

REVIEW

Modifiable factors governing indoor fungal diversity and risk of asthma

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Summary

Exposure to dampness and fungi in the home is a known risk factor for individuals with allergic asthma. Inadequate heating and ventilation may lead to dampness and concomitant increased exposure to spores of allergenic fungi such as *Aspergillus* and *Penicillium*. These fungi have been cultured from sputum of asthmatic and non-asthmatic individuals, and implicated in the initiation or exacerbation of asthma. Indoor environmental factors influence the presence and concentrations of fungal propagules and, in turn, risk of asthma outcomes. This review aims to identify modifiable risk factors in the built environment that have been shown to influence fungal composition indoors, and to examine this association with the risk of asthma development and/or exacerbation. A complex interaction between residential characteristics, the built environment and the behaviour of people regulate the diversity and concentrations of indoor fungi. Modifiable factors include build age, architectural design, level of maintenance, variations in construction materials, presence of pets, heating and ventilation patterns. Risk of fungal contamination and asthma outcomes are also influenced by low occupant awareness concerning potential health effects and socio-economic factors. Addressing these factors provides an opportunity to improve future housing interventions, though it is not clear how the built environment and occupant behaviours interact to modify the diversity of indoor fungi and resultant risk of asthma. A combination of housing improvements combined with awareness programmes and the alleviation of fuel poverty can be used to lower the allergen burden associated with damp homes. Further research is needed to identify factors that regulate the concentration and diversity of indoor fungi and how this may act as a modifier for asthma outcomes.

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Introduction

The United Kingdom (UK) has one of the highest asthma prevalence rates for paediatrics [1] and adult populations [2] in the world, representing a significant burden to society and health providers. Asthma is a complex disease caused by a combination of genetic and environmental factors, involving gene–environmental interactions [3]. As the prevalence of asthma has increased within one or two generations, genetic factors alone cannot explain the rapid increase in prevalence nor variations between different regions of similar ethnic backgrounds [4]. For this reason, environmental changes are thought to play an important role in the expression of allergic diseases, which has led to an increased focus on exposures resulting from changes to the home environment.

Draft-proofing homes and changing heating practices to achieve greater household energy efficiency can result in poorer indoor air quality (IAQ) [5]. A public health concern is the increased risk of dampness-related problems and fungal contamination caused by inadequate ventilation and low occupant awareness [6] of the potential adverse health effects. Studies have estimated that increased dampness and fungal growth currently affects around 16% of European homes [7]. The risk of dampness may be greater in homes of tenants in the private or public rental sector, particularly those at risk of fuel poverty and living in cold homes. Social housing residents are of concern because their properties generally have higher average household energy efficiency ratings [8], which increases relative humidity (RH) and risk of condensation when combined with inadequate heating and ventilation [9].

Indoor humidity levels are important for health outcomes as it regulates concentrations of chemical agents (e.g. ozone at low RH) and a number of biological contaminants. These include the proliferation of house dust mites (RH > 60%) and increased fungal growth when RH exceeds around 70% [10]. Associated exposures resulting from elevated dampness include increased concentrations of fungal spores, hyphae, allergens, mycotoxins, endotoxins, cell wall β -glucans and volatile organic compounds (VOCs) [11], which poses a significant health risk. Interventions to reduce indoor dampness provide an opportunity to alleviate symptoms by lowering exposures to these contaminants. This review aims to identify modifiable risk factors shown to influence the species composition and concentration of fungi most closely associated with asthma and atopic disease.

Indoor environmental factors

Complex interactions exist between multiple sources of indoor and outdoor contaminants, including physical, chemical and biological agents. These are wide ranging and include particulates (PM_{2.5} and PM₁₀), asbestos, VOCs such as formaldehyde, carbon monoxide, nitrogen dioxide, ozone, polycyclic aromatic hydrocarbons, as well as biological contaminants and radon [12]. Their presence and concentrations depend on a variety of indoor products, activities and outdoor pollution levels. IAQ may be impacted by different construction materials, use of fungicides/biocides, heating and cooking systems, ventilation patterns, motor vehicle pollution, environmental tobacco smoke, household products and geographic location (urban versus rural or coastal regions). The following provides an overview of some interactions between known indoor pollutants associated with increased risk of asthma.

