Supplementary materials

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

Contents

S1. Exposure to formaldehyde in the English housing stock

Literature search for monitoring studies

We conducted a systematic literature search of Medline (PubMed), EMBASE and Scopus using the search strings contained in Table S1. Note that while we wanted to capture studies conducted in Scotland, Northern Ireland, Wales, as well as Ireland, we only considered studies conducted in England for the analysis in this paper.

Table S1. Search strings for formaldehyde monitoring studies.

Scopus	TITLE-ABS-KEY ((formaldehyde OR hcho) AND (exposure OR concentration OR measure* OR model) AND (residential* OR home OR bedroom OR 'living AND room' OR house OR dwelling OR flat OR apartment)) AND AFFILCOUNTRY (england OR ireland OR scotland OR wales OR 'northern AND ireland' OR 'united AND kingdom')
Medline	(((formaldehyde[Title/Abstract] OR HCHO[Title/Abstract]) AND (residen*[Title/Abstract] OR home[Title/Abstract] OR bedroom[Title/Abstract] OR 'living room'[Title/Abstract] OR house[Title/Abstract] OR dwelling[Title/Abstract] OR flat[Title/Abstract] OR apartment[Title/Abstract] OR rented[Title/Abstract])) AND (United Kingdom[MeSH Terms] OR Ireland[MeSH])
EMBASE	(formaldehyde OR HCHO) AND (residential OR residence OR home OR bedroom OR living room OR house OR dwelling OR flat OR apartment OR rented).af AND (exp United Kingdom/ OR exp Ireland/)
EBSCO	AB (formaldehyde OR HCHO) AND AB (residential OR residence OR home OR bedroom OR living room OR house OR dwelling OR flat OR apartment OR rented) AND AB (exposure OR concentration OR measurement OR model) AND SU ('United Kingdom' OR Ireland)

From this search we identified 38 records, of which 5 were relevant based on title and abstract screening. We then further screened out 1 paper on full text resulting in 4 papers retained (however only 3 were conducted in England as 1 was in Ireland) (Coggins et al. 2022; Gee et al. 2005; Stamp et al. 2022; Venn et al. 2003).
We then followed this up by running similar search strings through Google Scholar, which resulted in 6 relevant studies (published peer reviewed papers, conference papers, and reports) being identified (Burman and Stamp 2019; Crump et al. 2005; MHCLG 2019; Mohle et al. 2003; Raw et al. 2004; Wang et al. 2017). Lastly, we reached out to colleagues and experts in the field of IAQ in the UK and Ireland, which resulted in an additional studies being identified in England (Berry et al. 1996; McGill et al. 2015a), and 3 for Northern Ireland (McGill et al. 2015b; c; McGill et al. 2017).

For our analysis of formaldehyde in the English housing stock, we considered studies for inclusion which were conducted in England, conducted measurements in liveable room such as bedrooms, living rooms, or kitchens in dwellings (e.g., houses, detached or semi-detached, flats, apartments, bungalows), and conducted appropriate measurements for at least 3 days or more. We did include one study from England which conducted measurements for 24 hrs (McGill et al. 2015a) as the study design and measurements were carried out in a robust way. Characteristics of the included studies are in Table S2.

Table S2. Characteristics of included monitoring studies of indoor residential formaldehyde in England

Citation	Location	Time period of monitoring	Measurement duration	Number of dwellings	Type of dwellings	Rooms monitored
(Berry et al. 1996)	Avon	1991-1993 Monthly measurements throughout the year	3 d	174	Existing homes, constructed prior to 1993	Living room, Bedroom*
(Mohle et al. 2003)	Hertfordshire, London, Berkshire, Bedfordshire, Oxfordshire	2001	3 d	10	Existing homes built before 2000	Living room, bedroom

(Venn et al. 2003)	Nottingham	1998-1999	3 d	416	Existing homes built before 1998	Bedroom
(Raw et al. 2004)	Nationally representative sample of homes across England	1997-1999	3 d	833	Existing homes (built <1919 – 1998)	Bedroom
(Crump et al. 2005)	South of England	2002 heating and non-heating seasons	3 d	37	New homes built since 1995 and prior to 2002	Living room
(Gee et al. 2005)	Wythenshawe area near Manchester	--	5 d	200	Existing homes	Bedroom, living room
(McGill et al. 2015a)	England	2012-2013 non-heating season	24 hr	7	New zero carbon social rented properties (Passivhaus), built since 2012	Living room
(Wang et al. 2017)	York	2015	3 d	3	Existing homes	Living room
(MHCLG 2019)	Leeds, Manchester, Bolton, London, Didcot, Bristol	2015-2016	7 d	10	New homes, constructed prior to the end of 2014	Bedroom, living room
(Burman and Stamp 2019)	East London	2018 heating and non-heating seasons	7 d	5	New, low energy apartment blocks completed in 2014 and 2015	Living room, kitchen, bedroom
(Stamp et al. 2022)	London	2018 heating and non-heating seasons	7 d	5	New low energy apartments (built 2015)	Living room, kitchen, bedroom

*Note that the study by Brown et al also monitored in kitchen, bathrooms, second bedrooms, and outdoors in a subset of homes.
d:day; hr: hour

Given the large geographic coverage, large sample size (1,700 dwellings), mixture of existing and newly constructed homes, coverage of multiple seasons, and periods in which houses were constructed, we deemed the data sufficiently representative to estimate a national distribution of indoor annual average formaldehyde exposures for the purposes of this burden of disease analysis.

