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The Burden of Respiratory Disease from Formaldehyde, Damp and Mould in English Housing

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Abstract: Quantifying the burden of disease from exposure to poor indoor air pollution can support policy development. In England, there is current regulatory and public attention on the health implications of residential exposure to formaldehyde, damp and mould. However, there is scarce information on these health impacts at the population scale. As such, we assessed the burden of key respiratory diseases from residential formaldehyde, damp and/or mould for the English population aged 0–14 and 15–49. We obtained data on the percentage of dwellings affected by damp and/or mould from the English Housing Survey and estimated the distribution of residential formaldehyde concentrations (annual average ($\mu g/m^3$)) by pooling data from monitoring studies conducted in England. Exposures were combined with epidemiological relationships and national health data to estimate Population Attributable Fractions (PAFs), disease incidence, and Disability Adjusted Life Years (DALYs) lost associated with residential formaldehyde or damp and/or mould exposure in England. We made estimates for the year 2019 but also looked back several years in time. Exposure to formaldehyde was associated with approximately 4000 new cases of childhood asthma (~800 DALYs lost) in 2019, though the estimates were sensitive to the placement of the lower exposure threshold. Exposure to damp and/or mould was associated with approximately 5000 new cases of asthma (~2200 DALYs) and approximately 8500 lower respiratory infections (~600 DALYs) among children and adults in 2019, though the PAFs were unequally distributed across dwellings based on income and ethnicity. Alternative data sources suggest that the percentage of dwellings affected by damp and/or mould may even be higher, resulting in a possible 3–8-fold greater number of cases and DALYs. Our assessment emphasizes a potential respiratory health burden in England associated with residential formaldehyde as well as damp and/or mould, further highlighting the public health importance of good indoor air quality and good quality housing.

Keywords: burden of disease; indoor air quality; damp; mould; moisture; formaldehyde; HCHO; England; Europe; inequalities

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1. Introduction

Housing conditions, including poor indoor air quality, can have a significant impact on occupants' health and well-being [1,2], particularly as people spend the majority (~80%) of their time indoors [3,4]. Furthermore, there is robust evidence that exposure to poor air quality, both indoors and outside, can impact health throughout the life course [5–9]. Monitoring and microenvironmental modelling studies have been carried out worldwide to measure or simulate indoor air quality, often at the city scale, and are employed to understand the scale of population exposures [4,10–12]. Furthermore, quantification of the health impacts from exposure within indoor environments, at the population scale, has been performed previously for some key pollutants or sources/conditions affecting air quality: this includes second-hand smoke (SHS), fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2),

radon, damp and mould, carbon monoxide, and volatile organic compounds (including formaldehyde) in some European countries [1,13–17], the USA [18–20], Australia [21], New Zealand [22], and China [16], as well as household air pollution from burning solid fuels globally [23].

Quantification of population health impacts is often expressed as the additional cases of disease or mortalities, given the distribution of the exposure in the population. Alternatively, these attributable health impacts may also be expressed as disease burden, commonly represented by the Disability Adjusted Life Years lost (DALY) metric [24]. Quantification and comparison of the environmental burden of disease is a useful tool for risk communication, can allow for economic evaluations, and support evidence-informed decision- and policy-making.

In England, there is a need to quantify the health impacts of poor indoor air quality, as there are current government-led actions and responses underway, which may lead to emission control and may reduce exposures in residential settings, in particular for formaldehyde, and damp and mould [25–28]. As such, a population-based burden of disease assessment for formaldehyde and damp and mould is timely. Furthermore, quantification of the burden of respiratory diseases is particularly important in England, given their prevalence and cost to the economy [29–32].

1.1. Formaldehyde

Formaldehyde is a volatile organic compound (VOC), common in many indoor environments because of emissions from household and consumer products (e.g., cleaning products, air fresheners, and cosmetics), activities that involve combustion (e.g., cooking, tobacco smoking, wood burning, candles), off-gassing of building and construction materials, furniture, wallpapers, textiles and carpets, plywood panelling and fibreboard, as well as indoor chemical reactions [33,34]. It was one of the first compounds recognised as a possible hazard in indoor air and is considered to be one of the most abundant chemicals in indoor environments, such as homes and schools [34–37]. The varied sources of formaldehyde can result in both short, as well as long-term exposures, which led Public Health England (now the UK Health Security Agency) to adopt the World Health Organisation (WHO) short-term exposure guideline value (100 $\mu g/m^3$ 30-min average) and propose a long-term exposure (10 $\mu g/m^3$ annual average) health-based guideline value [38]. Acute exposures to formaldehyde are associated with irritation of the eyes, nose, throat, skin and respiratory tract [39,40]. Furthermore, based on epidemiological and toxicological evidence, the International Agency for Research on Cancer (IARC) has classified formaldehyde as carcinogenic [41]. The links between chronic formaldehyde exposures and cancers, such as leukaemia, lung cancer, Hodgkin's lymphoma, sinonasal cancer, and nasopharyngeal cancer, have been investigated, though the evidence is almost exclusively from occupational cohort studies in industrial settings [42–45] where levels of exposure, and mixtures with other pollutants, are greater than residential settings. Several recent reviews and meta-analyses of epidemiological studies have shown combined positive associations between formaldehyde exposures and asthma (diagnosis/self-report and exacerbation) within residential and school environments [20,42,46,47], which have been used to quantify the health burden (or conduct health impact assessments) of childhood asthma in some countries in Europe, the USA, and China [1,14,16,17,20]. Some epidemiological studies conducted in residential or school settings have also shown positive associations with rhinitis, dermatitis, and conjunctivitis [42], though combined associations were not statistically significant in a recent meta-analysis [42].

At the time of writing this paper, the US Environmental Protection Agency (EPA) is undertaking an updated toxicological review of formaldehyde [48], and the European Chemicals Agency (ECHA) [49], as well as the Health and Safety Executive (HSE) in Great Britain [28] are investigating options for possible restriction of emissions. In Europe, there are various labelling schemes published by authorities, such as the French Agency for Food, Environmental and Occupational Health & Safety (Anses; formerly AFSSET) and the

Committee for health-related evaluation of building products (AgBB) in Germany, aiming to reduce emissions of chemicals, including formaldehyde in indoor air. Furthermore, the concept of the 'Lowest Concentration of Interest' (LCI) has been developed to evaluate emissions from a single construction product after 28 days using a laboratory test chamber procedure. EU-LCI values [50] were derived based on epidemiological and toxicological data from risk assessments published by national and international committees or in peer-reviewed scientific literature. Since 2015, the AgBB has adopted the EU-LCI values and their derivation procedure to harmonise the health-based evaluation of emissions from construction products in the Europe [51].

1.2. Damp and Mould

Dampness refers to materials, structures and furnishings that contain or have absorbed excessive moisture (see Section 2.3.2 for a more detailed definition). It should not be confused with humidity, which is water vapour suspended in the air. Dampness can occur through poor building design, structural deficiencies, and/or poor insulation (e.g., lower thermal performance of the dwelling's envelope), allowing moisture to enter buildings [52,53]. Dampness can also occur from poor mechanical or natural ventilation, where indoor humidity generated through normal occupant activities (e.g., cooking, washing, or drying clothes indoors) is allowed to build up, causing condensation [29,54–56]. Furthermore, high humidity can occur from dampness in the home. Although they are not the same, they are inherently linked. In addition, dampness and/or high humidity can contribute to mould growth when indoor temperatures are warm enough for growth to occur [57,58], as well as support increased dust-mite concentrations and growth of some bacteria [53,59,60]. Dampness and humidity may also contribute to increased VOC concentrations within the home [29,60], such as formaldehyde [61,62].