Physical and chemical agents implicated in asthma include combustible products and associated particulates and chemicals. Environmental tobacco smoke is a known respiratory health risk and remains a key source of aerosol exposure to particulates and a mixture of chemical agents in the home [13]. Other combustion pollutants, resulting from cooking and heating generally occur within acceptable guideline concentrations [14] because these systems fall within building regulations [15]. Indoor VOCs are released by a number of products such as new furnishings, cleaning chemicals and the decay of water-damaged building materials. Exposure to VOCs increases the risk of asthma [16] and is shown to enhance bronchial responsiveness to mite allergen in sensitized individuals [17]. VOCs resulting from indoor chemicals and materials generally decay within 2–8 weeks [18], but are constantly replenished as new products are introduced into the home. In moisture

damaged buildings, microbial VOCs (mVOC) produced by fungi are more persistent [19], posing a significant respiratory hazard [20].

Increased exposure to biological pollutants such as house dust mites (HDM), pets, cockroaches, mice, endotoxins and various microbial agents have been associated with the development or exacerbation of allergic asthma. Few studies simultaneously quantify potential exposures to a large number of indoor contaminants, or how these interact to regulate immune system responses and asthma outcomes over time. This is further complicated by the fact that early exposure to some indoor agents have been shown to have opposing health effects [21]. Increased exposure to high concentrations of pet allergens (Fel d 1 and Can f 1), cockroach (Bla g 1), mouse urinary protein and *Alternaria alternata* antigen increases the risk of having asthma by 80% [22] in sensitized individuals. The presence and concentration of biological aeroallergens have been extensively reviewed [23] and shown to be important contributors to sensitization and asthma morbidity.

The indoor environment is a recognized risk factor for respiratory illnesses given the large amount of time UK residents spend in the home. Majority of age groups spend between 70% to 80% of their time indoors [24], which increases in the very young and elderly [25]. Living in damp homes adds an additional health risk and has been independently associated with adverse respiratory symptoms, regardless of atopic status [26]. Increased fungal growth is also a known respiratory hazard and readily occurs in damp homes due to a continuous reservoir of fungal spores from organisms such as *Penicillium*, which can remain viable for up to 5 years [27]. Fungal odour is an indicator of visible or hidden fungal growth that may occur from interstitial condensation for example. Both visible fungi and odour have been shown to be significant risk factors for the development of asthma [28], although it is not clear how seasonal changes or occupant behaviours modify dampness levels, associated pollutants, and asthma outcomes. Arguably, this is because few studies accurately investigate fluctuations of exposures and health outcomes over a sufficient period of time. This means that the exact mechanisms remain unknown, though recent work has suggested that fungal species diversity plays an important role in the development and/or exacerbation of asthma [29].

Indoor dampness and the fungal profile in the home environment

Fungi are eukaryotic, non-chlorophyllous, heterotrophic organisms that depend exclusively on external nutrients for growth and survival [30]. Fungal air spora present in indoor environments depends greatly on the outdoor sporulation of fungi, which is

regulated by the type of fungus and weather patterns [31]. Indoor fungal growth, species diversity and concentration of fungal propagules (hyphae and spores) are significantly modified by variations in relative humidity, ambient temperature, water activity, length of exposure to damp environments [32], lack of sunlight and ventilation [33]. Optimum fungal growth conditions requires high humidity, though many xerophilic species of the genus *Aspergillus* and *Penicillium* have the ability to survive in very dry environments [31]. *Penicillium* and *Aspergillus* species are of particular interest because these have also been shown to be the dominant indoor fungi in damp homes [30], and where propagule concentrations exceed those in their natural outdoor environments [34]. These species have been cultured fungi from sputum samples taken from asthmatic and non-asthmatic individuals, and are associated with an impaired post-bronchodilator FEV₁ [35]. This likely result from their small spore sizes (average 2–3 µm) and prolonged indoor suspension times [30]. Spores are readily inhaled where they can penetrate deep into the bronchioles and induce chronic inflammation of lung tissues caused by allergic reactions of the lower respiratory tract [33]. The associated risk of asthma is influenced by indoor fungal concentrations and species diversity because fungi vary in physiology, ecology and significance for health [36]. Identifying factors that modify fungi associated with an increased risk of asthma provides an opportunity for targeted health interventions.