We first extracted either the raw (Burman and Stamp 2019; McGill et al. 2015a; MHCLG 2019; Mohle et al. 2003; Wang et al. 2019) or summarised (e.g., means, medians, ranges, deciles) (Crump et al. 2005; Gee et al. 2005; Raw et al. 2004; Venn et al. 2003) data from the studies. Or in the case of (Berry et al. 1996) we digitized figures in the report (histograms) to re-create the data distributions. We further obtained the raw data upon request from the authors of (Stamp et al. 2022). Our aim was to construct a combined national distribution by pooling data distributions (e.g., datasets) across each of the studies. For studies where raw data were available, we pooled the data as they were given. Though when data were available for multiple rooms in the same house, we first calculated the average across the bedrooms and living rooms, so as not to inflate the sample size of the study. For the other studies with summarised data, we had to estimate and re-construct data distributions by randomly sampling data points (with *n* being equal to the number of monitored dwellings) to reflect the summarised parameters. For this sampling procedure, we assumed lognormal distributions setting the given means or medians as the centre of mass. Furthermore, if a geometric standard deviation was not given, we assumed it to be 2 $\mu g/m^3$, which was calculated across the 6 studies providing raw data. Finally, we constrained the distributions by setting minimum and maximum values given in the papers. However, if these were not given, we constrained the minimum of the distribution to 1 ug/m^3 and the maximum to be equal to the concentration reported at the top decile (top 10% of data) of the data distribution from the large and representative study by Raw et al 2004 (61 $\mu g/m^3$). If summaries for different seasons were given, we estimated a distribution for each season to enhance the seasonal representability of the dataset. The study by Venn et al 2003 reported the % of dwellings with formaldehyde concentrations within ranges, specifically: 0-16 $\mu g/m^3$,

16-22 μg/m^3, 22-32 μg/m^3, and >32 μg/m^3. We randomly sampled uniform distributions within each range, with the number of samples equal to the number of dwellings in that group (% multiplied by the group (case or control) totals). For the highest open exposure category (>32 μg/m^3) we assumed that the upper bound was equal to 61 μg/m^3 (32-61 μg/m^3) (see rational above).

The sample size of each individual study distribution was equal to the number of dwellings monitored in that study. As such, the final national distribution was naturally weighted by each study's sample size, with a few modifications:

- While the study by Raw et al 2004 monitored a nationally representative sample of dwellings in England (n=833), and was a very well conducted reported study, we decided to down-weight the sample size by a factor of 2 because the sample size was so large relative to the other studies that it almost completely influenced the pooled distribution. Furthermore, the study only captured homes constructed prior to 1998.
- The study by Gee et al 2005 only provided information on the median level of formaldehyde exposure and did not provide information on the distribution (SD, range, deciles, etc). Since the study sample size was relatively large (n=200 dwellings) compared to other studies, we downscaled the sample size by a factor of 2 to account for the uncertainty in this study's re-constructed exposure distribution.

The studies used to construct the main distribution (2019) were: (Burman and Stamp 2019; Crump et al. 2005; Gee et al. 2005; McGill et al. 2015a; MHCLG 2019; Mohle et al. 2003; Raw et al. 2004; Stamp et al. 2022; Venn et al. 2003; Wang et al. 2017)

We also used the full datasets from the studies by (Raw et al. 2004) and ((Berry et al. 1996), Chapter 5) to construct a national distribution for the year 1998 (Note that the data from (Berry et al. 1996) was held out of the construction of the main (2019) distribution).

Table S3. Summary statistics of the pooled dataset of indoor formaldehyde concentrations (μg/m^3) in English residences. Note that these summaries show the full pooled data distribution prior to the data on the extremes being trimmed off for the burden of disease analysis (see Methods in main paper).

	N studies	GM (GSD)	Median	Min	Max	References
England *Full pool of studies published between 2003 and 2022*	10	22.5 (2.2)	24.6	0.1	187.4	(Burman and Stamp 2019; Crump et al. 2005; Gee et al. 2005; McGill et al. 2015a; MHCLG 2019; Mohle et al. 2003; Raw et al. 2004; Stamp et al. 2022; Venn et al. 2003; Wang et al. 2017)
New homes built since 2010 *Mixture of energy efficient, Passivhaus, social housing and natural and mechanically ventilated homes*	4	23.8 (2.1)	24.3	6.2	187.4	(Burman and Stamp 2019; McGill et al. 2015a; MHCLG 2019; Stamp et al. 2022)
Housing stock built prior to 1998	2	22.3	22.5	1.0	171.0	(Berry et al. 1996; Raw et al. 2004)

GM: Geometric mean; GSD: Geometric standard deviation

S2. Damp and mould in the English housing stock (English Housing Survey data)

Table S4. Percentage of dwellings with any damp (i.e., any damp or mould) as reported in the English Housing Survey (DLUHC 2022)

	% of dwellings	
Year	All sampled dwellings	Sampled dwellings where age of youngest person is under 16 years
2019	3.4%	4.2%
2014	4.3%	5.4%
2009	8.1%	9.2%

Numbers in the table are pulled directly from the published English Housing Survey data tables (DLUHC 2022)

S3. Epidemiological studies and exposure response functions of respiratory conditions and residential formaldehyde exposure

We searched Medline (PubMed), EMBASE, Scopus, and Global Health databases (April 2023), which resulted in 23 records retrieved. After removal of duplicates, we reviewed 20 abstract and titles, of which 7 were reviewed on full text, of which 5 were potentially suitable (Liu et al. 2023; McGwin et al. 2010; Mendell 2007; Nurmatov et al. 2013; Yu et al. 2020). We also ran variations of the below search strings through Google Scholar and retrieved a further relevant meta-analysis by (Lam et al. 2021). Lastly, we reviewed the study by (Rumchev et al. 2002), as it has been used previously for formaldehyde burden of disease assessments (childhood asthma/wheeze) (Hanninen et al. 2014; Rojas-Rueda et al. 2019; WHO Regional Office for Europe 2011).