The UK, including England, has one of the oldest building stocks in Europe, with the highest proportion of homes dating back to before the second world war [63]. Older homes are typically characterised as having poorer energy efficiency and insulation [63], which can lead to heat loss and condensation [64]. While data from the English Housing Survey indicates that around 3–4% of homes have damp and/or mould in England (2017–2021) [64,65], self-reported information from the Energy Follow Up Survey indicates that damp and/or mould may be present in as many as 1 in 4 homes [66]. Furthermore, lower-income communities and households are more likely to be exposed to indoor dampness and/or mould due to potential overcrowding (that makes ventilation and air movement more difficult), fuel poverty (that leads to irregular heating in colder months), and a lack of proper ventilation and insulation [29,67,68]. New airtight, energy-efficient homes may also be at risk of increased levels of moisture unless appropriate ventilation measures are implemented and can extract moisture-laden air [29,69].

Mould, fungi, and bacterial growth can release spores, cells, fragments, and microbial volatile organic compounds (VOCs) into indoor air [68] and are associated with adverse health effects when inhaled [53]. Exposure to microbial contaminants, including indoor mould, is clinically linked to respiratory symptoms and infections, allergies, and asthma [68], and the epidemiological evidence has shown consistent positive associations between the presence of damp and/or mould in residences (from surveys/self-reports) with respiratory conditions, such as asthma (diagnosis/self-report and exacerbation), respiratory infections, rhinitis, and symptoms, such as cough and wheeze [1,29,53,70–75]. Furthermore, there is also some evidence that damp and/or mould may be associated with non-respiratory problems, such as throat, eye and skin irritations and infections, nausea, fever, tiredness and mental health problems [29]. Severe and prolonged mould exposure can also be fatal. In England, following an inquest, a coroner ruled that the tragic death of a 2-year-old boy in 2020 from acute airway oedema with severe granulomatous tracheobronchitis was due to prolonged environmental mould exposure in his home [25]. The subsequent Regulation 28 Report for the purpose of preventing future deaths led to a series of committed actions from UK government departments (DLUHC; DHSC) [25].

1.3. Study Aim

To aid national and local decision-making, we used epidemiological approaches to quantify and compare the burden of key respiratory diseases associated with residential exposure to formaldehyde, as well as damp and/or mould for the English population. By combining data on population exposures, epidemiological exposure–response relationships, and national health data, we aimed to estimate the attributable cases and burden in the population for the year 2019 (the most recent year where both exposure and health data could be obtained), as well as by looking back several years in time.

2. Materials & Methods

2.1. Overview of Estimation Approach

We used established epidemiological approaches to estimate the additional cases and burden of respiratory diseases from formaldehyde and damp and/or mould in English residences [24]. To do this, we used Population Attributable Fraction (PAF) approaches, which require information on population exposure distributions, epidemiological exposure–response functions (ERF), and national health data to estimate the attributable additional cases and burden of disease at the population scale (See Section 2.6 for details). These estimates should be interpreted as potential impacts at a population level (and not at the individual level), as the underlying epidemiological relationships are derived from a distribution of individual responses.

In addition to estimating the additional yearly cases of disease, we also used a comparative metric called Disability Adjusted Life Years lost (DALYs) to characterise the burden of disease in the population associated with the exposures [76]. The DALY is a standardised metric that provide a time-based measure of the years of life lived in a reduced health state (Years of Life Lived with Disability (YLD)) [77], as well as the decline in life expectancy due to death (Years of Life Lost (YLL)) from developing the disease/health condition. Both the morbidity and mortality components are estimated at a population level and then summed to form the total DALYs lost in a population. One DALY represents the loss of the equivalent of one year of full health.

2.2. Study Population

Based on the availability of data sources and epidemiological evidence (see Sections 2.5 and 2.6), we calculated estimates for the population who are normally resident in England, aged 0–14 (infants and children; population ~10 million) with respect to formaldehyde and damp and/or mould, and 15–49 (older adolescents and adults; population ~25 million) with respect to damp and/or mould [78]. Our target year of quantification was 2019, as it was the most recent year in which we obtained both exposure and health data that were not impacted by the COVID pandemic (e.g., 2020, 2021). We also calculated estimates for periods back in time, including 1998 for formaldehyde and 2014 and 2009 for damp and/or mould.

2.3. Exposures

2.3.1. Formaldehyde

Our aim was to derive a distribution of annual average indoor formaldehyde concentrations that were representative of concentrations found within the English housing stock. As this information was not readily available, we estimated a nationally representative distribution by pooling data from published monitoring studies identified through a systematic literature search (as detailed in Supplementary Materials S1 & Table S1). In total, we identified 11 studies published between 1996 and 2022 providing either raw or summarised monitoring data on indoor formaldehyde concentrations in English dwellings [35,36,79–87]. These studies were conducted in a variety of geographical regions, seasons, cities, and towns and included existing buildings, as well as new builds (those built after 2010) (Study characteristics are detailed in Supplementary Materials S1 & Table S2). In total, a sample of 1700 dwellings were monitored across the studies. Some studies additionally reported

measurements in both heating and non-heating seasons [35,79,80,85]. We pooled data from individual studies published between 2000 and 2022 to estimate a national distribution [36,79–87]. While the studies were conducted at various points in time, we assumed they were representative of the exposure situation in 2019 (target year of analysis, see Section 1.3). When the raw data were not available for a study (n = 4 studies), we first estimated (e.g., simulated) a data distribution by randomly sampling data points that were parameterised by the given summary statistics in each paper (e.g., means, medians, ranges, assuming a lognormal distribution). The contribution of each study to the national distribution was weighted by the corresponding study's sample size (n number of dwellings). The national distribution that we estimated had a total number of data points equal to the number of dwellings monitored across the studies, with a few exceptions where we down-weighted the contribution of a few studies. Details on these methods are in Supplementary Materials S1.

To assess potential changes over time in the burden of disease associated with residential formaldehyde concentrations, we used the information provided by the study by Raw et al. (2004) (dwellings monitored 1997–1999) and additionally Brown et al. (1996) (Chapter in [35]) (dwellings monitored 1991–1993) as the basis for an exposure distribution that we assigned to represent the time period around 1998.

Following the above procedures, we trimmed the datasets representing the national distributions to remove outliers. This was performed because the monitoring duration across studies ranged from 24 h to 7 days in each dwelling, and while we assumed that these measurements represented annual averages, short-term monitoring may have over- or under-estimated concentrations if they captured non-typical day/air pollution events. Thus, we trimmed off the top 1% of data points, which set the new maximum of the distribution to 100 $\mu g/m^3$, and rounded concentrations <1 to 1 $\mu g/m^3$. We then calculated the proportion of data points falling within each 1 $\mu g/m^3$ band between 1–100 $\mu g/m^3$ and made the assumption that this was representative of the exposed population in England on average annually (Figure 1).

Our estimated concentration distributions were lognormally distributed and had geometric means of 22.8 $\mu g/m^3$ (2019, main) and 21.7 $\mu g/m^3$ (1998). These estimated distributions are very much in line with what has been previously proposed as a typical range within European dwellings under typical residential conditions (20–30 $\mu g/m^3$) [33].

As described in Section 2.6, we calculated formaldehyde burden of disease estimates for children aged 0–14. We recognise that children do not spend their entire day at home, with a large proportion of their day-time spent in nursery or school. However, previous studies have shown that formaldehyde concentrations in nurseries and schools in Europe might be comparable, though perhaps slightly lower, to those in homes. For example, a study across 19 nursery schools in London found that the 3-month mean indoor formaldehyde concentrations ranged from 4 $\mu g/m^3$ to 25 $\mu g/m^3$ (mean 10 $\mu g/m^3$) [88]. Another study in six French cities found that formaldehyde concentrations (measured over the school week) in a large sample of classrooms ranged from 12 to 56 $\mu g/m^3$ (median: 26 $\mu g/m^3$) [89]. Additionally, the large-scale SINPHONIE study, which monitored indoor air quality (IAQ) in 115 schools in 23 European countries continuously for 5 days, recorded formaldehyde concentrations with a mean of 14.50 $\mu g/m^3$ and high of 50.3 $\mu g/m^3$ at the upper 99th percentile [90].