Few studies have successfully identified a combination of factors that can be reliably targeted to lower the risk of dampness and fungal contamination. Understanding potential risk factors and how they interact is difficult to assess because of the heterogeneity between studies. Many studies rely on property inspections and air/dust sampling, which has a number of limitations. For example, visible inspections may not reliably quantify fungal exposure (i.e. hidden fungal growth), variability in air sampler performance and factors that modify dust collection efficiency, for example, relative humidity and floor coverings [37]. The use of molecular techniques offer an opportunity to more accurately assess potential exposures resulting from the home environment [38]. These need to account for variations in the timing and extent of exposures resulting from seasonal variations, cleaning regimes, use of fungicides or the influence of different sources of moisture and location of fungal damage. The main sources of moisture in domestic buildings include water ingress through poor design, lack of maintenance and condensation. Condensation is caused by the temperature of any surface falling below dew point; this is the temperature at which air becomes saturated with water vapour [9]. Increased condensation occurs from a breadth of occupant activities that increases indoor vapour pressure over and above outdoor ambient levels, which allows moisture to condense when combined with inadequate heating and ventilation. There is a high degree of temporal variation in fungal diversity [39], which means that indoor fungal diversity is modified by the

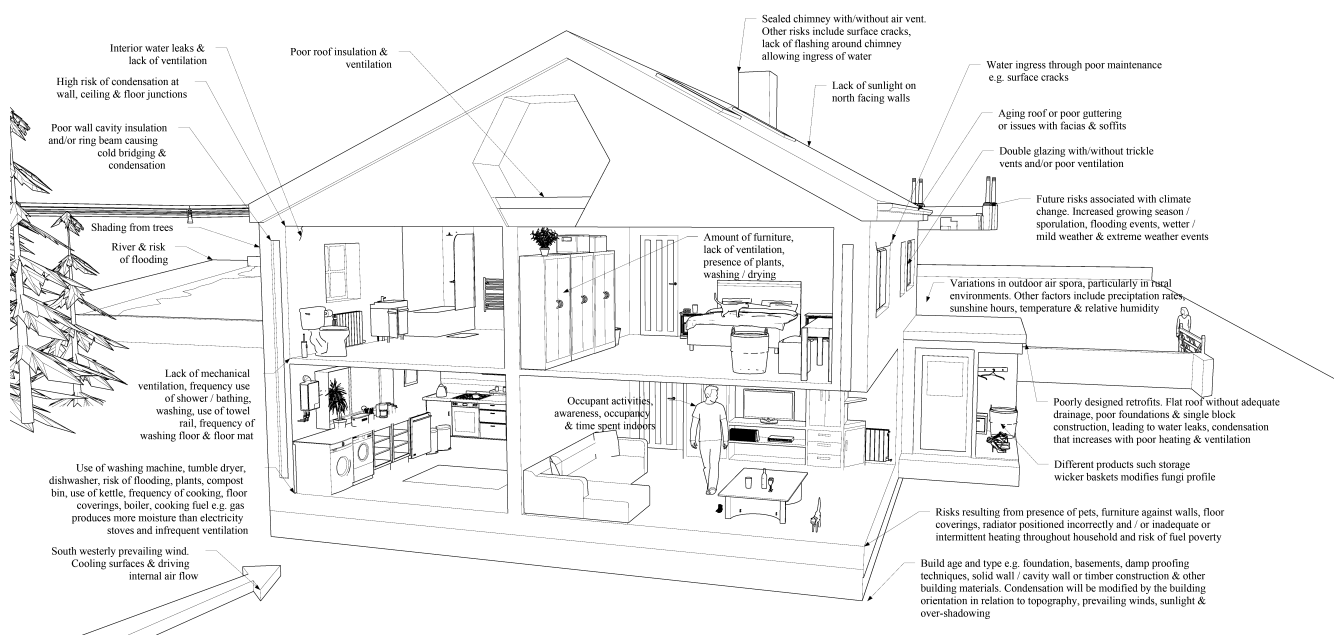


Fig. 1. Risk factors modifying the indoor fungal profile.

season, sporulation rates and ventilation patterns [40]. The resultant indoor fungal profile has been thought to be dependent on the interaction between the built environment and human behaviours (Fig. 1.0). A number of international studies (Table 1) have shown that the indoor fungal profile is influenced by complex interactions between the built environment (Table 2) and indoor human behaviours (Table 3).

