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Perspective

Risk of Fungal Growth in Nearly Zero-Energy Buildings (nZEB)

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Abstract: Research on nearly zero-energy buildings has addressed mainly the aspects of energy saving or technical and economic optimization, while some studies have been conducted on comfort and indoor air quality. However, the potential problems that may arise in low-energy buildings during the operational phase, and especially the risk of fungal growth, which can deteriorate the indoor environment and pose a health risk to the occupants, are yet to be extensively investigated. The present work intends to analyze previous research on microbial contamination in zero-energy buildings in order to identify the possible risks that may lead to fungal formation and the possible strategies to prevent the proliferation of molds. The methodology is based on a systematic literature review and subsequent critical analysis to outline perspectives on this topic. The main results indicate that high envelope insulation and inadequate ventilation are the leading causes of fungal growth in energy-efficient buildings. The need for more detailed regulation in this area is also highlighted. The study's outcomes underline the need for more attention to be paid to the design and management of zero-energy buildings, aiming to achieve the reduction in energy demands while ensuring the occupants' well-being.

Keywords: nearly zero-energy buildings (nZEBs); fungal growth; mold risk; indoor air quality; microbial contamination; mechanical ventilation systems

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1. Introduction

The green transition puts pressure on increasing energy savings through better building insulation and decreased ventilation losses [1]. Different sustainability goals can often contradict each other if not applied consciously, for example, when the health and well-being of occupants are overlooked or compromised by sustainable development practices [2].

Research has shown that indoor fungal growth can cause Building-Related Symptoms (BRS), especially in the case of damp, poorly maintained, or water-damaged buildings [3,4]. Ebbehøj et al. [3] examined 25 employees working in severely moisture-damaged buildings before and after renovation. The reported symptoms included eye, nose, and throat irritations, headache, fatigue, dizziness, and concentration difficulties. Based on a national survey conducted on multi-family buildings in Sweden, building dampness, mold, and insufficient ventilation are among the most critical risk factors associated with headaches and ocular symptoms [5]. Wang et al. [6] investigated the correlation between asthma, lung function, and specific volatile organic compounds (VOCs) found in homes affected by dampness and microbial growth. The survey involved 159 adults from three northern European cities (Reykjavik, Uppsala, and Tartu). The results showed an increased concentration of specific VOCs in the presence of certain mold species or indoor dampness.

Therefore, the association between VOCs and lung disease may be stronger in homes with mold and dampness problems [6]. Furthermore, laboratory experiments conducted by Maundrill et al. [7] demonstrated that long-term fungal contamination represents the most dangerous degradation mechanism for building materials. Mechanical tests were performed to measure the decay of 290 fibrous plaster samples subjected to moisture and fungal treatments over a two-year period.

As Ginestet et al. [8] explained, the leading causes of indoor fungal development are increased air moisture and water on building elements. These conditions can be triggered due to insufficient or lack of ventilation, faulty or ineffective heating, sensitive constructions and building elements, as well as structural problems, and accidental incidents leading to water damage. In this regard, several studies have investigated the relationship between fungal growth risk and building construction. Silveira et al. [9] and Xue et al. [10] analyzed the influence of thermal insulation and the solar orientation of external walls in different climates on the surface condensation risk and, thus, fungal growth. The conclusions indicate that the presence of thermal insulation decreases the risk of surface condensation. In contrast, insufficient ventilation and low surface temperatures are critical in creating ideal conditions for fungal growth [9]. Xue et al. [10] concluded that the wall orientation and insulation positioning are closely connected to the indoor moisture content, condensation, and mold risk. High heat flux at the exterior surface due to solar radiation can reduce the moisture content of the building envelope. On the other hand, exterior insulation can increase the condensation risk [10,11]. Morelli et al. [12] investigated the wind–vapor barrier ratio to avoid mold growth, in correlation with the internal humidity class and exterior climate, through 1-D hygrothermal simulations.

The risk of mold growth varies according to climatic conditions. The influence of the external climate is due to the association of fungi with the plants present outdoors. Furthermore, the humidity level is also influenced by the external climate and the occupants' behavior. For example, in hot climates, there is a known habit of opening windows more frequently and for extended periods, implementing high air changes. In contrast, in cold climates, there is a tendency to keep the windows closed, causing an increase in internal humidity, which increases the risk of condensation on inner surfaces when considering the lower temperatures.

Additionally, there is an increasing demand for the use of less energy-intensive and more sustainable building materials. Wood or other new, biogenic materials are, therefore, substituting traditional elements like brick and concrete in many cases [12–14]. However, organic materials are more sensitive to moisture, which makes them more susceptible to fungal growth and deterioration [2,12,13].

Moreover, based on the analysis by Lu et al. [15] and simulations on mass timber walls by Defo and Lacasse [16], the mold growth risk may rise in the future due to increased rain loads under the effect of climate change. The results depend on the specific climatic characteristics of each region evaluated in near- and far-future scenarios. The impact of climate change on the actual performance of energy-efficient houses has also been highlighted by Ozarisoy [17] and D'Agostino et al. [18].

The need for energy savings has changed the construction style to airtight and highly insulated buildings. The obligations of nearly Zero-Energy Buildings (nZEBs) are towards energy efficiency (reduction in thermal transmittance and infiltration) and moisture control (preventing forced air exfiltration). A reduction in heat losses is achieved through the airtightness of the building envelope, which minimizes uncontrolled air movement through infiltration.

The generally imposed requirements for obtaining zero-energy buildings are the heating and cooling demand limitations and the integration of energy from renewable sources. However, the concept has evolved over time, resulting in several generations of nZEBs [19], and it continues evolving towards even more ambitious goals. In fact, the "zero" target has been surpassed by "positive"-energy buildings [20], which aim to obtain a positive energy balance, i.e., the energy produced is higher than what is consumed.

A great opportunity is offered by the conversion of existing buildings into nZEBs. Considerable interest has been developed in this area in recent years, as improving the performance of the building stock has become a priority to achieve the zero-carbon objectives. However, as demonstrated by the comprehensive review conducted by Tetteh et al. [21], in the current framework for renovation, “energy efficiency” retrofitting has become the highest research priority, while “occupant behavior” and “indoor environmental quality” (comfort, satisfaction, air quality, etc.) are diminishing in prominence.

As the characteristics of buildings vary depending on context and specific use, different optimization strategies have been created to coordinate multiple needs. The optimization includes both the building envelope [22] and the systems, in particular mechanical ventilation and heat recovery [23], as well as high-performance HVAC technologies like geothermal heat pumps [24].