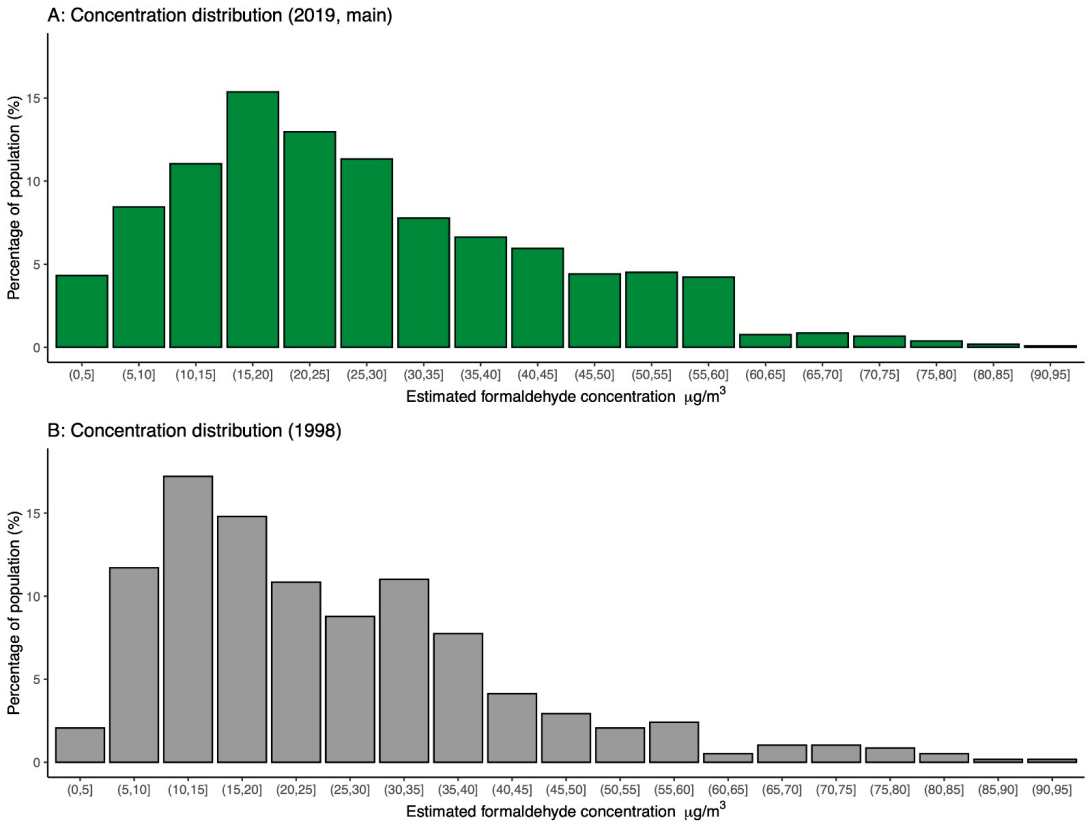

Figure 1. The estimated distribution of the percentage of the population in England exposed to annual average residential formaldehyde concentrations ($\mu g/m^3$) in 2019 (plot (**A**)) and 1998 (plot (**B**)).

2.3.2. Damp and Mould

We defined the prevalence of damp and mould in the English housing stock from the statistics provided by the English Housing Survey (EHS) [64]. The EHS is a continuous annual national survey commissioned by the Department for Levelling Up, Housing and Communities (DLUHC), which collects information on housing circumstances and conditions among a representative random sample of homes [91]. Within the EHS guidance, it is stated that a home is considered to have a problem with damp if the surveyor records damp that is significant enough to be taken into consideration when making their assessment. Therefore, according to the EHS, 'minor issues of damp are not recorded' [65]. The EHS includes data on three categories of damp and mould [92] (definitions as written in the EHS):

- **Rising damp:** where the surveyor has noted the presence of rising damp in at least one of the rooms surveyed during the physical survey. Rising damp occurs when water from the ground rises up into the walls or floors because damp-proof courses in walls or damp-proof membranes in floors are either not present or faulty.
- **Penetrating damp:** where the surveyor has noted the presence of penetrating damp in at least one of the rooms surveyed during the physical survey. Penetrating damp is caused by leaks from faulty components of the external fabric, e.g., roof covering, gutters etc. or leaks from internal plumbing, e.g., water pipes, radiators etc.
- **Condensation or mould:** caused by water vapour generated by activities like cooking and bathing condensing on cold surfaces like windows and walls. Virtually all dwellings have some level of condensation. Only serious levels of condensation or mould are considered in the EHS, namely where there are extensive patches of mould growth on walls and ceilings and/or mildew on soft furnishings.

While penetrating damp and traumatic damp are not distinguished as separate categories in the EHS, we acknowledge that these categories have more recently been distinguished in the literature as 'Penetrating Damp', which gets into buildings via gaps and cracks in the roof and walls, or via blockages or leaks in guttering and pipes, and cracked rendering; and 'Traumatic Damp' which is caused from leaking water, waste, and heating pipes, inside the building. This could also be from another property [74,93].

In addition to the above categories, the EHS provides statistics (% of dwellings) on 'any damp', which is the presence of one or more of the aforementioned categories. We use 'any damp' (which we call 'damp and/or mould') as our primary descriptor as it aligns most closely with what is most commonly assessed in epidemiological studies (see Section 2.4).

We chose 2019 as our main year of analysis as it was the most recent year in which data were not impacted by the COVID-19 pandemic and lockdowns. From 2020–2022, the EHS modelled, as opposed to measured, the prevalence of damp and/or mould in homes [65]. Furthermore, we extracted statistics for the years 2014 and 2009 to assess changes 5 and 10 years back in time from 2019.

The EHS provides statistics for all dwellings, as well as sub-categories defined by housing characteristics, tenure, and occupant sociodemographic information. To assign exposures to the adult age category (15–49 years old), we used the percentages calculated across all dwellings in the EHS, assuming that all, if not almost all, dwellings have at least one adult occupant. To assign exposures to the younger age category (0–14 years old), we assigned the percentages that were estimated for dwellings where the age of the youngest person in the household was under 16 years (see Supplementary Materials S2). For the purposes of our analysis, we also assumed that the proportion of dwellings exposed was equal to the proportion of the population exposed.

There are other sources of information that report additional estimates [29] to the EHS statistics. The 2017 Energy Follow Up Survey (EFUS) [66], which surveyed a sample of respondents (n = 1340) from the English Housing Survey in 2018 on damp and mould, reported that 27% of dwellings (self-reported) had the presence of 'some damp and/or mould patches on the walls or ceilings of their home'. Furthermore, households with children present (39%) compared with no dependent children present (23%) and households in the lowest income quintile (41%) compared to those in the highest two income quintiles (ranging from 16% to 23%) were more likely to report damp and/or mould problems. Furthermore, 14% of Western Europeans were estimated to live in dwellings with damp and mould as reported in the 2022 Health Homes Barometer Report (based on research by RAND) [94]. As such, to capture and communicate the uncertainty in the prevalence of damp and/or mould in our analysis, we, therefore, made additional estimates using these supplementary data.

2.4. Epidemiological Relationships

We considered epidemiological studies and their corresponding risk estimates (relative risk ratios (RR), odds ratios (OR) etc.) to be suitable for our analysis based on the following criteria:

- **Study design**: Meta-analysis; large/pooled prospective cohort studies
- **Age group**: Any
- **Geography**: Any
- **Exposure assessment**:
    - **Formaldehyde**: Residential formaldehyde (airborne), although we did consider meta-analyses that pooled studies from residential and school settings for children
    - **Damp and mould**: Residential damp and/or mould assessed via a survey (inspector/surveyor or occupant self-report)
- **Effect estimate**: Statistically significant and adjusted for confounders

Our selection criteria were aimed at identifying studies of pollutant-outcome pairs for which there was sufficient evidence of a consistent and unbiased statistical association.