Table S5. Search strings for formaldehyde epidemiological studies

Medline (PubMed) 7 hits	(formaldehyde[MeSH Major Topic] OR formaldehyde[Title/Abstract] OR HCHO[Title/Abstract) AND (wheeze[Title/Abstract] OR cough*[Title/Abstract] OR asthma[Title/Abstract] OR 'respiratory infection*'[Title/Abstract] OR 'lower respiratory infection*'[Title/Abstract] OR 'LRI'[Title/Abstract] OR 'upper respiratory infection*'[Title/Abstract] OR 'URI'[Title/Abstract] OR bronchial[Title/Abstract] OR bronchitis[Title/Abstract] OR bronchiolitis[Title/Abstract] OR pneumonia[Title/Abstract] OR eczema[Title/Abstract] OR 'atopic dermatitis'[Title/Abstract] OR rhinitis[Title/Abstract] OR 'allergic rhinitis'[Title/Abstract]) AND (epidemiology[MeSH Terms] OR epidemiolog*) Filters: Meta-Analysis, Systematic Review, Human
EMBASE 8 hits	((formaldehyde or HCHO) and (indoor* OR school* OR home* OR building* OR dwelling* OR residen* OR house* OR apartment* OR nursery*) and (wheeze or cough* or asthma or respiratory infection or lower respiratory infection or LRI or upper respiratory infection or URI or bronchial or bronchitis or bronchiolitis or pneumonia or eczema or atopic dermatitis or rhinitis or allergic rhinitis)).ti,ab. and epidemiolog*.af. and (Meta-Analysis or Review or Systematic Review).ti,ab. Filter: English, Human
Scopus 4 hits	(TITLE-ABS-KEY (formaldehyde OR HCHO) AND TITLE-ABS-KEY (wheeze OR cough* OR asthma OR 'respiratory AND infection' OR 'lower AND respiratory AND infection' OR 'lri' OR 'upper AND respiratory AND infection' OR 'uri' OR bronchial OR bronchitis OR bronchiolitis OR pneumonia OR eczema OR 'atopic A ND dermatitis' OR rhinitis OR 'allergic AND rhinitis') AND TITLE-ABS-KEY (review* OR 'systematic AND review' OR 'meta-analysis') ALL (epidemiolog*)) AND (LIMIT-TO (LANGUAGE , "English"))

Global Health 4 hits	((TI asthma OR TI respiratory infection* OR TI LRI OR TI URI OR TI bronchi* OR TI pneumonia OR TI rhinitis OR TI dermatitis OR TI eczema OR TI (wheeze or breathlessness or dyspnea or shortness of breath) OR TI cough*) OR (AB asthma OR AB respiratory infection* OR AB LRI OR AB URI OR AB bronchi* OR AB pneumonia OR AB rhinitis OR AB dermatitis OR AB eczema OR AB (wheeze or breathlessness or dyspnea or shortness of breath) OR AB cough*)) AND ((AB formaldehyde OR AB HCHO) OR (TI formaldehyde OR TI HCHO)) AND ((TI indoor OR TI school* OR TI home* OR TI building* OR TI dwelling* OR TI residen* OR TI house* OR TI apartment* OR TI nursery) OR (AB indoor OR AB school* OR AB home* OR AB building* OR AB dwelling* OR AB residen* OR AB house* OR AB apartment* OR AB nursery)) AND ((TI epidemiolog*) OR (AB epidemiolog*)) AND ((TI (meta-analysis OR meta analysis OR metanalysis) OR TI systematic review OR TI review) OR (AB (meta-analysis or meta analysis or metanalysis) OR AB systematic review OR AB review)) Filter: English

Childhood asthma

Lam et al 2021 (meta-analysed 9 studies) and Liu et al 2023 (meta-analysed 22 studies) were the most recent meta-analyses providing risk estimates for formaldehyde exposure and asthma diagnosis/self-report among children (Lam et al. 2021; Liu et al. 2023). When all contributing studies were pooled, both meta-analyses produced the same central odds ratio estimate (1.20), though unsurprisingly the 95% confidence intervals around the central estimates differed slightly. We decided to use this central odds ratio estimate combined with the 95% confidence interval given by Liu et al (1.20, 95% CI 1.11 – 1.31) as the confidence interval was derived from a larger pool of studies and was more precise. The age of children participating in the studies in Liu et al ranged from 6 months old to 15 years.

We also took note that Liu et al produced separate meta-analysed odds ratios for a subset of studies conducted in Western countries (OR: 1.03) and in Eastern countries (OR: 1.27). However, we chose to instead use the overall odds ratio (from all studies combined) for the following reasons:

- The odds ratio (OR) derived from pooling all studies in Liu et al 2023 was consistent with what was found in the meta-analysis by Lam et al 2021
- It is likely that the differences in the estimated ORs between Western and Eastern countries is influenced by the study designs of the contributing studies. Liu et al showed that the meta-analysed ORs for cohort (OR: 1.20) and case-control (OR: 1.28) studies were higher than cross-sectional studies (OR: 1.00), and notably the studies conducted in Eastern countries had a low proportion which were cross-sectional, compared to Western country studies. As such, we did not want to choose an OR which was predominantly influenced by cross-sectional studies, due to the limitations of evidence provided by this type of study design.

Adult asthma

The study by Lam et al was not able to meta-analyse an aggregate OR for asthma diagnosis among adults (Lam et al. 2021). The study by Liu et al did estimate an aggregate OR for adults (OR: 1.09, 95%CI 1.03-1.15) (Liu et al. 2023), however, there were only 7 contributing studies, of which 6 were cross-sectional and none were

longitudinal cohort studies. Furthermore, the studies assessing exposure within residential settings had a non-significant result (OR: 1.12, 95% CI 0.99, 1.27). As such, we took a conservative approach and did not use this evidence to conduct a burden of disease analysis for formaldehyde and asthma among adults in England. As the evidence-base, conducted among residential settings, develops, it is possible that this outcome will be included in future analyses.