Furthermore, questions about the actual usability and levels of well-being experienced within these high-efficiency buildings are rising [25,26]. After examining the air quality of 25 nZEB cases, Wu et al. [27] warned that overheating, contaminant accumulation, thermal discomfort, and Building Sickness Syndrome are frequently reported problems and that there are several indoor environmental quality (IEQ) risk factors, as well as other complex issues that need to be addressed in nearly zero-energy buildings as they can seriously affect the occupants’ health and well-being. Steinemann et al. [28] examined the issue of how green buildings, although they may improve energy efficiency and sustainability, may not necessarily enhance occupants’ health and well-being by improving indoor air quality. Furthermore, certain green practices and green products may actually degrade indoor air quality. A negative impact on health has also been reported due to excessive overheating in zero-energy buildings in a Mediterranean climate [29]. Therefore, the “green” label does not always imply good indoor air quality.

The occupants’ behavior significantly influences achieving the right balance between energy consumption and thermo-hygrometric comfort [30]. The maintenance and operation of the systems are also relevant. For example, when there is mechanical ventilation, the periodic replacement of the filters is essential to ensure adequate indoor air quality [31]. Studies based on monitoring campaigns and post-occupancy surveys have tried to evaluate the performance of zero-energy buildings during the operation phase and the occupants’ satisfaction level. However, the fungal growth risk in nZEBs has not been tackled yet. In this regard, a gap in the literature has been identified.

1.1. Motivation and Objective

Based on the examined literature, it emerges that the fungal formation risk in zero-energy buildings and high-performance buildings has not been clearly identified. The present research intends to draw attention to the problem of mold formation and air quality in low-consumption buildings. Indoor microbial contamination threatens human health, while its detection poses a challenge, especially when the affected area is hidden. The perspective provided by this work helps to improve the understanding of this phenomenon and outlines possible intervention strategies to prevent and assess the adverse effects associated with fungal growth in nZEBs.

The present work intends to address the following research questions:

- Is there a relevant body of literature dealing with the risk of fungal formation in energy-efficient buildings, and particularly in nearly zero-energy buildings?
- What are the possible causes of mold growth in nZEBs?
- What solutions and intervention strategies can be adopted to prevent the formation of fungi and ensure a trade-off between energy efficiency and air quality in nZEBs?

The originality of the proposed work can be expressed in three points. First, it draws attention to the emerging challenges of nearly zero-energy buildings and directs future studies toward approaches that combine energy-saving needs with the occupants’ well-being. Secondly, the risk of hidden mold contamination in nZEBs is investigated, with particular focus on the operation of mechanical ventilation. Finally, the need for integrated design and interdisciplinary collaboration (e.g., designers, health experts, building automation and control systems specialists, and legislators) is highlighted to define measures aiming to obtain healthy nZEBs.

1.2. Structure Description

The article is organized into four main sections. In the first phase of the study (Section 2), an extensive survey of the existing literature was conducted using the VOSviewer software to identify literature trends during the last decade. Subsequently, the literature search used specific keywords to focus on works produced in the last three years.

In the second step, a thorough literature analysis was conducted, focusing, on the one hand, on the possible causes of mold formation in nearly zero-energy buildings and generally in energy-efficient buildings (Section 3). On the other hand, possible suggestions to avoid the problem of mold growth in nZEBs are provided (Section 4). The latter is accompanied by the description of the available tools for the detection and identification of the problem, if present, and for the prediction of mold formation to adopt suitable solutions already at the design stage.

Finally, the main findings are discussed, and possible perspectives are outlined (Section 5). Figure 1 illustrates the adopted methodology.

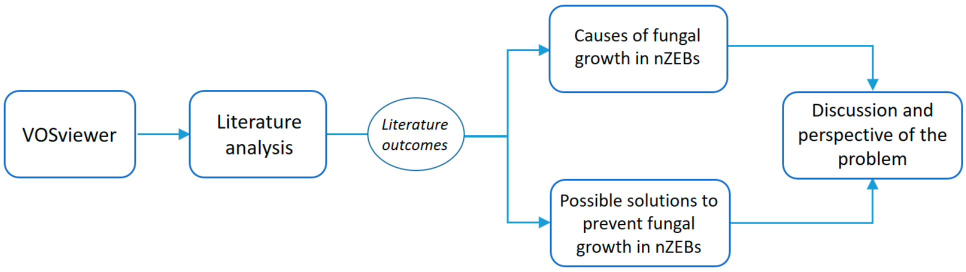

Figure 1. Methodology outline.

2. Methodology

2.1. Research Trend over the Past Years

To analyze the direction and focus researchers have been moving towards, overlay visualizations were developed using the VOSviewer software v1.6.17. The overlay map (Figure 2) based on keywords shows a concentrated occurrence of the keyword "indoor air quality" (with the larger size bubble). The keywords "fungi", "mold", "ventilation", and "thermal comfort" appear with the same occurrence (or same bubble size), which could be interpreted as having the same importance among the documents found. However, these keywords appeared to be used around 2014 (purple). After that, the keywords "indoor air quality", "ventilation", and "indoor environment" were employed around 2017, but "thermal comfort", "hygrothermal performance", and "mould growth" appeared towards 2018–2019 (light green). Lately, between 2020 and 2023 (yellow), the keywords "COVID-19", "condensation", "energy performance", and "air pollutants" have appeared.

This tendency shows that the research direction is moving towards assessing the energy and hygrothermal performance based on condensation and mold growth, which is the specific subject of this perspective paper.

The overlay map based on terms in the title and abstract (Figure 3) shows two distinctive clusters around "concentration" (on the left-hand side) and "performance" (on the right-hand side). The color contrast between these two clusters revealed a focus shift from fungal concentration aspects and health effects (having a peak period around 2014) towards performance assessment in buildings (around 2017) and solutions via humidity control, materials, and other technologies, such as air purifiers (beyond 2020).