Following an initial scan of review papers, large synthesis reports, and previous burden of disease or health impact assessments [1,14,16,17,39,42,43,74,95], we systematically searched the epidemiological literature for studies investigating the relationship between residential (a) formaldehyde concentrations/exposures as well as (b) damp and/or mould with the following respiratory diseases, illnesses, and/or symptoms: asthma, respiratory infections, rhinitis, cough, and wheeze (details of the literature search are in the Supplementary Materials S3 & Table S5 and S4 & Table S6). The epidemiology literature includes studies that assessed exposure via indoor concentrations (or presence indoors), as well as personal exposures. However, for consistency, we use the terminology *exposure–response function* (ERF) to describe these relationships.

If multiple studies (meta-analyses or large/pooled and prospective cohort studies) were identified for the same health outcome-exposure pair, we considered the study design(s) (prioritising evidence from prospective cohort studies or meta-analyses of prospective cohorts) and prioritised studies which provided the most up-to-date body of evidence. As shown in Table 1, we selected ERFs for asthma (diagnosis/self-report) associated with formaldehyde and damp and/or mould [20,42,73,96], lower respiratory infections (LRI) associated with damp and mould [70], and as secondary outcomes—allergic rhinitis and bronchitis associated with damp and/or mould [70,72,96] (additional details on study selection is in the Supplementary Materials S3 and S4). Note that the OR with the closest outcome definition to LRI was found in Fisk et al. [70] and defined as 'Respiratory infections excluding common cold and nonspecific upper respiratory infections'. We assumed that this OR could apply to LRIs as the outcome definition is largely made up of sub-types of LRI's and the risk estimate was similar to Bronchitis (OR: 1.45 [95% CI 1.32–1.59]), which is a sub-type of LRI [70].

Table 1. Epidemiological exposure–response functions (ERFs).

Exposure	Health Outcome	Source	Type of Study	Number of Studies/ Cohorts	ERF (e.g., RR, OR) [95% CI]	ERF Lower	ERF Upper	Ages (yrs)
Main (primary) estimates								
Formaldehyde (μg/m^3)	Asthma	Liu et al., 2023 [42]	Meta-analysis	22	1.20 [1.11–1.31] per 10 μg/m^3 *Meta-analysis by Lam et al., 2021* [20] *(n = 9 studies) produced the same central effect estimate*	50 μg/m^3 * (primary) 20 μg/m^3 (sensitivity); 60 μg/m^3 (sensitivity)	100 μg/m^3 **	0–14
Damp and/or mould (% of dwellings)	Asthma	Quansah et al., 2012 [73]	Meta-analysis	16	1.50 [1.25–1.80]	-	-	0–14
Damp and/or mould (% of dwellings)	Asthma	Wang et al., 2019 [96]	Longitudinal cohort study	Large cohort pooling data across 5 Scandinavian countries	1.43 [1.12–1.83]	-	-	15–49
Damp and/or mould (% of dwellings)	LRI ***	Fisk et al., 2010 [70]	Meta-analysis	15	1.50 [1.32–1.70] *Respiratory infections excluding common cold and nonspecific upper respiratory infections* ***	-	-	0–14 15–49

Table 1. *Cont.*

Exposure	Health Outcome	Source	Type of Study	Number of Studies/ Cohorts	ERF (e.g., RR, OR) [95% CI]	ERF Lower	ERF Upper	Ages (yrs)
Secondary estimates								
Damp and/or mould (% of dwellings)	Allergic Rhinitis	Jaakkola et al., 2013 [72] ****	Meta-analysis	19 *****	1.43 [1.34–1.53]	-	-	0–14
Damp and/or mould (% of dwellings)	Allergic Rhinitis	Wang et al., 2019 [96]	Longitudinal cohort study	Large cohort pooling data across 5 Scandinavian countries	1.28 [1.08–1.52]	-	-	15-49
Damp and/or mould (% of dwellings)	Bronchitis	Fisk et al., 2010 [70]	Meta-analysis	13	1.45 [1.32–1.59] *Acute or chronic bronchitis*	-	-	0–14 15–49

ERF: Exposure–response function; LRI: Lower respiratory infection; OR: Odds ratio; RR: Relative risk ratio; 95% CI: 95% confidence interval. * Due to the uncertainty of threshold effects, we determined a range of lower thresholds (i.e., counterfactuals) for the ERF, above which elevated risks are assumed to occur (See Supplementary Materials S5 for details). For the sensitivity analysis, at the lower end, we set a threshold at 20 $\mu g/m^3$ and at the higher end at 60 $\mu g/m^3$. We chose a central counterfactual level to sit at 50 $\mu g/m^3$ for our primary estimate. ** Upper end of the exposure distribution in the burden of disease analysis (See Section 2.3.1). Note that the maximum exposure level recorded in the meta-analysis was 214 $\mu g/m^3$ [42]. *** The estimated OR with the closest outcome definition to LRI in [70] was '*Respiratory infections excluding common cold and nonspecific upper respiratory infections*'. We assumed that this OR could apply to LRIs as the outcome definition is largely made up of sub-types of LRI's and the risk estimate was similar to Bronchitis (OR: 1.45 [95% CI 1.32–1.59]), which is a sub-type of LRI [70]. **** Multiple ORs were given for allergic rhinitis. We used the OR that was stratified by age for children up to 16 years (Table E8 in [72]) as the majority of studies included in the meta-analysis were for children. ***** 19 is the total number of studies meta-analysed in [72] for allergic rhinitis. However, the exact number corresponding to the subset among children was not specified.

2.5. Health Data

We obtained data on annual incidence and DALYs lost for asthma and LRIs in England for the corresponding years of exposure from the Global Burden of Disease (GBD) project [97,98]. In addition to other age categories, the GBD data are provided for infants and children (aged 0–14) and older adolescents and adults (15–49). We extracted and used both the central estimates of the total numbers and rates per 100,000 people, as well as the 95% confidence intervals around the central estimates for each year that we had exposure data.

2.6. Attributable Burden of Disease Calculations and Analyses

We combined the exposure distributions with the epidemiological ERFs in Equation (1) (damp and/or mould) and (2) (formaldehyde) to calculate PAFs for each pollutant-health outcome pair. PAFs are defined as the proportion of the incidence of disease in the population, that is due to the exposure distribution within the population and represents the proportional reduction in disease or death that would occur if exposure to the risk factor were reduced to zero or some other counterfactual level [99,100].

$$(\text{damp and/or mould}).\ \text{PAF} = \frac{p \times (RR - 1)}{p \times (RR - 1) + 1} \quad (1)$$

$$(\text{formaldehyde}).\ \text{PAF} = \frac{\sum_{i=1}^{n} p_i \times (RR_i - 1)}{\sum_{i=1}^{n} p_i \times (RR_i - 1) + 1} \quad (2)$$

In Equation (1) (damp and/or mould), p represents the proportion of the population exposed to residential damp and/or mould, and RR is the relative risk ratio increase in the health outcome given exposure compared with no exposure. We used Equation (2) for formaldehyde, as we had a full exposure distribution represented on a continuous scale and corresponding risk estimates. In Equation (2) (formaldehyde), i represents the formaldehyde concentration level in 1 $\mu g/m^3$ increments; n is the total number of concentration level increments within the defined valid range for the PAF calculation; p_i

represents the proportion of the population exposed to concentration level i; and RR_i is the relative risk increase in the health outcome at concentration level i.