The built environment

The UK housing stock is undergoing significant changes to achieve greater energy efficiency to reduce carbon emissions from the housing sector [41]. These changes help to protect against temperature-related illnesses and alleviate the impact of fuel poverty [42]. Well-designed and targeted energy efficiency measures have been shown to improve general and respiratory health, particularly in populations residing in cold homes and those with pre-existing respiratory problems [43]. This shift in housing energy policy is being achieved through retrofitting of existing households with increased airtightness and insulation. These measures generally fall outside of building regulations, that is, they require no structural changes and, consequently, are performed without appropriate scrutiny [41]. There is also little evidence available to quantify how these changes impact IAQ and respiratory health, though adequate ventilation to control IAQ is controlled by Building Regulations Approved Document Part F [44].

Ventilation

To maintain adequate IAQ, the UK building regulations requires a minimum whole dwelling ventilation rate of not < 0.3 L/s per square metre of internal floor area, which corresponds to around 0.5 air changes per hour (ach^{-1}) [45]. Measurements across the European housing stock shows that ventilation is in practice often lower than this recommended rate [6], which increases risk of condensation [9] and promotes microbial contamination [36]. The recommended ventilation rate also fails to account for differences in the required ventilation rates between property types or variations in occupant activities and awareness, which modifies the risk of dampness.

Properties at risk of increased dampness are those being upgraded with energy efficiency measures without the provision of adequate ventilation, which requires mechanical ventilation (MV) systems accompanied by a shift in behavioural patterns. There is insufficient evidence showing how these factors interact and modify the fungal profile. Recent work cannot fully explain the role of ventilation patterns (i.e. infiltration of fungal spores), seasonal variations and the resultant indoor fungal profile. An association has

been shown to exist between seasonality and fungal sporulation patterns, which vary by genus and resultant indoor microbial exposures [40]. The influence of seasonal variations may not be indicative of homes suffering from dampness problems or account for occupant activities. These factors can allow the concentration of some species to exceed levels of outdoor spore loads, which in turn increases the risk to health. Indoor fungal growth can be controlled through the provision of adequate ventilation to control moisture levels and associated increases in chemical and biological contaminants. To be effective, this must be combined with adequate heating to consistently maintain the temperature of the building envelope and avoid risk of condensation [9].

Heating

Recommended ambient indoor temperatures for thermal comfort are between 18 and 21°C [9], although the evidence base for these values is questionable. Ambient temperatures fluctuate over time and regulate the risk of condensation and species diversity because fungi require different temperatures for optimal growth conditions, which generally occurs between 18 and 32°C [30]. This effect may explain why different heating systems have been shown to modify the fungal profile (Table 2), for example central heating in UK homes have been shown to have higher concentrations of *Cladosporium* [34]. There is also likely to be an interaction with different moisture generation and required ventilation rates of a variety of domestic heating systems and boilers, which are set out in 2010 Building Regulations [Part J [15] and F [44]]. This is further complicated by a shift from solid to liquid fuels to achieve greater air tightness (i.e. the trend in sealing up of chimneys), without consideration of variations in the required air exchange rates to maintain adequate IAQ. The extent of this issue, the resultant risk of condensation and changes in fungal diversity remain unknown and requires further investigation.

Build type & age

The physical built environment can be used to predict populations at risk of being exposed to elevated dampness and fungal contamination. Architectural design will have an impact, with flats potentially experiencing lower levels of total air-borne fungi due to higher indoor temperatures and lower transmission rates of fungal spores [46]. This is dependent on the number of residents and ventilation patterns because flats require higher air exchange rates (0.7 ach^{-1}) to control moisture [45]. High-risk properties include older houses or terraced properties (> 90 years old) shown to increase

Table 1. Studies reporting built environment and behavioural risk factors for indoor fungi