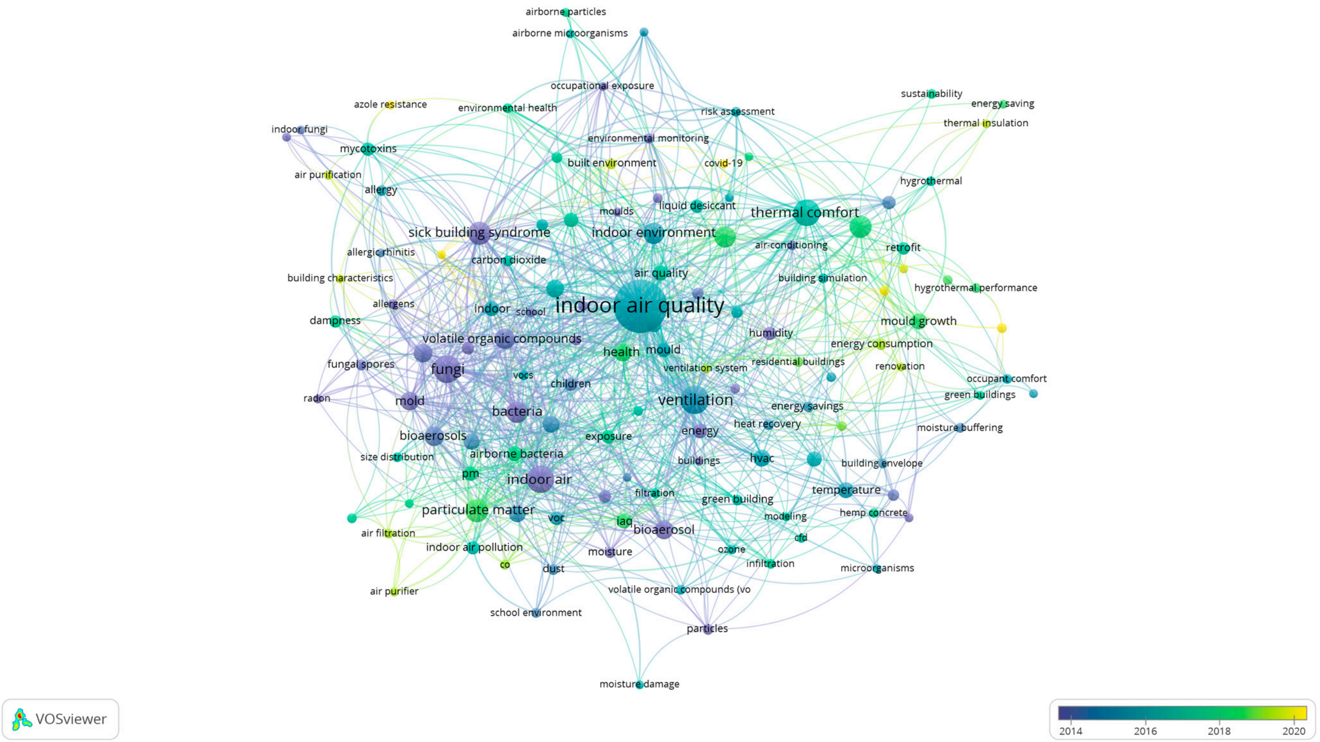

Figure 2. Overlay map based on keywords occurrence. The keyword occurrence threshold is five, where only 130 keywords met such threshold.

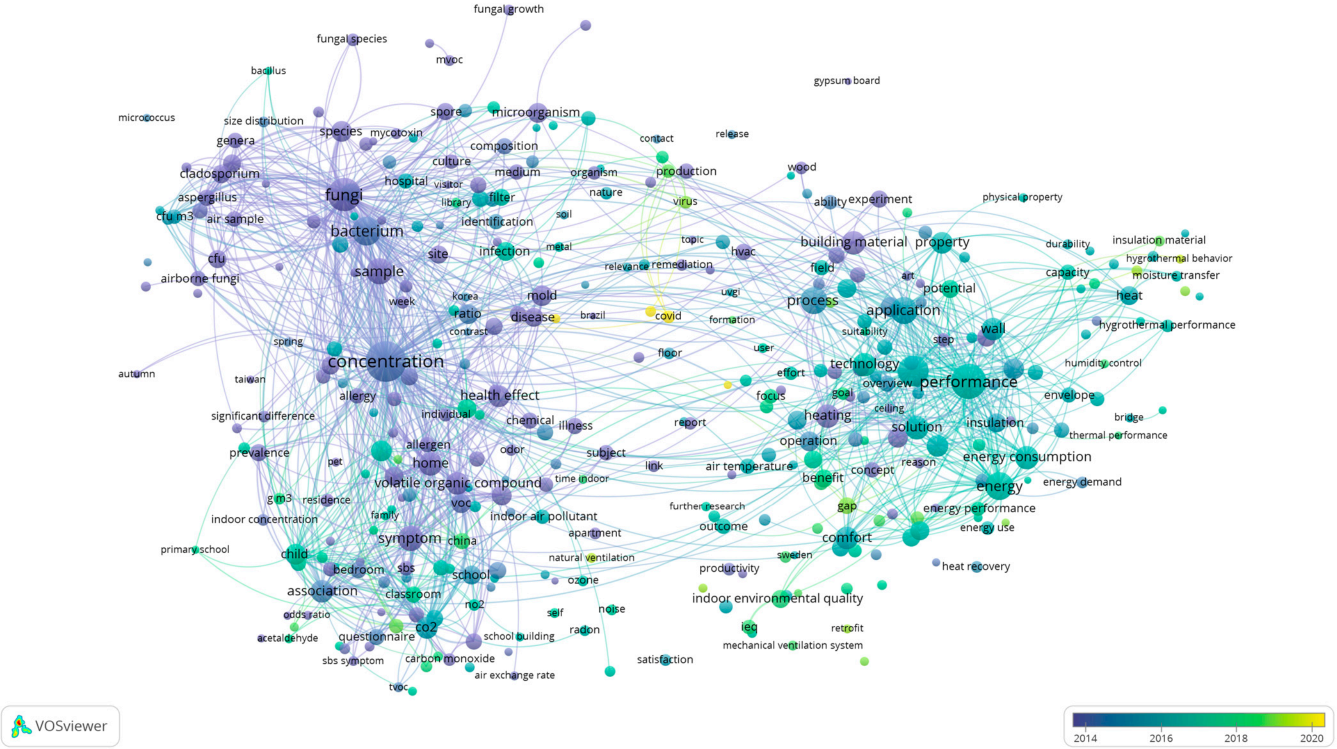

Figure 3. Overlay map based on the terms in the title and abstract. The terms occurrence threshold is ten, where only 622 terms met such threshold.

However, no mention of “nZEB” and “NZEB” was found in the 1128 documents employed in the mapping, which means these terms or keywords did not appear more than the recommended thresholds (five times for the keywords and ten times for terms in title and abstract). The keyword "nzeb" appears with a threshold of two. Only when a threshold of one is selected do the keywords "zero carbon-ready building", "zero energy building", and "zero-energy building" appear. This leaves a gap in the literature on how mold growth control affects the achievement of zero-energy buildings.

The literature search for the development of the overlay maps was limited to the years from 2010 to 2023 within the SCOPUS database to retrieve information from the literature concerning indoor air quality and mold growth in buildings. About 1000 references were encountered; only 113 were strictly related to this review's main subject. The first selection criterion corresponds to selecting only the documents where indoor air quality and mold growth are directly linked to aspects within zero-energy buildings (ZEBs). Due to a low number of studies, a unique selection of documents was performed for those directly related to each aspect of ZEBs. In these, mold growth can threaten indoor air quality and energy consumption, i.e., the design, construction, systems and efficiency measures, operation and maintenance, and regulations. The final list of documents chosen to be analyzed agrees with the observations in Figures 2 and 3.