When ORs were given, we assumed them equivalent to RRs for inclusion in the PAF calculation as initial risks (<10%), and the odds ratios themselves were small across the included health outcomes [101,102]. Furthermore, the risk estimate for formaldehyde exposure and asthma was given in a 10 $\mu g/m^3$ increment increase, which we rescaled to 1 $\mu g/m^3$ assuming a linear relationship, as has been performed previously [14,17]. For this continuous exposure, we set the lower ERF threshold (counterfactual level) at 50 $\mu g/m^3$. Lower ERF thresholds are set to reflect threshold effects (if such a threshold exists and is known) and/or a reluctance to extrapolate relationships beyond the range of available data [103]. However, due to the uncertainty in determining a lower ERR threshold for formaldehyde and asthma, we also chose a lower (20 $\mu g/m^3$) and upper range (60 $\mu g/m^3$) for which we made sensitivity estimates. These were based on several studies and meta-analyses showing positive associations between formaldehyde exposures and asthma development (or markers of symptoms) observed above 20 $\mu g/m^3$, and particularly above 50 and 60 $\mu g/m^3$ (further details on setting PAF exposure thresholds are presented in the Supplementary Materials S5 & Table S7) [20,46,47,104–106].

To estimate the incidence of disease associated with exposure in the population, we multiplied the PAFs by the corresponding central disease incidence estimates in the population (see Section 2.5). Furthermore, we quantified attributable DALYs by multiplying the PAFs by the corresponding central DALY estimates for that disease. The 95% confidence intervals (CIs) that are presented around these central estimates were derived by combining the uncertainty (95% CIs) reported for the ERFs and the health data (incidence; DALYs).

We selected two age groups for quantification, 0–14 (infants and children) and 15–49 (older adolescents and adults). For simplicity, we herein refer to them as children and adults. As the age groupings within our exposure, epidemiological, and health data were not always strictly aligned, these groupings reflect the best combination of what was available across these varied data sources (e.g., exposure datasets, disease incidence and DALYs), as well as what was available from epidemiological studies. Furthermore, we did not make estimates for older adults (>50 years old) as the epidemiological evidence was not as abundant among this age group, and the accuracy of the evidence for asthma among older adults could be compromised by the misclassification between asthma and chronic obstructive pulmonary disease [107,108].

We calculated primary estimates for the PAFs, disease incidence, and DALYs lost for asthma associated with formaldehyde (0–14 yrs) or damp and/or mould (0–14; 15–49 yrs), as well as lower respiratory infections (LRI) associated with damp and/or mould (0–14; 15–49 yrs). We calculated estimates for the year 2019 (main year), as well as 1998 for formaldehyde exposures, and five (2014) and ten (2009) years back in time for damp and/or mould exposures prior to 2019.

As secondary estimates, we also calculated PAFs for bronchitis and allergic rhinitis associated with damp and/or mould (as detailed in Supplementary Materials S6). Bronchitis is a sub-type of LRI, and so this was included as a secondary estimate so as not to double count cases. Furthermore, the GBD project (see Section 2.5) currently does not provide incidence or DALY estimates for bronchitis or allergic rhinitis, and we were also not able to identify comparable estimates from other informational sources.

Calculations and visualisations were conducted in the open-source statistical computing language and environment R (Version 4.2.1) and Microsoft Excel (Version 2208 (Build 15601.20660)).

3. Results

3.1. Formaldehyde Burden of Disease

Formaldehyde concentrations in English residences were associated with contributing to 2.5% of asthma cases among children in England, resulting in approximately 800 DALYs lost among this age group in 2019 (Table 2). The estimates were also highly sensitive to

the choice of the lower exposure threshold of effect applied in the PAF calculation (see footnote to Table 2). We also estimated a higher number of new cases and DALYs lost in 1998 (new cases: 6100; DALYs: 1300) compared with 2019. This was due to a combination of the fact that a larger proportion of the population was estimated to live in dwellings with formaldehyde concentrations at the higher end of the 1998 distribution (60–100 μg/m^3: 4.8% in 1998 compared with 3.5% in 2019), as well as there being a higher underlying incidence and DALYs of asthma for children in 1998 compared with 2019 in England (based on GBD project data).

Table 2. Burden of disease estimates for residential formaldehyde and damp and/or mould in England in 2019.

Health Outcome	Age Group (Yrs)	Exposure Distribution	PAF [95% CI]	Disease Incidence [95% CI]	Disease Incidence per 100,000 People [95% CI]	DALYs Lost [95% CI]	DALYs Lost per 100,000 People [95% CI]
Formaldehyde		**μg/m^3**					
Asthma *	0–14	GM: 22.8 GSD: 2.0 **	0.025 [0.013–0.039]	4038 [1423–9184]	40 [14–91]	777 [246–2021]	8 [2–20]
Damp and/or mould		**% of dwellings (EHS)**					
Asthma	0–14	4.2%	0.021 [0.010–0.033]	3389 [1120–7654]	34 [11–76]	652 [193–1684]	6 [2–17]
LRI	0–14	4.2%	0.021 [0.013–0.029]	3902 [1998–6624]	39 [20–66]	193 [104–314]	2 [1–3]
Asthma	15–49	3.4%	0.014 [0.004–0.027]	1632 [330–4086]	6 [1–16]	1520 [274–4299]	6 [1–17]
LRI	15–49	3.4%	0.017 [0.011–0.023]	4554 [2588–7239]	18 [10–28]	397 [247–571]	2 [1–2]

CI: Confidence interval; DALYs: Disability Adjusted Life Years; EHS: English Housing Survey data; GM: Geometric mean; GSD: Geometric standard deviation; PAF: Population Attributable Fraction; LRI: Lower respiratory infection. * The central (primary) ERF lower exposure threshold is set at 50 μg/m^3. When the ERF lower exposure threshold is set to 20 μg/m^3 (sensitivity), approximately 6660 DALYs are estimated. When the ERF lower exposure threshold is set to 60 μg/m^3, approximately 230 DALYs are estimated. ** Geometric mean and standard deviation of the exposure distribution used for the burden of disease calculation (outliers were removed, resulting in an allowable range between 1 and 100 μg/m^3).

3.2. Damp and Mould Burden of Disease

We estimated that exposure to damp and/or mould in English residences contributed to between 1.4–2.1% (PAF %) of asthma incidence and 1.7–2.1% of LRIs among children or adults in England in 2019 (Table 2). This amounted to approximately 2800 DALYs lost from both asthma and LRIs among children and adults combined in 2019. We also made secondary estimates of PAFs for allergic rhinitis and bronchitis, with exposure to damp and/or mould estimated to contribute between 0.9% (adults)–1.8% (children) and 1.5% (adults)–1.9% (children) of new cases, respectively in 2019 (Supplementary Materials S6).

Our primary estimates, shown above, are based on the exposure distributions provided by the EHS. However, other sources claim that as many as 14% (Western European estimate [94]) or 27% of homes (39% with children dependants) [66] could have damp and/or mould present. This could result in a possible 3- to 8-fold higher estimated number of cases and DALYs lost (Table 3).

Table 3. Sensitivity analysis of alternative exposure distributions for damp and/or mould and the impact on the burden of disease estimates.

Health Outcome	Source of Exposure Information	% of Dwellings with Damp and/or Mould *	PAF	Disease Incidence (per 100,000 People)	DALY Rate (per 100,000 People)
Children (0–14)					
Asthma	Healthy Homes Barometer Report [94]—Western Europe	14%	0.065	106	20
LRI	Healthy Homes Barometer Report [94]—Western Europe	14%	0.065	122	6
Asthma	Energy Follow Up Survey [66]—England	39%	0.163	265	51
LRI	Energy Follow Up Survey [66]—England	39%	0.163	305	15
Adults (15–49)					
Asthma	Healthy Homes Barometer Report [94]—Western Europe	14%	0.057	25	24
LRI	Healthy Homes Barometer Report [94]—Western Europe	14%	0.065	70	6
Asthma	Energy Follow Up Survey [66]—England	27%	0.104	46	43
LRI	Energy Follow Up Survey [66]—England	27%	0.119	127	11

DALY: Disability-Adjusted Life Years (DALY) lost; LRI: Lower respiratory infections. * Where a separate exposure estimate for homes with children was not provided, the '% of homes' estimate is applied to the 0–14 age group for the burden of disease calculation.

Since 2009 (10 years prior to 2019), estimated asthma incidence and LRIs associated with damp and/or mould exposure decreased by 52–62%, and since 2014 (5 years prior to 2019), by 17–26% among children and adults. Similar decreases were observed for DALYs and also when comparing rates that accounted for the size of the population and its change over time (Figure 2).