Other health outcomes

Liu et al reviewed studies investigating associations of formaldehyde exposures in civil buildings (dwellings, schools, and offices) with bronchitis (n=3 studies), conjunctivitis (n=2 studies), dermatitis (n=4), ear infection (n=1), lung cancer (n=1), pneumonia (n=2 studies), pregnancy outcomes (n=2), and rhinitis (n=6 studies), but was only able to meta-analyse across studies of rhinitis and dermatitis, of which non-statistically significant results were found. Similarly, as the evidence base develops further in the future, we will keep these outcomes under continual review.

S4. Epidemiological studies of respiratory conditions and residential damp and mould exposure

We searched Medline (PubMed), EMBASE, Scopus, and Global Health databases (February 2023), which resulted in 177 records retrieved. After removal of duplicates, we reviewed 146 abstract and titles, of which 20 were reviewed on full text. After full text review, 10 articles (meta-analyses, reviews, large pooled cohort studies) were retained as suitable (Caillaud et al. 2018; Dai et al. 2022; Fisk et al. 2019; Fisk et al. 2010; Jaakkola et al. 2013; Kanchongkittiphon et al. 2015; Mendell et al. 2011; Park and Cox-Ganser 2011; Quansah et al. 2012; Tischer et al. 2011).

We also ran a search through Google Scholar and reviewed the reference list of previous damp and mould burden of disease/ Health Impact assessments (Hanninen and Asikainen 2013; Knibbs et al. 2018; Mudarri 2016; Riggs et al. 2021; Rojas-Rueda et al. 2019; WHO Regional Office for Europe 2011), which resulted in the identification of an addition 3 suitable studies (Fisk et al. 2007; Wang et al. 2022; Wang et al. 2019).

Table S6. Search strings for damp and mould epidemiological studies

Medline (PubMed) - 1 35 hits	(damp[Title/Abstract] OR dampness[Title/Abstract] OR mould[Title/Abstract] OR mold[Title/Abstract] OR 'water damage'[Title/Abstract] OR mildew[Title/Abstract] OR condensation[Title/Abstract] OR moisture[Title/Abstract] OR fung*[Title/Abstract]) AND (wheeze[Title/Abstract] OR cough*[Title/Abstract] OR asthma[Title/Abstract] OR 'respiratory infection*'[Title/Abstract] OR 'lower respiratory infection*'[Title/Abstract] OR 'LRI'[Title/Abstract] OR 'upper respiratory infection*'[Title/Abstract] OR 'URI'[Title/Abstract] OR bronchial[Title/Abstract] OR bronchitis[Title/Abstract] OR bronchiolitis[Title/Abstract] OR pneumonia[Title/Abstract] OR eczema[Title/Abstract] OR 'atopic dermatitis'[Title/Abstract] OR rhinitis[Title/Abstract] OR 'allergic rhinitis'[Title/Abstract]) AND (epidemiology[MeSH Terms] OR epidemiolog*) Filters: Meta-Analysis, Systematic Review, Humans, from 2010 – 2023
Medline (PubMed) – 2 68 hits	(damp[Title/Abstract] OR dampness[Title/Abstract] OR mould[Title/Abstract] OR mold[Title/Abstract] OR 'water damage'[Title/Abstract] OR mildew[Title/Abstract] OR condensation[Title/Abstract] OR moisture[Title/Abstract] OR fung*[Title/Abstract]) AND (wheeze[Title/Abstract] OR cough*[Title/Abstract] OR asthma[Title/Abstract] OR 'respiratory infection*'[Title/Abstract] OR 'Respiratory Tract Infections'[MeSH] OR 'lower respiratory infection*'[Title/Abstract] OR 'LRI'[Title/Abstract] OR 'upper respiratory infection*'[Title/Abstract] OR 'URI'[Title/Abstract] OR bronchial[Title/Abstract] OR bronchitis[Title/Abstract] OR bronchiolitis[Title/Abstract] OR pneumonia[Title/Abstract] OR eczema[Title/Abstract] OR 'atopic dermatitis'[Title/Abstract] OR rhinitis[Title/Abstract] OR 'allergic rhinitis'[Title/Abstract]) Filters: Meta-Analysis, Humans, from 2010 – 2023
EMBASE + Global Health 64 hits	((damp or dampness or mould or mold or water damage or mildew or condensation or moisture or fung*) and (indoor* OR school* OR home* OR building* OR dwelling* OR residen* OR house* OR apartment* OR nursery*) and (wheeze or cough* or asthma or respiratory infection or lower respiratory infection or LRI or upper respiratory infection or URI or bronchial or bronchitis or bronchiolitis or pneumonia or eczema or atopic dermatitis or rhinitis or allergic rhinitis)).ti,ab. and epidemiolog*.af. and (Meta-Analysis or Review or Systematic Review).ti,ab. Filter: English, Human, 2010-2023
Scopus 10 hits	(TITLE-ABS-KEY (damp OR dampness OR mould OR mold OR 'water AND damage' OR mildew OR condensation OR moisture OR fung*) AND TITLE-ABS-KEY (wheeze OR cough* OR asthma OR 'respiratory AND infection' OR 'lower AND respiratory AND infection' OR 'lri' OR 'upper AND respiratory AND infection' OR 'uri' OR bronchial OR bronchitis OR bronchiolitis OR pneumonia OR eczema OR 'atopic AND dermatitis' OR rhinitis OR 'allergic AND rhinitis') AND TITLE-ABS-KEY (review* OR 'systematic AND review' OR 'meta-analysis') ALL (epidemiolog*

	)) AND (PUBYEAR > 2009 AND PUBYEAR < 2024) AND (LIMIT-TO (LANGUAGE , "English"))

*We restricted the search to the years 2010-2023 as we were already aware of several well-conducted meta-analyses/reviews which had been published post 2010.