Country and year of publication	No. homes	Recruitment	Targeting low SES	Damp %	Fungi %	Identification of housing characteristics identified by trained investigator				Air sampling	Dust sampling	Outdoor sample	Genera level	Species level	PCR analysis	Analysis: odds ratio (95% CI)
USA 2003 [46]	496	Prospective cohort of new born babies in 499 homes	x	34	38	y	y	y	y	y	y	y	y	x	x	y
Australia 1999 [64]	485	European Community Respiratory Health Survey (ECRHS)	x	25	36	y	–	y	y	y	y	x	y	x	x	x
UK 2010 [34]	124	Volunteers from the University of Leicester, University Hospitals of Leicester and associates	x	–	–	y	y	y	x	x	x	y	y	x	x	y
Australia 1998 [61]	80	Volunteers from local schools and doctors surgeries	x	42	–	y	x	y	x	x	x	y	y	x	x	x
USA 2002 [80]	880	Birth cohort in Connecticut and western Massachusetts (1996 and 1998)	x	29	–	y	–	y	x	x	x	x	y	x	x	x
New Zealand 2005 [47]	613	1391 telephone interviews	x	46	35	x	–	x	x	x	x	x	x	x	x	y
USA 2004 [66]	414	The Inner-City Asthma RCT Study	y	46	–	y	y	y	x	x	y	y	y	x	x	y
USA 2001 [68]	1000	Prospective cohort study for the development of asthma in neonates	x	–	–	y	–	y	x	x	x	x	y	y	x	y
USA 2013 [81]	288	Cincinnati Childhood Allergy and Air Pollution Study	x	–	–	y	–	x	y	y	y	x	y	y	y	x
European 2002 [82]	16 687	European Community Respiratory Health Survey (ECRHS)	x	12	22	x	–	x	x	x	x	x	x	x	x	y

Table 2. Built environment factors influencing indoor fungi in the home environment

Exposure	Country of Study	Definition of outcome: fungi	Direction of association
Living in a Flat	UK [34] USA [46]	Total spore concentration, <i>Cladosporium</i> & <i>Didymella</i> spores/m ³ air/day Total indoor airborne fungi CFU/m ³ . <i>Dust</i> CFU/g; <i>Aspergillus versicolor</i> , <i>Aureobasidium</i> , <i>Cladosporium</i> and <i>Penicillium</i>	↓
Living in a house or Terraced property	UK [34]	<i>Aspergillus/Penicillium</i> -type and <i>Tilletiopsis</i> spores/m ³ air/day	↑
Living in older properties built <1980	UK [34] Europe [82] USA [81] New Zealand [47] USA [68]	<i>Tilletiopsis</i> & <i>Aspergillus/Penicillium</i> -type spores/m ³ air/day Reported visible fungi Higher environmental Relative Mouldiness Index (ERMI) of 36 fungi Reported visible fungi Median fungal concentration (≥999 CFU/m ³) versus low (<500 CFU/m ³)	↑ ↓
Property with a basement	Europe [82]	Reported visible fungi	↑
Properties with inadequate insulation	UK [34] New Zealand [47] Australia [61]	<i>Aspergillus/Penicillium</i> -type spores/m ³ air/day Reported visible fungi Viable CFU/m ³ /Total spores/m ³	↑ ↑/–
Foundation type stumps versus slab	Australia [61]	Viable CFU/m ³ Total spores/m ³	–/↑
Carpeting	USA [81] USA [46]	Environmental Relative Mouldiness Index (ERMI) of 36 fungi <i>Dust</i> CFU/g; <i>Aspergillus versicolor</i> , <i>Aureobasidium</i> , <i>Cladosporium</i> and <i>Penicillium</i>	↓ ↑
Homes with central heating or forced air heating	UK [34] Europe [82] USA [66]	<i>Cladosporium</i> spores/m ³ air/day Reported visible fungi Total fungi CFU/m ³	↑ ↓ ↓
Forced air steam/hot water heating	USA [80]	Other fungi (excl. <i>Penicillium</i> and <i>Cladosporium</i>)	↑
Presence of extractor fans	Australia [64]	Total fungi CFU/m ³	↓
Water leaks or poor condition of the property	USA [80] USA [66] Europe [82] New Zealand [47] Australia [61]	<i>Cladosporium</i> Total fungi CFU/m ³ Reported visible fungi Reported visible fungi Viable CFU/m ³ /Total spores/m ³	↑ –/↑
Little sun exposure	New Zealand [47]	Reported visible fungi	↑

