Knowledge | *Experimental framework* | Develop a common approach or methodology to the research |
| | *Mould growth phenomenon* | Improve understanding of the relationship between mould growth, design features, construction, commissioning, and maintenance |
| | *Occupants* | Integrate social and behavioral studies to analyze the role of building occupants and the drivers of their actions |
| | *Ventilation* | Identify benchmark, critical limits and guidelines; develop strategies to increase resiliency to occupants'' misuse |
| Policy | | Develop a clear workflow for the regular update of the regulations |
| Application | | Translate research into practice |

present state, the available mould growth knowledge is limited to the experimental campaigns performed by researchers about steady-state conditions in cool climates. However, building operations and maintenance are critical aspects that contribute to modifying over time the operational conditions that may lead to mould growth. Thus, understanding and tracking the performance of building over time and changing conditions is essential to better formulate design and maintenance strategies that could mitigate or prevent moisture-related damages.

Another knowledge gap is related to the possible ventilation strategies. Indeed, although evidences suggest that energy efficient buildings may suffer from mould growth due to lower ventilation rates, this correlation is still not clear as there isn't a consistent body of knowledge that can be used to provide suitable strategies to minimize the risk, intended both as a clearer policy framework for designers, and as guidelines for the building occupants. For example, research aimed at increasing the ventilation systems (and strategy) resilience to users' misuse is highly needed. Indeed, ventilation systems should be able to account for increased indoor hygrothermal loads due to under ventilation of the spaces and increased the moisture generation. Additional research into mechanical ventilation systems that could provide a correct and separate management of both the sensible and latent load may assist in reducing the risk of mould growth due to excessive indoor moisture levels [188].

Advancements on the understanding of the phenomenon are necessary to inform the next generation of policy that could guide the construction sector toward the provision of healthier built environments. However, the current building codes are unable to fully capture the mould growth issue, relying on a series of assessment methods that are already proven to be out-of-date. Indeed, current policies should be updated to provide a consistent assessment framework, acknowledging the importance of a correct approach and including the currently informative standards into the normative framework. For example, any reference to steady-state assessments should be eliminated to avoid the oversimplification of the mould growth risk and increase the awareness about its complexity and importance.

The Policy framework has the potential and the duty to become the connection between research and practice, and to support the translation of new knowledge into clear guidelines and concrete benefits for the built environments. To promote the translation of the research into practice, it is essential to develop, initiate and maintain a pathway of implementation that involves the different stakeholders. Indeed, establishing a feedback loop where all the information form researchers, designers and builders can be exchanged and used to integrate the different perspectives into one innovation agenda, as advancements focused on only one aspect will not be sufficient to understand the multifactorial relationships between mould growth, human health and buildings.

## 8. Conclusions

This paper investigated the mould growth issues in relation to energy efficient buildings. Although mould is often associated with old constructions, there are continuous reports about its occurrence in newly built homes [189], opening the question about the suitability of current design practice and policy frameworks to reduce the risk. Indeed, mould can have significant impacts on the life of the building occupants, both in terms of economic loss and adverse health effects.

Energy efficient standards, coupled with stringent provisions to respond to the increasing level of outdoor air pollution, are driving towards airtight and highly insulated buildings to reduce the uncontrolled air exchange with the exterior environment. However, this is leading to a reduction of the indoor air change rates, resulting in higher latent loads that are not fully dissipate.

These increased hygrothermal loads, coupled with the diffused use of organic-based materials for construction purposes, can easily generate optimal conditions for mould to grow by providing abundant nutrients and moisture to the fungal spores.

The current design policy and guidelines are unable to fully capture the risk, and they offer inaccurate assessments methods. The reason can be found in the inconsistency of the testing methodology used to investigate mould growth, which results in growth models which are unable to inform the design and the policy framework.

Furthermore, building occupants behaviour has a significant role in assisting mould growth. This variable is highly unpredictable, and it requires a change in the design strategies towards a higher level of resiliency in regard to users misuse of the indoor space, and a cultural shift of building users towards a more aware and conscious behaviour with regard to the risks of mould.

Improvements and advancements in these fields may support designers and policy-makers to address the issue of mould growth and, consequently, to reduce its incidence. The ultimate goal is to provide clear direction that could assist in meeting both the SDG 13 and SDG3, toward climate resilient and healthy environments.

## Declaration of competing interest

None.

## Acknowledgments

The Authors would like to acknowledge Ana Subotic for the help and support.

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