Choice of studies and exposure-response functions for the burden of disease analysis are listed in Table 1 in the main paper, and further rational for study selection is given below.

Asthma

Through our systematic search, we screened several meta-analyses and/or large pooled cohort studies investigating the association between damp and/or mould exposure and asthma, among both children and adults (Fisk et al. 2019; Quansah et al. 2012; Tischer et al. 2011; Wang et al. 2022; Wang et al. 2019). For childhood asthma development, we chose to use the meta-analysed summary effect estimates from (Quansah et al. 2012) because this meta-analysis included the most recent pool of studies (1990 – 2012), and only included higher quality study designs (cohort/longitudinal and incident case-control studies). Furthermore, we used the overall summary effect estimate (from the Random Effects Model; Table S2 in (Quansah et al. 2012)) as the majority of included studies were conducted among children. The effect estimate for 'Any Exposure' (1.50 (95% CI 1.25 – 1.80)) was used as the main effect estimate applied to damp and/or mould exposure. While the meta-analysis by (Fisk et al. 2019) was more recently published than (Quansah et al. 2012), the study focussed on school exposures.

Interesting to note is that the recently published multi-centre cohort study by (Wang et al. 2022), which followed children over time and assessed onset of asthma prior to and after 10 years of age found a higher OR after 10 years of age (OR 1.71 95% CI 1.35 – 2.17 due to 'Dampness/mould during both follow up periods') compared with the period prior to 10 years of age (OR 1.18 95% CI 1.01 – 1.39).

For the burden of disease estimates of adult asthma, we used the odds ratio for doctor diagnosed asthma associated with 'Any Dampness' (OR: 1.43 95% CI 1.12 – 1.83) given by (Wang et al. 2019), which is a longitudinal multi-centre cohort study covering a large population of adults in Iceland, Norway, Sweden, Denmark, and Estonia (n=11,506 adults)) that were followed-up over 10 years. Notably, this estimate is similar in magnitude to what was found in the meta-analysis by Quansah et al which meta-analysed mostly studies among children, but also some among adults.

Respiratory tract infections

At the time of writing and publishing this paper, the meta-analysis by (Fisk et al. 2010) was the only published study that we identified which provided meta-analysed summary effect estimates for respiratory infections associated with dampness or mould. As mentioned in the main paper, the OR with the closest outcome definition to lower respiratory infections (LRI) in (Fisk et al. 2010) was 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 LRI's, the studies which were used to derive the meta-analysed effect estimate were primarily of LRI sub-types (bronchitis and pneumonia), and the effect estimate (1.50 95% CI 1.32 – 1.70, Table 3 (column 3) in Fisk et al 2010) was similar to the effect estimate specific to Bronchitis (acute or chronic) (1.45 95% CI 1.32 – 1.59), which is a sub-type of LRI (Fisk et al. 2010). As the summary effect estimates were calculated by pooling studies among children and adults, we assumed they could apply equally to the child and adult populations in our burden of disease analysis, which seems to be a reasonable assumption as age stratified analyses for all respiratory infections resulted in similar ORs. Furthermore, a mixture of cohort, case-control, and cross-sectional studies were used and only studies which controlled for at

least 4 key confounders were included (age, gender, smoking (e.g., active smoking, smoking in home, smoking by mother during pregnancy), and some measure of socioeconomic status (SES)).

Lastly, we would also like to point out that at the time our paper went to press, a new meta-analysis looking at the associations between residential damp and mould exposure and respiratory infections, respiratory symptoms, and rhinitis/wheeze among children in high-income countries also went to press (https://www.sciencedirect.com/science/article/pii/S1526054223000398?ref=pdf_download&fr=RR-2&rr=7ec2e827bc4c23cb) (Groot et al. *Paediatric Respiratory Reviews*. In press.). Groot et al. In press (2023) meta-analysed associations between respiratory infections and exposure to a) mould, exposure to b) dampness, and exposure to c) mould and/or dampness. While Groot et al did not distinguish between different types of respiratory tract infections, their estimated effect measure for all 'respiratory tract infections' associated with mould and/or dampness was similar (1.49 95% CI 1.28 – 1.74) to the one we selected from Fisk et al 2010 specific to 'Respiratory infections excluding common cold and nonspecific upper respiratory infections' (1.50 95% CI 1.32 – 1.70), which was primarily estimated from studies of LRI sub-types (see information above).

Allergic rhinitis

We used the meta-analysis by (Jaakkola et al. 2013) to provide the summary effect estimate for allergic rhinitis among children associated with any damp or mould, which included studies published between 1950 - 2012. For children, we used the summary effect estimate which was calculated specifically among the sub-sample of studies among children aged up to 16 years old from the random effects model (1.43 95% CI 1.34 – 1.53, taken from Table E8 in (Jaakkola et al. 2013)) combining all exposures together (e.g., any dampness or mould). While the study by Jaakkola et al also meta-analysed studies looking at rhinitis and rhinoconjunctivitis, the evidence base was strongest for allergic rhinitis, and included estimates from 3 cohort studies which had consistent findings with the cross-sectional and case-control studies.

Though, as a sensitivity analysis in the paper, we also made burden of disease estimates for allergic rhinitis among children using an alternative OR (1.15 95% CI 1.003 – 1.32) given by (Wang et al. 2022), which followed offspring (n=17,881) from the adults enrolled in the original RHINE study over time (see description of (Wang et al. 2019) above for details) (used the OR for 'dampness/mould during both follow up periods').

We also used the longitudinal multi-centre cohort study by (Wang et al. 2019) (described above) to provide the odds ratio (1.28 95% CI 1.08 – 1.52) for allergic rhinitis among adults associated with any damp or mould at follow-up, because the vast majority of included studies in (Jaakkola et al. 2013) were among children.