concentrations of *Aspergillus* and *Penicillium* species [34]. Housing quality is a function of build age where older properties are more likely to suffer from elevated levels of dampness and fungal contamination, due in turn to a combination of factors. Firstly, older properties need more maintenance to prevent ingress of water [47], and secondly, they are more likely to hold higher moisture levels in the building fabric due to the use of antiquated construction materials and techniques. These too are likely to be influenced by variations in the type of construction, the location of insulation, variations in techniques to prevent water ingress (e.g. the use of damp proof membranes) and advances in building materials.

The use of materials such as gypsum and wall paper, different types of wood products, concrete and other flooring materials promote different groups of fungi when water-damaged. Dominant fungi that favour these materials include fungal genera such as *Aspergillus*, *Penicillium*, *Cladosporium*, *Stachybotrys*, *Ulocladium*, *Aureobasidium* and *Trichoderma* [48], and a number of less frequent contaminants known to produce allergens

[30]. This work is important because it demonstrates that fungal diversity is modified by the use of different construction materials and time of construction, which will be influenced by adoption of UK Building Regulations 1965 and the 1984 Building Act [49]. Further work is required because this study relied on the culturability of fungi on mycological media and used direct microscopy for species identification, techniques that lack accuracy compared to modern DNA sequencing technologies, and which are biased towards more abundant and faster growing species that dominate isolation plates [35]. The development of new building materials resistant to specific groups of fungi implicated in asthma may provide an opportunity to prevent exposures and reduce respiratory symptoms. This requires an in-depth knowledge of the physical built environment, occupant behaviours and how they interact, particularly with respect to potential increases in the indoor chemical load and health risks resulting from the use of treated materials.

The majority of the work to date appears to focus on American architecture (Table 1), which differs to the built

Table 3. Occupant behavioural factors influencing indoor fungi in the home environment

Exposure	Country of Study	Definition of outcome: fungi	Direction of association
Increased occupancy	New Zealand [47]	Reported visible fungi	↑
Increased indoor temperature	USA [66]	<i>Aspergillus</i> , <i>Penicillium</i> and total fungi CFU/m ³	↓
	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↑
Increased indoor relative humidity	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↑
Increased frequency opening windows	Australia [61]	Viable CFU/m ³ and Total spores/m ³	↓
Opening windows at night time	Australia [64]	Total fungi CFU/m ³	↑
Using cooker extractor fan	Europe [82]	Reported visible fungi	↓
Using air conditioner	USA [81]	Environmental Relative Mouldiness Index (ERMI) of 36 fungi	↓
	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	
Use of a dehumidifier	USA [46]	Total dust borne fungi and <i>Cladosporium</i> (CFU/g)	↑
Use of a humidifier	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↓
Solid fuel used within the house in the last 12 months	Australia [64]	Total fungi CFU/m ³	↓
Presence of a dog	USA [46]	Total <i>Cladosporium</i> (CFU/g)	↑
	UK [34]	<i>Didymella</i> & <i>Aspergillus/Penicillium</i> -type spores/m ³ air/day	↓
Presence of a cat	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↑
	UK [34]	<i>Didymella</i> spores/m ³ air/day	↑
	USA [66]	<i>Aspergillus</i> , <i>Penicillium</i> and total fungi CFU/m ³	
	Australia [64]	Total fungi CFU/m ³	
Cockroaches	USA [66]	<i>Aspergillus</i> and total fungi CFU/m ³	
Spiders	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↑
Vacuuming	Australia [64]	Total fungi CFU/m ³	↓
Use of drapes, curtains/blinds	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↓
	Australia [64]	Total fungi CFU/m ³	
Low income	USA [68]	High fungal concentration (≥1000 CFU/m ³) versus low (<500 CFU/m ³)	↑

environment in the UK, due to variations in the regulatory framework, building techniques and climate. The UK has a wide range of build ages and a high proportion of traditional builds that are difficult to retrofit and need to be dealt with holistically [50]. American housing has experienced increasing trends in the use of air conditioning and water leakages from the outside [51]. This is indicative of more open building envelopes and/or properties in poor physical condition. This is evident in inner city US homes that experience higher rates of cockroach, mice and rat infestations [52], which represent significant risk factors for allergic asthma. The UK scenario differs due to recent changes in the housing policy in response to climate change and fuel poverty. This can increase exposures to dampness and associated allergens [53] and result in different health outcomes, although there is little evidence to support this relationship in the UK or demonstrate how it may differ in comparison with other housing stock located in different countries.