2.2. Literature Search

After exploring the research trend through the VOSviewer visual maps, a systematic literature review was conducted on the specific topic in the context of the last three years. The investigation was carried out by searching the Scopus database. In the first phase, the association of words "nZEB" and "fungi", or "nZEB" and "mould", was used, but very few results were obtained. Subsequently, the acronym "nZEB" was replaced with the full name "nearly Zero Energy Buildings" and the more general one "Zero Energy Buildings" to broaden the scope of research. However, the results remained limited. Consequently, to extrapolate a greater number of articles, the search was extended using the more general combination "Zero Energy Buildings" and "contaminants", and "Zero Energy Buildings" and "Indoor Air Quality." However, by limiting the field to the category of zero-energy buildings, the findings from the literature were reduced. Finally, the search was further enlarged by inserting the keyword "buildings" combined with the words "fungi", "mold", "dampness", and "moisture." Furthermore, a check was performed by removing the filter for the time period. However, only a few works completed prior to the period of the last three years were deemed particularly interesting to include in the expanded, final literature list. The literature was subsequently analyzed in detail, and the results are reported below.

3. Expected Problems of Energy-Efficient Buildings

The authors deduced the risk areas of energy-efficient buildings through the literature analysis. The domains that require attention are related to the buildings' construction details and practices, mechanical ventilation and its operation, regulations about the prevention of fungal growth, and the occupants' behavior and operation practices. For example, according to research conducted by Kang and Nagano [32], there is evidence to support the presence of organic contaminants inside nearly zero-energy residential buildings in Japan. Kang and Nagano [32] investigated a building where several energy efficiency measures were implemented in the design, including sealing of the envelope, the installation of a highly efficient heating system with heat pumps, and the integration of solar collectors. A ventilation system was set up, using an earth tube and a sensible heat recovery ventilator, supplying fresh air. The results showed that the concentrations of fungi and bacteria vary according to the season and the occupants' lifestyle, while higher concentrations are found in summer. Furthermore, it was found that the environment inside the earth tube favors the growth of fungi.

3.1. Buildings' Construction Details and Techniques

Several studies have pointed out that highly insulated and airtight buildings are prone to increased moisture levels indoors, which can lead to an accumulation of indoor air pollutants if sufficient natural or mechanical ventilation is not ensured [33,34]. Specific parameters can increase the risk of indoor dampness and lead to the right conditions for fungal growth already before the completion of the construction phase [8]. New buildings may face problems of built-in moisture in the envelope due to construction techniques that use materials with high moisture content, water damage incidents, or poorly executed construction details, combined with the lack of regulations and control [8,34]. Ingebretsen et al. [35] analyzed the microclimatic conditions in air cavities and roofs by collecting wood moisture, air temperature, and humidity data for three case buildings in Norway. Even though significant differences are registered between case buildings and the position of the sensors, there was a risk for mold formation in all analyzed buildings. In particular, the authors [35] highlight the critical issues related to ventilated cavities. Insufficient cavity ventilation can prevent structures from drying out, increasing humidity levels and leading to mold growth. Excessive ventilation, on the other hand, can cool the inside layer of the cladding, causing condensation and, thus, mold formation. The air cavities showed higher annual temperature amplitudes for long periods than the external air, which occurs to a greater extent for the ZEB Laboratory [35]. Furthermore, poorly designed or faulty installed wind and air barriers in external walls can lead to water condensation in the construction [34]. Finally, the wide use of economic interior finish solutions with poor hygroscopic properties is worsening the situation [34].

When it comes to interventions in existing buildings, it may be challenging to upgrade them to reach the energy performance of new buildings (nZEBs) [36,37]. Window replacement or the application of internal insulation can lead to indoor dampness if the solutions are not well thought out and designed with focus on the moisture performance of the building [34]. The results of a study by Morelli and Møller [38] show that in some cases, the relative humidity behind the internal insulation would reach 95% during the heating season. The same problems have been documented for interventions in historic buildings that require internal thermal insulation [39]. As Lu et al. [15] highlighted, these actions expose the structures to an increased risk of humidity accumulation due to condensation and the impossibility of drying, causing mold growth and material decay.

3.2. Mechanical Ventilation Risks of Poor Maintenance or Faulty Operation

High-performance buildings are less susceptible to high humidity compared to traditional buildings [40]. It is believed that the implementation of mechanical ventilation prevents mold development indoors [8]. At the same time, in heavily polluted areas, mechanical ventilation has substituted natural ventilation to reduce the entrance of external pollutants [2]. Therefore, in new buildings, the installation of mechanical ventilation is often mandatory [8]. However, not many studies have verified the effectiveness of such solutions in energy-efficient buildings [33]. Additionally, the ventilation system may often malfunction, or its performance can be tampered with by the occupants' behavior or intervention, e.g., reduction in ventilation to save energy for heating.

As outdoor air is the primary source of fungal spores indoors, mechanical ventilation is more effective than natural ventilation in creating a better indoor environment while decreasing the relative humidity levels that significantly affect fungal growth. Yet, that is only if the filters are changed regularly (once or twice per year), as fungi can grow in the filters and create an indoor source of spores. Niculita-Hirzel et al. [33] hypothesized that mechanical ventilation is not more effective in reducing indoor fungal growth. Lin et al. [41] provided observed data on the diffusion and retention of biological contaminants by HVAC systems, indicating that they can operate efficiently in removing dispersed fungal spores in the absence of internal or external sources. On the other hand, in the presence of mold, the diffusion of spores within the room is very fast. Additionally, integrating a mechanical ventilation system during the design stage has proven more efficient than a system added during renovation.

In air-handling units (AHUs), fungal growth has often been isolated from the blower wheel fan blades, ductwork, cooling coil fins, and insulation [42]. More specifically, the blower wheel fan blades are the most contaminated locations. On a positive note, they are easily accessible for sampling. Extensive sampling from AHUs by Wilson et al. [43] revealed *Cladosporium* spp. (*Cladosporium cladosporioides* or *Cladosporium sphaerospermum*) to be the most commonly isolated from blower wheel fan blades, ducts, and cooling coil fins. At the same time, species from *Penicillium chrysogenum*, *Aspergillus* spp., and *Paecilomyces* spp. were found at the cooling coil fins and insulation. The article has shown that mold growth is very common in AHUs, as the right conditions of water activity and substrate can be provided. If the filters are improperly maintained or not changed regularly, they can serve as a microbiological niche. The spores can enter AHUs, either from outdoors or indoors, through the return air system. No clear correlations were drawn between the risk of contamination and the operating conditions of the units.