S5. ‘Counterfactual’ lower exposure level for the PAF calculation of childhood asthma and formaldehyde

The lower exposure thresholds (counterfactuals) applied to RRs in PAF calculations are set to reflect threshold effects (if present and known) and/or a reluctance to extrapolate beyond the range of available data at the lower end of the exposure distribution (Gowers et al. 2020). Below a counterfactual exposure threshold, it is assumed that there is no increased risk of health effects. For formaldehyde and asthma, a range of counterfactuals have been used in previous burden of disease calculations, and it is not exactly known what the threshold of effect may be from the available epidemiological evidence (as described below).

The WHO conducted a burden of disease assessment of asthma and formaldehyde exposures among infants and young children (WHO Regional Office for Europe 2011) using risk estimates (ORs) from the study by (Rumchev et al. 2002). The Rumchev study (infants in Australia) observed an increased OR for children exposed in the 50-59 and 60+ $\mu g/m^3$ categories, and no increased ORs for children exposed between 10-29 ug/m^3 and 30-49 $\mu g/m^3$. The WHO assessment used the OR comparing infants exposed above 60 $\mu g/m^3$ with infants exposed below 10 $\mu g/m^3$ (1.39) in their PAF equation.

In 2014, Hänninen et al (Hanninen et al. 2014) published a burden of disease assessment where the Rumchev estimate was used again to reflect the relationship between asthma and formaldehyde among infants and young children, however the OR was rescaled to reflect a linear relationship with 1 $\mu g/m^3$ increment increases. In the PAF calculation, Hänninen et al set the counterfactual lower exposure level to be 100 $\mu g/m^3$ to reflect the current WHO guideline level for formaldehyde exposure (World Health Organisation 2010). However, we note that this guideline is actually set to identify a safe level with regards to eye irritation from short-term exposure and is not based on asthma evidence or data. Furthermore, a sensitivity analysis was conducted in an accompanying report where the counterfactual exposure level in the PAF calculation was set down to 40 $\mu g/m^3$, which resulted in a large (as suspected) increase in the estimated burden of disease (EBoDE Working Group 2011).

In 2019, Rojas-Rueda et al (Rojas-Rueda et al. 2019) conducted a similar assessment to the one by Hänninen et al (also using the OR from (Rumchev et al. 2002)), setting the counterfactual exposure level to 100 $\mu g/m^3$ to reflect the WHO guideline level. However, in a sensitivity analysis, they set the counterfactual level to 60 $\mu g/m^3$.

Since these burden of disease assessments were conducted, new meta-analyses of childhood asthma and formaldehyde exposures (at school and home) have been published (Lam et al. 2021; Liu et al. 2023; Yu et al. 2020). The study by Yu et al found that there was an increased OR of asthma for children with exposures below and above 22.5 $\mu g/m^3$ (though a non-significant increased OR at the higher end of exposure due to a lack of power). The study by Lam et al 2021 did not provide a threshold of effect for the meta-analysed risk estimate, however, the range of minimum exposures measured across the included 9 meta-analysed studies were 1 $\mu g/m^3$ to 16 $\mu g/m^3$. Some studies included in the Lam review also showed increased ORs at the 20-50 and >50 $\mu g/m^3$ levels compared with <20 $\mu g/m^3$ (Garrett et al. 1998) as well as >60 $\mu g/m^3$ (Krzyzanowski et al. 1990) ((Lam et al. 2021) supplementary Figure 6). The meta-analysis by Liu et al 2023 did not comment on a possible threshold of effect.

The meta-analysis of asthma and formaldehyde conducted by (McGwin et al. 2010) made the following statement which was drawn from the study by Franklin et al 2000: ‘*individuals with a home formaldehyde concentration of at least 50 ppb had a significantly increased volume of exhaled nitric oxide, which serves as a marker of airway inflammation’* (Page 3850). Lastly, Health Canada’s 8-hour residential indoor air quality guideline value for formaldehyde exposures at 50 $\mu g/m^3$ was based on the health evidence for asthma in children.

The above evidence highlights that there is still uncertainty around whether positive associations with asthma diagnosis/self-report are present at lower exposure levels, though several studies do point to associations observed above 20 $\mu g/m^3$, and particularly above 50 and 60 $\mu g/m^3$. As such we have decided to set a range of lower ERF thresholds based on the evidence at hand, which will allow us to calculate a range of burden estimates

reflecting the uncertainty in this assessment. At the lower end, we set the counterfactual to 20 μg/m^3 and at the higher end at 60 μg/m^3. We have chosen a central counterfactual level to sit at 50 μg/m^3. We will use the central counterfactual as our primary estimate in the analysis but show the range of estimated burden of disease values when shifting the counterfactual to higher or lower levels.

Table S7. Proposed lower exposure thresholds for PAF calculations

Range	**Formaldehyde exposure (concentration) level μg/m^3**
Counterfactual exposure level (lower end)	20
Counterfactual exposure level (mid-range)	50
Counterfactual exposure level (higher-end)	60

S6. Damp and mould Population Attributable Fractions for allergic rhinitis and bronchitis

Table S8. The Population Attributable Fractions for allergic rhinitis and bronchitis associated with exposure to damp and/or mould in English housing in 2019.