Indoor behaviours

Human behaviours significantly modify indoor fungal diversity due to variations in heating and ventilation patterns previously described. This depends on the number

of people living in the home, time spent indoors, the size of properties and lifestyles. Overcrowding is a typical risk factor and a common issue in low SES populations, which is further impacted by fuel poverty [54]. Fuel poverty and low occupant awareness prevents adequate heating throughout the property and, combined with low ventilation rates, increases the risk of condensation. Inadequate heating and ventilation, for example, to reduce fuel bills, causes changes in air pressure, which promotes the migration of warm moist air from warm to colder areas of a property, which allows moisture to condense [9] and fungi to proliferate. Failure to resolve any disparities in SES and to implement behavioural initiatives alongside property improvements may explain some short-term benefits of previous intervention work [55], where dampness has returned to pre-intervention levels within 12 months [56]. This also increases concentrations of fungi such as *Aspergillus fumigatus* [57], which produces a number of allergens and immunomodulatory compounds, and is a known infectious pathogen of immunocompromised individuals [58]. Low-cost interventions with the provision of home educational programmes have been shown to reduce the indoor allergen load [59] and spore concentrations [60], though this requires further research due to the short follow up periods employed.

A balanced indoor environment needs to be accompanied by adequate heating and ventilation in both poorly and well-insulated homes [9]. Dominant fungal species depend on local variations in the microclimate at the surface of different growth substrates [61] and can be controlled by the use of mechanical ventilation that provide higher ventilation rates [62]. Reducing the reliance on ventilation systems by occupants provides an opportunity to improve IAQ, as does enabling or educating occupants to ventilate with the provision of adequate heating. This may include the use of hydrostatic extractor fans, positive displacement pumps and air filtration systems with heat recovery (MVHR), which are expensive to retrofit and may not deliver cost-effective benefits [63]. The simple addition of a correctly powered extractor fan in appropriate rooms (e.g. kitchen, bathroom, laundry area) may have the same effect at a reduced cost.

Fungal incidence is also influenced by plants, dust, carpets, use of wooden materials, furniture [33] and the presence of pets [64]. Presence of pets have been shown to consistently modify the indoor fungal profile (Tables 3) and increases the risk of both the presence and severity of visible fungal contamination in social housing [65]. The number of pets are likely to lead to increased moisture levels and modify fungal diversity because animal hair and dander acts as a transport medium [64] for spores into the home environment. This appears to be primarily driven by the presence of cats (Table 3) that influence concentrations of air-borne *Aspergillus* and *Penicillium* spores, which have also been associated with cockroaches [66] and birds [67]. These associations may result from chance alone, which may explain some inconsistent findings [68]. This illustrates the complex interaction between the built and human environments, highlighting the difficulty in delivering effective housing intervention.

To date, there has been insufficient research conducted in the UK to understand how dampness, resultant fungal contamination and poor health outcomes may be modified by recent changes in the built environment. Future interventions must combine adaptable housing improvements to address variations in architectural design, and effective occupant awareness and behavioural initiatives [69]. Measures also need to be implemented to address socio-economic inequalities that prevent those in fuel poverty benefiting from home improvements [70]. Further research into occupant behaviours may help explain and overcome some of the impacts resulting from socio-economic factors that inhibit the success of some health and housing interventions.