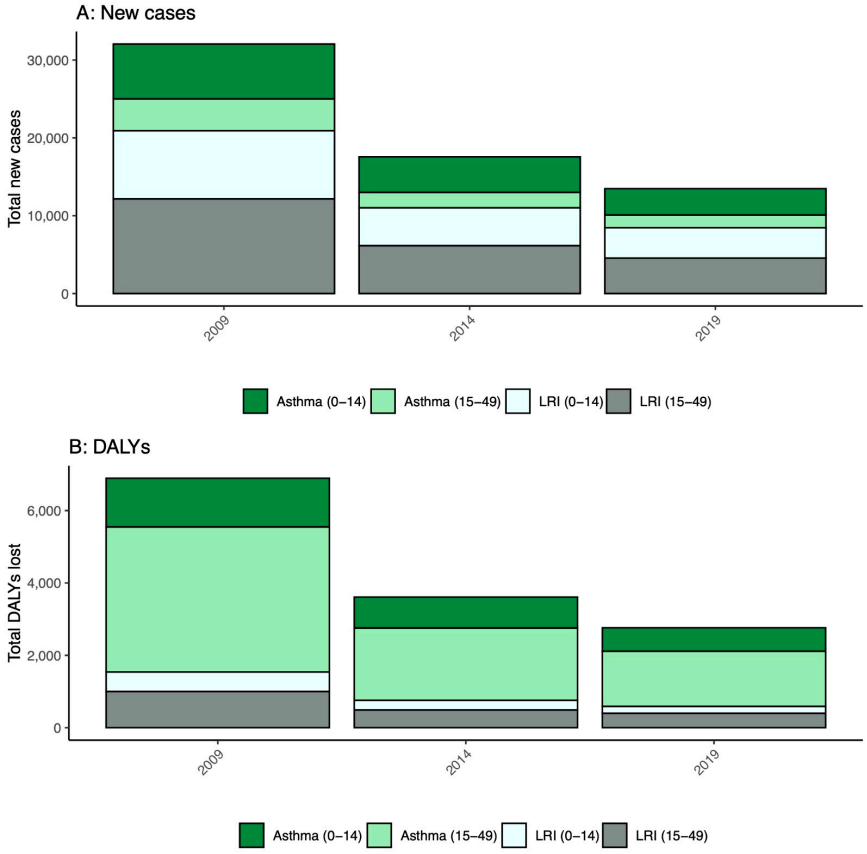

Figure 2. Estimated change over time in damp and/or mould-associated asthma or LRI incidence (i.e., new cases) (plot (**A**)) and DALYs lost (plot (**B**)) in England. The numbers in brackets in the legend refer to age groups (0–14 years, infants and children; 15–49 years, older adolescents and adults).

To assess potential inequalities, we calculated separate PAFs for adults based on EHS exposure data for the percentage of dwellings with any damp where (a) an occupant(s) was living with a long-term illness or disability, (b) dwellings were in different income quintile groups, and (c) dwellings were grouped by the ethnicity of the household reference person (HRP) (as defined by the EHS).

Adults living in dwellings where an occupant(s) was living with a long-term illness (compared with *not*) and where the HRP identified as black, Asian, or another minority group (compared with *white*) had 1.6 to 2.5 times higher PAFs for asthma or LRI, respectively (Figure 3). Furthermore, dwellings in the lowest income quintile (1st) had 2.7 times higher PAFs compared with dwellings in the highest income quintile (5th), with a clear stepwise trend for dwellings in different income groups in between. These relative differences in PAFs are driven entirely by differences in exposure distributions (see Supplementary Materials S7 for exposure distributions) as we did not have stratified ERFs by sub-groups. The relative differences in PAFs for children were similar to adults as we could not separate exposures for dwellings with children that were additionally stratified by the aforementioned categories [64].

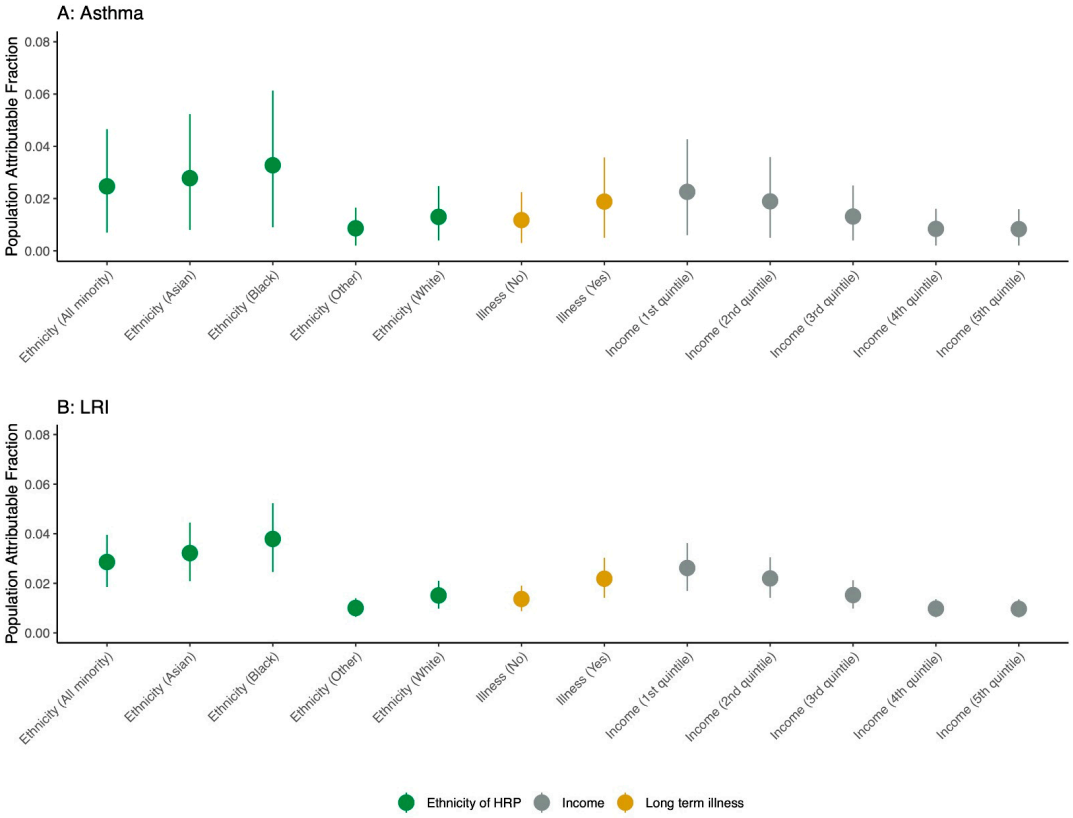

Figure 3. Population Attributable Fractions for asthma (plot (**A**)) and lower respiratory infections (LRI) (plot (**B**)) among adults associated with damp and/or mould in English residences (2019). Legend: HRP: Household reference person; LRI: Lower respiratory infections; PAF: Population Attributable Fraction.

4. Discussion

To aid national and local decision-making, our work utilizes epidemiological approaches to quantify and compare the burden of key respiratory diseases associated with residential exposure to formaldehyde, as well as damp and/or mould, for the English population.