Poor or a lack of maintenance increases the risk of mold growth inside duct surfaces in HVAC systems. That is because duct cleaning often follows a visual inspection only based on the dust quantity rather than on mold content [44], and the spore aerosolization rate increases with the colony age [45]. Few studies have focused on fungal aerosolization and resuspension inside ventilation ducts. Li [46] studied this phenomenon with *Aspergillus niger* over the elbow and reducer duct with circular and rectangular sections, while Liu et al. [47] studied hydrophobic particles in a straight-duct uniform section.

Aerosolization increases when the spores grow at the center of rectangular ducts rather than at the corners. Similarly, it increases with the reducer's constriction angle and elbow angle [46]. Ventilation and the regular use of air conditioning are critical factors in potentially reduced aerosolization [47]. The resuspension rate increases with particle size [47] and air-flow velocity [47,48], while a slight roughness in ducts' walls decreases this rate. However, humidity and temperature variations do not impact the resuspension rate significantly [47]. Higher mold levels of floor dust were found in rooms with mechanical ventilation systems than in rooms with extractor fans only [49]. However, another large study showed insufficient effectiveness in only using exhaust fans to remedy mold problems [50]. The filtration efficiency of an air-handling unit installed in a low-energy office building was analyzed by Pavard et al. [42], showing that the microbial concentration of fresh air entering the AHU was higher than that in the air extracted from the office. Bakker et al. [51] demonstrated that the low efficiency of the upstream filters of an air conditioning plant determines an increase in bacteria and fungi introduced through aerosolization into the environment.

Previous studies [52] have reported the relationship between indoor humidity levels and ventilation rates, with different associations. Indeed, some indicate that indoor humidity decreases as ventilation rates increase, while others point out the opposite effect. A low air exchange rate could increase the risk of health symptoms [49] with higher prevalence when using mechanical rather than natural ventilation [53]. Furthermore, the actual ventilation rates do not always comply with the minimum demands set by the standards.

Even though mechanical ventilation is supposed to prevent the increase in indoor dampness, incorrect design and sizing can compromise the effectiveness of such systems [34]. Alaidroos and Mosly [54] tackled the issue of maintaining adequate indoor air quality levels in buildings with high mechanical ventilation rates in hot and humid climates. The results demonstrated that increasing the ventilation rate causes an increased risk of mold growth due to the high outdoor humidity levels of the specific climate in which the building is located. Moreover, the ventilation rate is more significant for the mold index than the cooling setpoint temperature. On the other hand, Almatawah et al. [55] evaluated the concentration of airborne microbes (bacteria and fungi) in the external and internal environment for a case study in Kuwait's hot and arid desert climate. The concentration of fungi was very high in summer and winter, demonstrating a very high level of contamination.

In many European countries, the air-tightness standards can be pretty strict [34]. When sufficient ventilation is not ensured due to inadequate air change rates, such dwellings may have increased concentrations of fungal particles and indoor pollutants, decreased indoor air quality, high indoor dampness, condensation on buildings' surfaces, and fungal growth [2,13,34]. Relying solely on mechanical ventilation can also create problems during the construction phase, when the ventilation is not yet operational, or in case of an electric power cut. Finally, the systems often rely on the occupants' behavior to operate as designed, while most systems do not control humidity levels [2].

3.3. Building Regulations

Even though there is definitive proof of the adverse health effects of fungal growth in buildings, indoor mold standards are inconsistent and lack clear and restrictive guidelines [2]. For example, ventilation requirements are dictated by the energy savings and occupants' comfort levels. However, in many cases, these requirements might be contradictory or not weigh the same. Airtightness has increased in high-performance buildings; nevertheless, the standards regarding ventilation rates have not changed compared to traditional buildings [52]. An approach toward humidity control and fungal growth risk is missing [2,52]. Coulburn and Miller [56] conducted an integrative review to investigate the prevalence, risk factors, and impact associated with mold in Australian housing. The authors draw attention to the extent and prevalence of diagnosed mold in buildings constructed following the regulations. The limited focus of regulations and standards related to indoor microbial pollutants like bacteria, viruses, and fungi is probably due to the difficult assessment process for these pollutants [57,58].

Some studies have focused on analyzing the influence of temperature and relative humidity on the concentration levels of pollutants indoors. De Jonge and Laverge [59] performed dynamic modeling of volatile organic compounds (VOCs) using the zero-energy house "E-cube", which is characterized by high air tightness and is equipped with demand-control ventilation. The results highlight the significant influence of temperature and humidity on the internal concentration levels of VOCs, which exceed the permitted levels set by the guidelines. This underlines the importance of adequately designing the mechanical ventilation systems and related control strategies, considering the dynamic behavior of VOCs. Finally, sometimes the standards and regulations are not oriented to avoid the risk of increased humidity, for example, in the case of small- and medium-sized residential high-performance buildings in China [52].

3.4. Energy Savings in Heating and Fuel Poverty

Fuel poverty has a socio-economic aspect related to inadequate heating, the conditions and maintenance level of buildings, as well as financial limitations that may, for example, be connected to the overcrowding of houses. When buildings are over-occupied, indoor relative humidity increases, while the design ventilation rates may become insufficient [8]. On the other hand, inadequate heating can lead to cold surfaces and, consequently, to water condensation and mold development. In many countries, the recommended indoor air temperature has decreased by 1 or 2 degrees due to the energy crisis that started in 2022. Even though this decrease can lead to significant savings in energy consumption, there is a significant risk of mold formation on cold surfaces due to moisture condensation [34].

In the comprehensive, holistic review carried out by Coulburn and Miller [56] for mold-affected housing in Australia, risk factors linked to poor housing conditions, poor-quality rental accommodation, and socioeconomic aspects have been reported by most processed studies. The works reviewed show the association between conditions of poverty and the reporting of indoor mold problems. Households highlight the difficulty of keeping the home warm or cool due to the poor quality of the construction and the need to save on bills. The authors [56] also pointed out the high prevalence of poor-quality housing and indoor mold in socioeconomically disadvantaged groups.

The investigation carried out by Sharpe et al. [60] in the UK found energy poverty to be affecting a third of the survey participants (671 households). Energy-poor behaviors associated with insufficient or no heating due to the high costs increase the risk of mold contamination. Furthermore, the mediation analysis conducted on the collected data showed that fuel-poor occupants might not benefit from energy efficiency measures on buildings due to the residents' ineffective heating and ventilation practices.

4. Suggestions

4.1. Necessary Steps to Avoid Fungal Growth Problems in nZEBs

There is a need for regulations that include assessment procedures (commissioning) [8,61], prevention/mitigation strategies that are planned already at the design process and implemented during the construction phase [2,8,34], and an operation period [2,8]. It is also essential to raise awareness concerning better practices for occupants [2,34,61]. Such regulations must be localized to match the specific context of the building location, climate, construction type, energy usage, and fungal species, among other factors [62].