Indoor damp, fungi and risk of asthma

Asthma is a lifelong chronic inflammation disorder of the airways [71] and is influenced by a number of demographic and lifestyle risk factors. These may

include family history, age, sex, BMI, SES, ethnicity and other environmental factors [72] such as diet and exposure to environmental tobacco smoke. It is known that exposure to indoor dampness and fungal contamination increases the risk of asthma outcomes [73], which may be modified by a range of dampness/fungal related problems. The potential health risks associated with indoor fungi depend on the timing and extent of exposure [74] to different fungal species and components (for example, fungal spores and hyphae, cell wall structural components such as β -glucans, allergens and mycotoxins). Exposure to allergenic fungi, particularly members of the phyla Ascomycota and Basidiomycota, increases the risk of asthma in both atopic and non-atopic individuals. *Aspergillus*, *Penicillium*, *Alternaria*, *Cladosporium*, *Helminthosporium*, *Epicoccum* and *Aureobasidium* are thought to affect between 6 and 24% of the general population and 80% of asthmatics [30].

It is difficult to assess the risk of asthma initiation resulting from exposure to increased concentrations of fungal species because the majority of work to date has used inaccurate microscopical techniques for identification, and have employed case-control or cross-sectional studies to investigate relationships. A prospective birth cohort using 'mould-specific' PCR found that *Aspergillus ochraceus*, *Aspergillus unguis* and *Penicillium variable* doubled the risk of the onset of asthma in children aged 7 [75]. While this study provides further insight into the relationship between fungal diversity and asthma, work is needed to further investigate these findings due to the small population sample and recruitment from atopic parents. However, this work indicates that asthma outcomes are influenced by fungal diversities and concentrations found in damp homes and offers a unique opportunity to reduce exposures and ameliorate symptoms, exacerbation and/or disease initiation. Allergy to fungal species often appears as type I immediate, IgE-mediated hypersensitivity [33] (as identified by skin prick tests), making it possible to identify high-risk fungal species indoors to enable targeted intervention. The potential to eradicate fungal species as a public health intervention is limited by the uncertainty between the cause and effect of different fungi such as increased risk associated with *Alternaria alternata* [76], and sensitization to *Aureobasidium pullulans* and *Helminthosporium* [77]. This is further complicated by both the cross-reactivity of species [78] and multiple sources of allergens, making it difficult to reliably target specific groups of fungi.

The adoption of a new range of molecular detection methods to unambiguously identify fungal species associated with asthma is promising and supports this work. The provision of evidence linking damp indoor environments and fungal diversity to adverse health outcomes has practical implications by informing future health

interventions. For example, these could be used to target high-risk populations such as those sensitized to specific fungi that are more likely to suffer from severe asthma [79], households with infants, and other important fungal-related health problems. These may include life threatening infections, allergic bronchopulmonary aspergillosis, aspergilloma (fungus ball), invasive pulmonary aspergillosis, chronic necrotizing aspergillosis and allergic fungal rhinosinusitis [58], not reviewed here. It is also still unclear whether the reduction in total fungal load to improve health outcomes would not have the same effect as targeting specific groups of fungi, due to the complex interactions already described. The work reviewed here supports efforts to reduce the risk of dampness to lower exposures to increased chemical and biological contaminants associated with damp environments. Further research is necessary to identify factors modifying indoor sources of *Aspergillus* and *Penicillium*, which provides an opportunity to improve the health of those living in high-risk properties. This should be considered alongside other fungi associated with asthma initiation or exacerbation.

Conclusion

A complex interaction between multiple built environment and behavioural risk factors regulate indoor fungal concentrations and species diversity in damp homes. Home improvements such as effective energy-efficiency upgrades with the provision of adequate ventilation can be used to lower the total allergen burden in homes. To reduce the risk of dampness and fungal contamination, these measures must be combined with proven awareness initiatives (i.e. those addressing differences in lifestyles and occupant behaviours) and measures to alleviate fuel poverty. The exact relationship between increased exposure to high-risk indoor

fungal species such as *Aspergillus* and *Penicillium* and asthma outcomes remain unknown. Further research is required to identify modifiable factors shown to influence fungal species in the built environment, and in turn how this acts as a modifier for asthma outcomes. Such work can be used to inform future interventions by targeting high-risk fungal species to reduce the risk of disease exacerbation or initiation. An important public health question is whether it is more effective to use costly intervention works to modify the built environment, to use behavioural awareness campaigns, or to use a combination of both.

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Conflict of interest

We declare that none of the authors involved in writing this paper have any conflict of interests with respect to the content of this article.

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