4.1. Formaldehyde

We estimated the burden of disease from asthma associated with residential formaldehyde concentrations among children in England using the most up-to-date epidemiological evidence available [20,42]. Several meta-analyses of epidemiological studies since 2010 have consistently shown positive associations between childhood asthma (diagnosis /self-report) and formaldehyde concentrations/exposures (at home or at school), when associations were meta-analysed across studies [20,42,46,47]. Of note is that the two most recent meta-analyses that reviewed either 9 [20] or 22 studies ([42]; included several non-English studies that were previously not considered in other meta-analyses), calculated the same summary effect estimate (OR (central estimate): 1.20) for childhood asthma based on doctor-diagnosed or self-reported outcomes. While the epidemiological evidence base continues to grow, and summary effect estimates from meta-analyses show statistically significant positive associations, there are still a disproportionately lower number of prospective cohort studies compared with case-control or cross-sectional studies. Prospective cohort studies tracking the incidence of asthma among a population followed over time are still very much needed, and as such, we will continue to monitor the research in this space and update our work as necessary in the future. Furthermore, while the study by Liu et al., 2023 calculated an OR of asthma for adults (OR: 1.09, 95% CI 1.03–1.15), only seven contributing studies were included in the meta-analysis, of which six were cross-sectional, and none were prospective cohort studies. Furthermore, the studies conducted in residential settings had a combined effect estimate that was not statistically significant. Consequently, we took a conservative approach and did not use this evidence to quantify the asthma burden associated with formaldehyde exposures among adults in England. As the evidence base develops, it may become possible to make quantifications in the future. Lastly, continued monitoring of the evidence-base also extends to other health endpoints, such as rhinitis (n = 8 studies) and dermatitis (n = 6 studies), for which there is suggestive epidemiological evidence of a positive association from case-control and cross-sectional studies, though the meta-analysed summary effect estimates are not currently statistically significant, as reported in [42].

The available epidemiological studies can only provide information on associations with asthma diagnosis or self-report. So, while it is possible that formaldehyde can contribute to the development of asthma, it is also possible that formaldehyde as an irritant triggers symptoms, which then, in turn, can lead to diagnosis [20]. Furthermore, there remains uncertainty in the biological mechanisms linking formaldehyde with specific adverse respiratory outcomes, though studies support a potential role for formaldehyde in the development and exacerbation of asthma. These include mechanistic evidence that suggests formaldehyde: binds to proteins, can induce IgE-mediated immune responses and mast cell degranulation; irritate the airways and promote inflammation, increase immune cell infiltration, airway epithelium permeability and impaired ion transport; and activate the airway epithelium to induce oxidative stress and release pro-inflammatory cytokines (e.g., IL-4, IL-13) [20,59,109–113]. These effects can, in turn, lead to airway hyperresponsiveness and bronchoconstriction, airway remodelling and mucus hypersecretion [111,114–116], which are all features of asthma. In addition, formaldehyde can modify airborne substances that cause allergic reactions and enhance sensitisation to such aeroallergens [117]. The heterogeneity of methods and models used in such studies, however, makes it difficult to draw definitive conclusions. Studies differ in terms of the type of animal model or cell, or disease 'state'; the specific formaldehyde concentration and form (including how concentrations are reported), exposure platform; as well as endpoint analyses. In addition, asthma itself is a multifactorial disease that is influenced by a combination of genetic, environmental, and immunological factors. We will, therefore, continually review the evidence on formaldehyde and asthma and update our burden of disease estimates as necessary.

4.2. Damp and Mould

Damp and mould is a generic term encompassing a number of potential hazards that can affect respiratory health but are often grouped together in epidemiological investigations [53]. In reality, exposure to damp indoor conditions and mould can impact respiratory health through varying and potentially different mechanisms and pathways, as discussed in the Introduction. For our analysis, while we considered moulds to represent a singular category (together with damp), mould can constitute many species of fungi, and not all are harmful to human health. Mould is the name given to one of the structures that many different and diverse, but not all, fungi can form. Such fungi produce threads (hyphae) that form larger networks (mycelia) and release spores [52,68,118], which can range in size between 2–10 μm in diameter. Fungal species, known to be either pathogenic and/or allergenic, that are commonly found in indoor air include *Aspergillus*, *Penicillium* and *Cladosporium* spp. [53,118,119], and their spore composition can be affected by several different factors (including outdoor fungal spore concentrations, climate, and weather, and common allergenic outdoor fungal species) [53,120]. Apart from the release of spores, mould can release other fungal components, such as toxins, mycelium and hyphal fragments, and microbial VOCs [121]. Indeed, the presence of mould odour (from the release of microbial VOCs) has been associated in epidemiological studies with an increased risk of asthma, as well as allergic rhinitis [72,73,119].

Understanding the precise mechanisms by which damp and/or mould can contribute to or exacerbate airway disease and infection is difficult. However, studies suggest that fungal allergens can activate cell surface receptors, mainly through protease activity, including Protease Activated Receptor 2 [122] and Epidermal Growth Factor Receptor [123], as well as inducing oxidative stress [124] within airway epithelial cells. Downstream, immune cells are recruited to the airway [125], leading to mucus hypersecretion, loss of epithelial barrier integrity and airway hyperresponsiveness, all typical hallmarks of allergic asthma [126]. As with the formaldehyde evidence, heterogeneity in models and methods within studies means that further research is required to fully elucidate these mechanisms [127].

4.3. Inequalities and Trends over Time

The differences estimated over time for formaldehyde- or damp and mould-related respiratory health burdens were the result of both changes in exposure distributions [65], as well as declines in the overall respiratory health burden in England each year [128]. Declines over time in the percentage of homes with damp and/or mould (as reported by the EHS) may be linked to changes in building/housing-related policy, legislation and regulations (e.g., building regulations; the introduction of Energy Performance Certificates (EPC) in 2007) [129,130], construction of new housing stock, and even housing tenure, as EHS data show that the number of homes owned outright has steadily increased since 2009 (damp and/or mould is least prevalent in owner-occupied homes and the most in privately rented) [64,65]. The declines in asthma disease burden for both children and adults in England, which have also been observed in other high-income countries, could be related to improved asthma control through increased utilisation of medications and better compliance [131]. With regards to indoor formaldehyde concentrations, while the estimated distributions for 2019 (main) and 1998 had similar central tendencies and skewness (partly because the large study by Raw et al., 2004 [36] contributed to both distributions (see Section 2.3 and Supplementary Materials S1)), the 1998 distribution had a higher proportion of the population at the upper tail of the distribution resulting in higher PAFs when an ERF exposure threshold of 50 $\mu g/m^3$ or 60 $\mu g/m^3$ was applied. A study by Halios et al. (2022) also illustrated that residential formaldehyde concentrations may be decreasing over time in European homes [34], which is in line with European regulations [132], voluntary industry actions in Europe to reduce emissions (e.g., wood panel industry), and also changes to English building regulations (e.g., ventilation) [133]. The lack of systematic and comparable frequent monitoring surveys of indoor air quality to characterise the English housing stock is a major barrier to tracking trends over time

and evaluating the effectiveness of policies and interventions. National indoor air quality (IAQ), or preferably indoor environmental quality surveillance, to capture both IAQ and biological contamination in relation to ventilation and other indoor parameters could fill this critical data gap.

The EHS data on damp and/or mould captures inequalities across dwellings based on characteristics such as ethnicity, income, and long-term illness and disability [64]. These inequalities were carried forward to the PAFs that we estimated for each sub-group. Unfortunately, we did not have nationally representative health data, stratified by the aforementioned groups, to further estimate the total number of new cases of asthma/LRIs and DALYs associated with exposure in the population. However, we do know that respiratory diseases are particularly linked to deprivation and other social determinants of health [134,135]. In the UK, asthma is more prevalent in lower-income communities, and the incidence rates are also significantly higher in black and minority ethnic groups [136]. Therefore, we expect that inequalities in exposures coupled with inequalities in underlying health conditions will contribute to an even greater environmental burden of disease for some of these groups.

4.4. Interpretation and Comparison of Environmental Burden of Disease Estimates

Interpretation of the environmental burden of disease estimates in the context of risk communication and policy development requires a careful understanding of the inherent uncertainties in these quantification approaches, which require several simplifying assumptions [24]. However, in the real world, the way these relationships unfold is often more complex. For example, the epidemiological relationships we used to calculate PAFs represent average risks estimated amongst exposed and unexposed populations. We recognise that some sub-groups are more vulnerable to exposures and subsequent adverse health effects, including certain age groups, immunocompromised individuals, those with underlying respiratory conditions, and those who have had previous exposures to fungi that may predispose/precede allergy (i.e., sensitised) [74,137].