On the one hand, the literature has shown that the risk for mold growth, visible or not, increases in environments with relative humidity (RH) above 80% [63]. Conversely, significantly lower risk has been found in environments with RH lower than 40% (for example, when working with *C. cladosporioides*) [64], specifically in materials such as hempcrete and straw [63,65,66]. Thus, correct material selection during the construction phase should reduce the risk. Furthermore, this could be achieved with the use of clay or lime plaster by pre-treating the materials with anti-fungal substances [63] or by using non-porous [47] or water- and moisture-protected materials [63,67]. Other materials, such as glass wool, cement blocks, and compressed earth brick, retain less moisture than hemp-based biomaterials [65]. Finally, adding insulation layers could also help reduce the mold index to near zero [68], whereas an insulation thickness of at least 40 mm appeared to be enough to reduce the condensation risk, regardless of the presence of thermal bridges [69].

On the other hand, for indoor environments with high relative humidity (RH), during the operation phase, the literature recommends mitigation measures such as control of the relative humidity fluctuations [70] rather than controlling indoor air temperature fluctuations [64]. The same applies to highly insulated, airtight buildings with reduced air infiltration and hygrothermal buffering, where it becomes necessary to control the fluctuation in indoor RH. That cannot be achieved through the supply of outdoor air by a mechanical ventilation system, and therefore there is need for other humidity-buffering technologies [70], like air dehumidification devices [34]. However, in case of microbial contamination in air-handling units (AHUs) or other areas of the dwelling, it is necessary to clean the affected areas using anti-microbial agents and following the standards and industry recommendations, as well as using high-efficiency particulate air (HEPA) vacuum cleaning, unless the contamination is so extensive that the replacement of the components or materials might be a better practice [43].

Quality assurance and moisture safety commissioning processes are necessary for nZEB renovations, consisting of fixed regulations and inspections of all implemented solutions before, during, and after the completion of construction. During construction, it is crucial to ensure that all materials, structures, and products are protected against moisture and weather conditions. At the same time, all surfaces need to be dry and water-free before being covered [61].

When accounting for all the mitigation measures, an increase in the overall energy consumption of the building could occur, thus increasing the risk of non-compliance with the energy efficiency regulation requirements for nZEBs or Passive Haus. However, supposing that the recommendations to avoid the mold growth risk during the construction phase are followed, the energy efficiency requirements for nZEBs may only be affected by the initial investment costs and the periodical commissioning for indoor environmental quality assurance. The commissioning procedures or assessment methods for mold detection during the building's operation phase are presented hereafter.

4.2. Detection of Mold- and Moisture-Related Problems through Questionnaires

Questionnaires are among the most widespread tools for collecting data on the characteristics of buildings and how the interior spaces are experienced by the occupants, as well as their perception of air quality, comfort levels, and critical conditions [71]. Several authors have experimented with the use of questionnaires to investigate problems related to humidity and mold in homes, highlighting the difficulty of reporting the presence of fungal formations and, consequently, diagnosing the causes. This problem is reported, for example, by Marasinghe et al. [72]. The authors conducted a survey to test the validity of the data reported through self-administered questionnaires regarding the characteristics of the buildings and the presence of dampness. Inspections and measurements in the houses were conducted to verify the correspondence between the reported data and the actual situation. The questionnaires proved to be a useful data collection tool concerning the construction characteristics of the buildings. However, regarding the dampness indicators, less agreement was observed between the information reported by the occupants and that detected by the inspectors. The findings of this research thus highlight the need to use integrative tools, such as digital photos, moisture-sensitive devices, or more detailed information, to increase the validity of the questionnaires used to investigate mold and humidity problems in dwellings.

Wang et al. [73] conducted an extensive questionnaire-based survey campaign (40,279 questionnaires) in eight Chinese cities to investigate the perceived indoor air quality and home environment. The results disclosed a relationship between mold and odors and climatic conditions. In particular, visible mold or damp stains and mold odor are more common in cities of south China, characterized by higher mean ambient temperature. Also, these phenomena are more frequent in old buildings. Moreover, the study highlighted other associated factors for mold and dampness in the home, including pets and pests (rats/mice, cockroaches), low ventilation levels, and inadequate cleaning. A correlation was also found between dampness/mold, allergic rhinitis or asthma in adults, and the perception of odors. An observational assessment tool was developed by Park and Cox-Ganser [74] for evaluating indoor dampness and mold. The tool is based on visual and olfactory inspections and uses a standardized evaluation form supplemented by a questionnaire about the participants' respiratory diseases. Water stains, visible mold, mold odor, and moisture are detected, and their magnitude is scored based on intensity or size. All building components are included in the assessment (walls, ceiling, floor, windows, furniture, ventilation systems, pipes, and materials). The results showed significant associations between the individual exposure index and building-related respiratory symptoms. The proposed dampness and mold assessment sheet can be used for an initial assessment of building moisture and mold presence or following a water damage incident. Nevertheless, indoor microbial assessment cannot rely entirely on questionnaires, as occupants are often unaware of the mold-related problems in their homes, especially when it comes to hidden fungal growth.

Figure 4 shows the questions generally contained in questionnaires aimed at identifying the presence of fungi in indoor environments.

4.3. Detection Methods for Visible and Hidden Fungal Growth

Several detection methods for the assessment of indoor microbial contamination have been studied over the years and are commonly used by inspection companies. These methods can be used during the construction or operation phase to characterize dampness and mold-associated growth in buildings. Such investigations should be held when there are signs or suspicions of microbiological growth or after water damage incidents (e.g., pipe leaks, flooding, water penetration). It is essential to raise awareness and educate occupants, owners, and operational staff about fungal growth risks so that they are qualified to prevent, assess the signs, and remedy indoor fungal growth. These methods could be classified as direct and indirect:

(a) Standardized Direct Methods:

Direct microbial assessment methods comprise various sampling protocols [43], depending on the purpose and source of the sample, combined with a variety of quantitative or qualitative analysis techniques: e.g., culture [44], direct microscopic spore count

(DMSC) [44], β-N-acetyhexosaminidase (NAHA) dosing [44], and qPCR [44]. Even though there are no standardized protocols or generally accepted guidelines to be followed, the research community has been actively working toward this direction.

(b) Indirect Methods:

There are several driving forces to moisture transport, such as capillary pressure, moisture content, vapor density gradient, partial water vapor pressure, relative humidity, and chemical composition, which can be used for assessing hygrothermal dynamics. Selecting the driving forces to find accurate hygrothermal results is a challenging task. However, the pressure inside buildings is assumed to be constant, so the literature suggests that using the vapor pressure difference as a potential guide for isobaric cases can give relatively better results [67].