	Exposure classification*	Age group	% of dwellings	ERF (RR, OR, HR) [95% CI]	Population Attributable Fraction [95% Confidence Interval (CI)]
Allergic Rhinitis (AR)	Any damp	0-14	4.2 %	1.43 [1.43 – 1.53] (Jaakkola et al. 2013)	0.018 [0.014 – 0.022]
Allergic Rhinitis (AR)	Any damp	15-49	3.4%	1.28 [1.08 – 1.52] (Wang et al. 2019)	0.009 [0.002 – 0.017]
Bronchitis	Any damp	0-14	4.2%	1.45 [1.32 – 1.59] (Fisk et al. 2010)	0.019 [0.013 – 0.024]
Bronchitis	Any damp	15-49	3.4%	1.45 [1.32 – 1.59] (Fisk et al. 2010)	0.015 [0.010 - 0.019]
Sensitivity analysis					
Allergic Rhinitis (AR)	Any damp	0-14	4.2%	1.15 [1.003 – 1.32] (Wang et al. 2022)	0.006 [0.00 – 0.013]

*'Any damp' in the EHS can also be described as any damp and/or mould.

S7. Percentage of dwellings with any damp (inequalities analysis)

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. Data in this table is taken directly from ((DLUHC 2022) (Table DA5103 (SST5.3))).

Group	% of dwellings
Income groups	
1st quintile (lowest)	5.4
2nd quintile	4.5
3rd quintile	3.1
4th quintile	2.0
5th quintile (highest)	2.0
Long term illness or disability	
Yes	4.5
No	2.8
Ethnicity of HRP	
white	3.1
black	7.9
Asian	6.7
other	2.0
all minority	5.9

HRP: Household reference person

References

Berry, R.; Brown, V.; Coward, S.; Crump, D.; Gavin, M.; GRimes, C., et al. Indoor Air Quality in Homes; Parts 1 and 2 – the Building Research Establishment Indoor Environment ed^eds. Watford, UK; 1996

Burman, E.; Stamp, S. Trade-offs between ventilation rates and formaldehyde concentrations in new-build dwellings in the UK. AIVC; 2019

Caillaud, D.; Leynaert, B.; Keirsbulck, M.; Nadif, R. Indoor mould exposure, asthma and rhinitis: findings from systematic reviews and recent longitudinal studies. European Respiratory Review 2018;27:170137

Coggins, A.M.; Wemken, N.; Mishra, A.K.; Sharkey, M.; Horgan, L.; Cowie, H., et al. Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings. Build Environ 2022;219

Crump, D.; Dimitroulopoulou, S.; Squire, R.; Ross, D.; Pierce, B.; White, M., et al. Ventilation and indoor air quality in new homes. 2005

Dai, X.; Dharmage, S.C.; Lodge, C.J. The relationship of early-life household air pollution with childhood asthma and lung function. European Respiratory Review 2022;31:220020

DLUHC. English Housing Survey data on dwelling condition and safety. 2022;Feb 2023:https://www.gov.uk/government/statistical-data-sets/dwelling-condition-and-safety

EBoDE Working Group. European Perspectives on Environmental Burden of Disease: Estimates for Nine Stressors in Six European Countries. in: Hanninen O., Knol A., eds. Helsinki, Finland; 2011

Fisk, W.J.; Chan, W.R.; Johnson, A.L. Does dampness and mold in schools affect health? Results of a meta-analysis. Indoor Air 2019;29:895-902

Fisk, W.J.; Eliseeva, E.A.; Mendell, M.J. Association of residential dampness and mold with respiratory tract infections and bronchitis: a meta-analysis. Environ Health 2010;9:72

Fisk, W.J.; Lei-Gomez, Q.; Mendell, M.J. Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. Indoor Air 2007;17:284-296

Garrett, M.H.; Abramson, M.J.; Hooper, B.M.; Rayment, P.R.; Strasser, R.P.; Hooper, M.A. Indoor environmental risk factors for respiratory health in children. Indoor Air 1998;8:236-243

Gee, I.L.; Watson, A.F.R.; Tavernier, G.; Stewart, L.J.; Fletcher, G.; McL Niven, R. Indoor air quality, environmental tobacco smoke and asthma: A case control study of asthma in a community population. Indoor Built Environ 2005;14:215-219

Gowers, A.M.; Walton, H.; Exley, K.S.; Hurley, F.J. Using epidemiology to estimate the impact and burden of exposure to air pollutants. Phil Trans R Soc A 2020;378:20190321

Hanninen, O.; Asikainen, A. Efficient reduction of indoor exposures: Health benefits from optimizing ventilation, filtration and indoor source controls. National Institute for Health and Welfare; 2013

Hanninen, O.; Knol, A.B.; Jantunen, M.; Lim, T.A.; Conrad, A.; Rappolder, M., et al. Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries. Environmental Health Perspectives 2014;122:439-446

Jaakkola, M.S.; Quansah, R.; Hugg, T.T.; Heikkinen, S.A.; Jaakkola, J.J. Association of indoor dampness and molds with rhinitis risk: a systematic review and meta-analysis. J Allergy Clin Immunol 2013;132:1099-1110.e1018

Kanchongkittiphon, W.; Mendell, M.J.; Gaffin, J.M.; Wang, G.; Phipatanakul, W. Indoor environmental exposures and exacerbation of asthma: an update to the 2000 review by the Institute of Medicine. Environmental health perspectives 2015;123:6-20

Knibbs, L.D.; Woldeyohannes, S.; Marks, G.B.; Cowie, C.T. Damp housing, gas stoves, and the burden of childhood asthma in Australia. Med J Australia 2018;208:299-302

Krzyzanowski, M.; Quackenboss, J.J.; Lebowitz, M.D. Chronic Respiratory Effects of Indoor Formaldehyde Exposure. Environ Res 1990;52:117-125

Lam, J.; Koustas, E.; Sutton, P.; Padula, A.M.; Cabana, M.D.; Vesterinen, H., et al. Exposure to formaldehyde and asthma outcomes: A systematic review, meta-analysis, and economic assessment. Plos One 2021;16

Liu, N.R.; Fang, L.; Liu, W.; Kan, H.D.; Zhao, Z.H.; Deng, F.R., et al. Health effects of exposure to indoor formaldehyde in civil buildings: A systematic review and meta-analysis on the literature in the past 40 years. Build Environ 2023;233