While we estimated the burden of disease associated with both formaldehyde and damp and/or mould as independent exposures, in reality, a given disease can be influenced by more than one causal mechanism, which may require the joint action of multiple components causes [24,99]. Furthermore, there is uncertainty as to whether co-exposures may result in cumulative effects that could amplify an adverse health effect [59,112,138]. For example, a study by Duan et al., 2020 [59] found that mice exposed to both formaldehyde and high humidity suffered increased inflammation and hypersecretion of mucus in the airways than either exposure alone. The effects of various exposures may not be strictly additive, and as such, our burden of disease estimates for formaldehyde and damp and/or mould should not be summed together.

The ability to compare the national environmental burden of disease estimates across countries/regions and over time depends greatly on the consistency of input parameters and assumptions, such as choice of health outcomes, ERFs, counterfactuals, and underlying health data. For instance, we estimated a central PAF% of 2.5% and 8 DALYs (per 100,000 children aged 0–14) in England in 2019 associated with formaldehyde exposures. Though previously, the WHO estimated a PAF% for children aged 0–3 of 3.7%; Hänninen et al., 2014 estimated 0–2 DALYs per million children (0–3 years old) in six European countries; and Rojas-Rueda et al. 2019 estimated 0.60 DALYs per 100,000 children 0–3 years in European countries [1,14,17]. The differences in our estimates to those of Hänninen et al. and Rojas-Rueda et al. can, to some extent, be explained by the ERFs (previous studies used an OR from Rumchev et al., 2002 [104]). However, we predominantly ascribe these differences to the placement of the lower exposure thresholds applied to the PAF calculations (e.g., counterfactuals). Hänninen et al. and Rojas-Rueda et al. chose a threshold corresponding to the WHO's short-term guideline for formaldehyde (100 $\mu g/m^3$, which is based on studies of eye irritation) [2]. Meanwhile, we chose a range of thresholds based on the epidemiological evidence of chronic exposure to formaldehyde and asthma (see

Supplementary Materials S5). Lastly, a recent publication by Morantes et al., 2023 [139] presented DALY estimates for residential formaldehyde exposures (median: $>10^2$ per 100,000 people). However, it is not clear what country or time period these relate to. They also assumed typical dwelling concentrations to reach 100 $\mu g/m^3$, which is higher than what we would expect in the average English or European dwelling [33,34,36].

4.5. Uncertainties and Limitations

We estimated or obtained data on formaldehyde concentrations and damp and mould at people's place of residence. However, the time that children and adults spend at school, work, or other locations will have an impact on their total exposure profile. While we did compare several studies of formaldehyde concentrations in schools and nurseries in London and other cities in Europe and found that the levels were largely similar, future indoor air burden of disease work could explore the development and use of time-weighted exposure profiles representing typical exposures for sub-groups of the population. Any future work could also consider how the COVID-pandemic has changed working-from-home patterns and subsequent exposures.

As mentioned earlier in the Discussion, damp and mould are often grouped together in epidemiological investigations. However, some previous epidemiological studies have shown that associations between specific metrics of damp or mould, such as mould odour, visible mould, dampness, and water damage, with asthma and rhinitis can vary in magnitude [72–74]. The epidemiological evidence is further dominated by subjective, qualitative exposure assessments (e.g., visible water damage; visible mould; mouldy odour). Fewer studies have used objective, quantitative microbial metrics [74,119] for exposure assessment, and as previously mentioned, not all types of fungi are harmful. As such, we expect some degree of exposure misclassification built into the epidemiological risk estimates we use, which are based on binary, subjective classifications of damp and/or mould presence. Furthermore, binary exposure classifications do not allow for the development of exposure–response curves and the evaluation of potential thresholds of the effect [74], which remains a continued source of uncertainty. Lastly, based on the wide range of dwellings estimated to have damp and/or mould from different sources [29,64,66,94] (3.4–27%), there is clearly a discrepancy in what the actual number may be in England, and furthermore, what classifies as a damp and/or mould problem and how different assessment approaches will impact the result [29].

There is very little information on what the shape of the ERF between formaldehyde and asthma might look like. This also extends to whether there is a threshold effect and, if so, at what concentration. For our PAF calculations, we chose a range of plausible thresholds based on the available evidence (see Supplementary Materials S5 for details). Our resulting burden of childhood asthma estimates had a wide range, highlighting a key area of uncertainty in the quantification of this relationship and the need for further epidemiological studies (preferably high-quality prospective cohorts).

For some exposure–outcome pairs, we used aggregated effect estimates derived from the meta-analysis of RRs or ORs from prospective cohort studies, case-control studies, and cross-sectional studies. Due to the static nature of cross-sectional studies, they can only provide information on associations with disease prevalence. However, when combined in a meta-analysis with risk estimates from prospective cohort and case-control studies, we assumed that the resulting aggregate estimate reflected the relative increased risk (incidence) of disease for the purposes of our PAF calculations.

There are several advantages to using the GBD project's national estimates of disease incidence and DALYs. The dataset is comprehensive, providing estimates across time (yearly), space (nationally, and even in some cases sub-nationally), age groups, and health outcomes, which are estimated within a unified global framework, lending itself well for comparative analyses [97,98]. However, it should also be recognised that these estimates in many cases are modelled, and so any inaccuracies will be propagated through an environmental burden of disease analysis where they are used. Confidence inter-

vals are provided around the central estimates, which we additionally incorporated into our analysis.

For asthma, there is a lag period between exposures and the eventual development of the disease [140]. This lag period, which can last from weeks to years and can vary greatly between individuals, is not formally accounted for in our analysis. We assumed that exposures in each year of analysis contributed to environmental health burdens for that corresponding year. Future research could explore the feasibility and methodological implications of incorporating lag times into this type of work. Lastly, both formaldehyde and damp and/or mould are additionally associated with the exacerbation of symptoms among those who have asthma [20,95,96,141]. While this was not explicitly accounted for in our analysis, increased severity of symptoms naturally contributes to a larger burden of disease (e.g., reduced quality of life; additional GP/hospital visits; having to take time off school/work) and is thus, a part of the morbidity component of the DALY.

5. Conclusions

By combining information on population exposures, epidemiological exposure–response relationships, and national health data, we estimated the burden of key respiratory diseases associated with residential exposures to formaldehyde and damp and/or mould in England. While the estimates for 2019 were lower than previous years, 800 DALYs lost among children (asthma) and 2800 DALYs lost among children and adults (asthma and LRI) were still estimated to be associated with formaldehyde, and damp and/or mould exposures, respectively. Furthermore, given that alternative data sources cite a higher prevalence of damp and/or mould than the EHS, it is also possible that our numbers are an underestimate. By showing the potential societal health impacts of poor indoor air quality from residential exposures to formaldehyde and damp and/or mould at the national level, we hope this work can support ongoing policy and guidance development to improve indoor air quality and reduce the corresponding health consequences and inequalities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments10080136/s1, Table S1: Search strings for formaldehyde monitoring studies. Table S2: Characteristics of included monitoring studies of indoor residential formaldehyde in England. Table S3: Summary statistics of the pooled dataset of indoor formaldehyde concentrations ($\mu g/m^3$) in English residences. Table S4: Percentage of dwellings with any damp (i.e., any damp or mould) as reported in the English Housing Survey (DLUHC 2022). Table S5: Search strings for formaldehyde epidemiological studies. Table S6: Search strings for damp and mould epidemiological studies. Table S7: Proposed lower exposure thresholds. Table S8: The Population Attributable Fractions for allergic rhinitis and bronchitis associated with exposure to damp and/or mould in English housing in 2019. Table S9: Inequalities in the percentage of dwellings with any damp (i.e., damp and/or mould) in 2019, as defined by the English Housing Survey.

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Data Availability Statement: All data used in the analyses are publicly available and have been referenced throughout the paper.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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