Among the indirect detection methods are modeling approaches that allow a relationship to be established between relative humidity and mold growth, e.g., the Sedlbauer model [75], the Sautour relationship (considered an improvement to the former) [75], and the VTT model [76]. Other approaches are implementing the temperature factor as an indicator of condensation risk (or mold growth), i.e., ISO 13788 [77], ASHRAE 160-2009 [78]; comparing only the relative humidity of indoor air [79]; comparing barrier temperatures [79], i.e., BS5250; and comparing the air vapor pressures [79]. However, standardized indicators have proven to not consistently provide reliable results in predicting the risk of mold growth [50].

(c) Other Proposed Methods:

Some innovative methods and techniques are under investigation and are intended to attain more consistent and reproducible results. For example, the proposed fungal spore source strength tester (FSSST) can assess the aerosolization potential of fungal spores from contaminated surfaces. It can be effectively used in the field to measure the highest possible level of spore concentration released from a mold source in an indoor environment [80]. Another creative method is the electronic nose (e-nose), developed by Suchorab et al. [81], to detect fungal-contaminated materials and surfaces at an early stage by using MOS-type sensors.

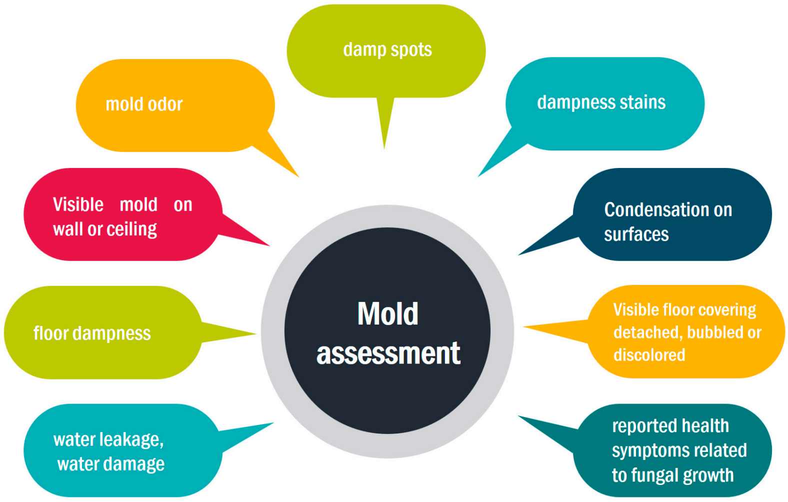

Figure 4. Questions to assess fungal formations in buildings.

4.4. Prediction Models

In evaluating the mold growth risk, the accuracy of the prediction models plays an important role. These models have evolved, improving their reliability and adopting numerous parameters that can contribute to the development of fungi in indoor environments.

A new dynamic mold growth model was developed by Boardman et al. [82], namely the Dose–Response Simple Isopleth for Mold, which can predict the moisture risk in wooden buildings. A mold germination isopleth is calculated based on the critical relative humidity, which depends on the surface temperature and relative humidity conditions. The model's predictions have been compared with field studies, proving its reliability. The model can be effectively used to evaluate the risk of mold starting from temperature and relative humidity data measured in the field or provided by hygrothermal simulations.

Moon and Augenbroe [83] have highlighted the need to construct a practical indicator for predicting mold growth. The authors draw attention to the disparity between the theoretical analysis of mold risk, based on simulations, and the risk in actual conditions, comprising uncontrolled and unconsidered factors intervening with mold formation. Four categories are identified as the causal factors of unpredicted mold growth: spore source, substrate conditions, HVAC maintenance and operation, and local building details. The research proposes a method based on a mold germination graph, considering additional building parameters in idealized situations. These are then used to define a practical performance indicator by introducing the additional causal factors evaluated for each case.

Using reliable and consistent data regarding the hygrometric properties of materials in modeling and simulating vapor transfer through structures makes predictions more robust. The required data can only be obtained through laboratory experiments. With this aim, Olaoye et al. [84] demonstrated how a low-cost hygrothermally controlled test room could be used instead of the more expensive climatic chamber to successfully conduct tests on the hygrometric properties of materials. In particular, a flexible membrane was tested, for which the water vapor resistivity and diffusion properties were determined.

4.5. Smart Technologies to Prevent Fungal Formation

Alternatively, low-consumption, humidity-buffering technologies with sensors have been shown to prevent fungal formation. Regarding ventilation strategies, a ventilation solution that uses an artificial thermal bridge with a dewpoint sensor that is designed to activate the ventilation system when the conditions become critical in risk areas of the inner envelope helps avoid constant ventilation and high energy consumption, along with the risk of mold development [1]. Another ventilation technique based on indoor CO_2 levels combined with a hygrothermal sensor is analyzed in [85], aiming to maintain good environmental conditions with low energy consumption while mitigating the condensation risk [85]. However, the authors in [79] suggest a deflection of wind-driven rain as the most effective strategy for decreasing the risk of mold growth. Other solutions could be the improvement of the water tightness of the envelope and cladding (red matt clay brick cladding walls) ventilation. Advances in sensor technology and smart control systems can help in monitoring indoor air quality and ensuring healthy and comfortable conditions for occupants [86].

5. Discussion

Nearly zero-energy buildings are an effective solution for reducing greenhouse gas emissions and decarbonizing the built environment. Indeed, the advancement in technologies has made it possible to achieve very-high-performance buildings with minimal energy requirements. Energy-efficient buildings are highly insulated and airtight to achieve low energy consumption, which can lead to an augmented moisture level if sufficient ventilation is not ensured. Indoor dampness is the main trigger for the formation of microbial growth. Therefore, indoor spaces can become fertile grounds for the germination of spores, the growth of molds, and the accumulation of pollutants indoors, often without the occupants being aware of the problem.

Most nearly zero-energy buildings are equipped with mechanical ventilation, which can create good indoor environmental conditions by removing humidity and indoor pollutants and preventing outdoor contaminants from entering the building. However, the situation can transform if the mechanical ventilation is not designed or dimensioned correctly, if it malfunctions, is not operated properly, or its designed operation is tempered by the occupants' accidental or intentional interference. Furthermore, if the mechanical ventilation system is not maintained correctly and checked regularly, there is a high risk that fungal growth can initiate inside the ducts and other components of the system.

Another area that requires special attention is the construction techniques and the sensitive building elements. This does not apply only to energy-efficient buildings, but airtight dwellings are more sensitive to trapped moisture than traditional buildings with high infiltration and exfiltration rates. Increased moisture and dampness can originate from errors or faulty installation, materials or other elements with high moisture content, water damage incidents, etc. Special attention must be given to isolated interventions that might not be well designed or thought through, i.e., adding insulation, implementing low-quality interior finishes, replacing windows, etc.