McGill, G.; Oyedele, L.O.; Keefe, G. Indoor air-quality investigation in code for sustainable homes and passivhaus dwellings. World Journal of Science, Technology, and Sustainable Development 2015a;12:39-60
McGill, G.; Oyedele, L.O.; McAllister, K. Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. International Journal of Sustainable Built Environment 2015b;4:58-77
McGill, G.; Oyedele, L.O.; McAllister, K. An investigation of indoor air quality, thermal comfort and sick building syndrome symptoms in UK energy efficient homes. Smart and Sustainable Built Environment 2015c;4:329-348
McGill, G.; Sharpe, T.; Oyedele, L.O.; Keeffe, G.; McAllister, K. An Investigation of Indoor Air Quality in UK Passivhaus Dwellings. Smart Energy Control Systems for Sustainable Buildings: Springer International; 2017
McGwin, G.; Lienert, J.; Kennedy, J.I. Formaldehyde Exposure and Asthma in Children: A Systematic Review. Environmental Health Perspectives 2010;118:313-317
Mendell, M.J. Indoor residential chemical emissions as risk factors for-respiratory and allergic effects in children: a review. Indoor Air 2007;17:259-277
Mendell, M.J.; Mirer, A.G.; Cheung, K.; Tong, M.; Douwes, J. Respiratory and allergic health effects of dampness, mold, and dampness-related agents: A review of the epidemiologic evidence. Environmental Health Perspectives 2011;119:748-756
MHCLG. Ventilation and Indoor Air Quality in New Homes. London, UK; 2019
Mohle, G.; Crump, D.; Brown, V.; Hunter, C.; Squire, R.; Mann, H., et al. Development and application of a protocol for the assessment of indoor air quality. Indoor Built Environ 2003;12:139-149
Mudarri, D.H. Valuing the Economic Costs of Allergic Rhinitis, Acute Bronchitis, and Asthma from Exposure to Indoor Dampness and Mold in the US. J Environ Public Health 2016;2016:2386596
Nurmatov, U.B.; Tagiyeva, N.; Semple, S.; Devereux, G.; Sheikh, A. Volatile organic compounds and risk of asthma and allergy: A systematic review of observational and interventional studies. Eur Respir J 2013;42
Park, J.H.; Cox-Ganser, J.M. Mold exposure and respiratory health in damp indoor environments. Frontiers in Bioscience - Elite 2011;3 E:757-771
Quansah, R.; Jaakkola, M.S.; Hugg, T.T.; Heikkinen, S.A.; Jaakkola, J.J. Residential dampness and molds and the risk of developing asthma: a systematic review and meta-analysis. PLoS One 2012;7:e47526
Raw, G.J.; Coward, S.K.D.; Brown, V.M.; Crump, D.R. Exposure to air pollutants in English homes. J Expo Anal Env Epid 2004;14:S85-S94
Riggs, L.; Keall, M.; Howden-Chapman, P.; Baker, M.G. Environmental burden of disease from unsafe and substandard housing, New Zealand, 2010-2017. B World Health Organ 2021;99:259-270
Rojas-Rueda, D.; Vrijheid, M.; Robinson, O.; Marit, A.G.; Grazuleviciene, R.; Slama, R., et al. Environmental Burden of Childhood Disease in Europe. International Journal of Environmental Research and Public Health 2019;16
Rumchev, K.B.; Spickett, J.T.; Bulsara, M.K.; Phillips, M.R.; Stick, S.M. Domestic exposure to formaldehyde significantly increases the risk of asthma in young children. Eur Respir J 2002;20:403-408
Stamp, S.; Burman, E.; Shrubsole, C.; Chatzidiakou, L.; Mumovic, D.; Davies, M. Seasonal variations and the influence of ventilation rates on IAQ: A case study of five low-energy London apartments. Indoor Built Environ 2022;31:607-623
Tischer, C.; Chen, C.; Heinrich, J. Association of asthma and allergy with domestic mould and mould components in children: A systematic review. Allergy: European Journal of Allergy and Clinical Immunology 2011;66:201-202
US EPA. IRIS Toxicological Review of Formaldehyde-Inhalation (External Review Draft, 2022). Washintgon, DC; 2022
Venn, A.J.; Cooper, M.; Antoniak, M.; Laughlin, C.; Britton, J.; Lewis, S.A. Effects of volatile organic compounds, damp, and other environmental exposures in the home on wheezing illness in children. Thorax 2003;58:955-960
Wang, C.M.; Barratt, B.; Carslaw, N.; Doutsi, A.; Dunmore, R.E.; Ward, M.W., et al. Unexpectedly high concentrations of monoterpenes in a study of UK homes. Environ Sci-Proc Imp 2017;19:528-537

Wang, J.; Janson, C.; Malinovschi, A.; Holm, M.; Franklin, K.A.; Modig, L., et al. Asthma, allergic rhinitis and atopic dermatitis in association with home environment-The RHINE study br. Sci Total Environ 2022;853

Wang, J.; Pindus, M.; Janson, C.; Sigsgaard, T.; Kim, J.L.; Holm, M., et al. Dampness and mould at home and at work in the RHINE study: Increased onset and decreased remission of adult respiratory symptoms, asthma and rhinitis. Eur Respir J 2019;54

WHO Regional Office for Europe. Environmental burden of disease associated with inadequate housing. Bonn; 2011

World Health Organisation. WHO guidelines for indoor air quality: selected pollutants. Bonn: WHO European Centre for Environment and Health; 2010

Yu, L.L.; Wang, B.; Cheng, M.; Yang, M.; Gan, S.M.; Fan, L.Y., et al. Association between indoor formaldehyde exposure and asthma: A systematic review and meta-analysis of observational studies. Indoor Air 2020;30:682-690