Awareness of the problem is required on all fronts, from designers and construction teams to the building owners, occupants, as well as operating and maintenance staff. Designers are called to perform accurate assessments in the planning phase to devise the most appropriate solutions to ensure healthy internal conditions. Construction workers must have expertise in the field, especially in the installation of systems, which play a crucial role in nZEBs. The occupants must be suitably educated and informed to be able to correctly use zero-energy buildings, without compromising their efficiency and without, on the other hand, generating unhealthy internal conditions. Finally, the operating and maintenance staff must follow a well-structured maintenance plan to detect signs of dampness and fungal growth and know how to assess or remediate fungal contamination incidents, if necessary.

Altogether, the literature underlines the importance of the proper design of mechanical ventilation systems and related control strategies [59]; detailed condensation risk analyses during early design stages [13]; climate-specific design, especially for new construction solutions [13,87]; and the monitoring of hygrothermal conditions in the building envelope for low-energy dwellings to verify whether the moisture safety requirements are met and to predict moisture-related risks during the building's service life [88]. Additionally, planning and periodically reviewing HVAC systems' maintenance and cleaning activities, including all system components, e.g., ducts, filters, blower wheel fan blades, cooling coil fins, air-handling unit water tanks, etc. [2,55]. Finally, system monitoring may be a way to ensure its correct operation.

Greater attention to this problem is also required from legislators and those responsible for drafting the technical standards. There is, in fact, a lack of regulations and guidelines in this area. The current regulations envisage only "indirect" types of control for the formation of fungi in buildings through control parameters such as temperature and relative humidity. However, precise limits of these parameters have yet to be established, with a particular focus on zero-energy buildings. Some regulations provide reference values without, however, specifying when, how, and how often to verify these values, which can constantly vary during the operation phase of the building. Therefore, implementing standards and regulations for the operation phase, focusing on indoor microbial pollutants, is crucial. Adopting a "precautionary approach" is also suggested before future measures on energy efficiency requirements are introduced, as they can increase the risk of surface and interstitial condensation with the consequent formation of mold [56].

Automation and control systems could provide a possible aid for the prevention of mold growth. These, if properly integrated into the building, should be able to decouple the management of the house from occupants' habits. Through an apparatus of sensors and actuators, automation systems or the most recent evolution of intelligent and cognitive systems can act to maintain adequate levels of temperature and internal humidity, as well as detecting the presence of contaminants to intervene promptly.

6. Conclusions

This study aims to raise awareness about the risk of indoor fungal contamination in nearly zero-energy buildings. Indisputably, indoor environmental quality cannot be compromised to decrease the energy consumption, tampering with the occupants' health and well-being. It is the authors' opinion that indoor mold formation and the construction practices for energy-efficient buildings have not been clearly associated, creating a pressing need to address the problem and define prevention strategies. From a theoretical perspective, this analysis presents an overview of the state of the art on the issue and identifies the most recurring risk areas that require focus and further research. The adopted measures must be considered and planned throughout all the stages of the building's lifetime, starting from the design to the construction phase and the operation period, which requires a multidisciplinary and integrated approach. From the practical perspective, this work suggests solutions and measures to help prevent dampness and mold growth incidents, as well as diagnostic techniques and detection methods in case of suspicions or signs of fungal growth.

Based on the results of the study, the following answers can be provided to the research questions:

- A gap in the literature on fungal development in zero-energy buildings has been identified. Even though a few studies have directly addressed the topic, the problem of indoor fungal contamination has not yet received enough focus to spark a generalized reaction from legislative institutes or motivate the industry to take action. There is enough proof that indoor fungal growth can cause or exacerbate adverse health problems for exposed occupants. Still, no organized and widespread efforts to tackle the problem have taken effect.
- The number of specific studies on mold growth in zero-energy buildings is small, so the complete picture of the causes is still unclear. Nevertheless, the literature analysis has revealed some clear risk areas and trigger factors for indoor mold contamination. The conclusions can be summarized into four areas: the building construction and sensitive areas that can result from errors or poorly designed solutions; insufficient or inadequate ventilation due to problematic operation or lack of proper/regular maintenance; lack of regulations and standards to address the problem and impose preventive measures; and occupants' behavior and daily habits, very often due to a lack of knowledge or awareness of correct practices.
- Consequently, to prevent or mitigate the risk of fungal formation in nZEBs it is necessary to adopt a suitable, multidisciplinary approach for the design and construction of energy-efficient buildings, with direct focus on this topic. That would entail a moisture control design and quality assurance practices during the construction phase. During the operation phase, it is essential to ensure that all systems function properly and receive regular inspections and maintenance. Of course, updating or implementing regulations to address the problem, together with informing and educating both professionals and occupants, are necessary steps toward these goals. Finally, using smart, automated control technologies can ensure healthy indoor conditions.

The following lines of future research have been identified:

- Expand the available data on the topic to assess the extent of the problem and provide further proof. This requires performing numerical and simulation analyses to better understand the potential risks and underlying conditions leading to mold formation. Then, a large-scale field study is needed to collect a large amount of data from energy-efficient buildings and evaluate the actual risk and causes.
- Define the necessary steps and activities for training, knowledge, and information dissemination for professionals, operating staff, owners, and occupants. Some critical aspects for preventing dampness- and mold-related problems are proper building and system operation, regular inspections and maintenance, correct occupational practices, etc. In this regard, commissioning and retrofitting processes need to include the aspects of moisture safety. Fungal detection methods need to be standardized, and intervention mechanisms and protocols must be appointed if suspicions of microbial contamination arise.

- Adjust the regulations to include a direct consideration and assessment of fungal growth risks in buildings. Clear guidelines and prevention measures are necessary, adjusted to the special conditions of different climates.
- The design and development of innovative technologies and automated control systems to measure and regulate indoor environmental parameters, including microbial products.
- Further investigation regarding material properties and especially new, biogenic materials that have not been researched enough yet.

This study does have some limitations. Even though the interaction is evident, the occupants' role and behavior need to be more extensively covered, as they play a critical role in mold-related problems in buildings. Therefore, further investigation is required in future studies. Furthermore, the range of detection methods and predictive models presented in the article is not exhaustive, since the purpose of the study is to define the leading causes of fungal growth in nZEBs and suggest possible solutions. For more in-depth knowledge of these tools, please refer to the suggested literature. Additionally, remediation strategies for fungal removal have not been addressed. Such techniques are essential to restore safe and healthy indoor conditions, ensure the conservation of building materials and elements, and interrupt the degradation process after the detection of fungal growth. Some damages could be irreversible if not addressed (for example, stains and detachments of surface finishes or the encrustation and corrosion of the system's pipes). This subject requires specific attention and extensive research to uncover the necessary actions to be implemented.

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Abbreviations

nZEBs	nearly Zero-Energy Buildings
VOCs	Volatile Organic Compounds
HVAC	Heating, Ventilation, and Air Conditioning
IEQ	Indoor Environmental Quality
AHU	Air Handling Unit
RH	Relative Humidity
HEPA	High-Efficiency Particulate Air filter

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