The protection from harm to populations of people provided by Exposure Limit Values

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ABSTRACT

The protection from chronic harm provided by exposure limit values (ELVs) is evaluated for indoor air contaminants set by regulatory bodies of member countries in the Air Infiltration and Ventilation Centre (AIVC). Significant variability was found in the regulated harm levels from ELVs for the same contaminants across different countries, highlighting inconsistencies in public health protection. The concept of a regulated harm budget (RHB) is introduced, representing the total allowed harm from regulated contaminants implicitly set by a regulatory body. Among AIVC countries, Spain is the only nation with an RHB of 2400 DALYs/10^5 person/year for the three key contaminants $PM_{2.5}$, NO_2, and formaldehyde. The RHBs for most AIVC countries exceeded harm values associated with smoking and alcoholism. This underscores the need for interventions to mitigate indoor air contaminant harm and reduce it to acceptable levels that are comparable to other regulated risks.

KEYWORDS

DALY, IAQ, health, regulated harm budget, ELVs.

1 INTRODUCTION

A health-centred approach was recently used (Morantes et al. 2024) to quantify and compare the chronic harm caused by indoor air contaminants in dwellings of the Global North using the disability-adjusted life-year (DALY). Epidemiological and toxicological evidence of population morbidity and mortality was used to determine Harm Intensities (HI), a metric of chronic harm per unit of contaminant concentration. The HIs are specific to each contaminant and can be used for any environment. The chronic harm per year for each contaminant is the product of a long-term median exposure concentration and an HI. The harm for each contaminant can be summed to identify the harm caused by many contaminants.

The magnitude of harm for each contaminant can be used to rank them and identify Contaminants of Concern (CoC). The most harmful contaminants in dwellings are fine particulate matter ($PM_{2.5}$), the coarse fraction of particulate matter ($PM_{10-2.5}$), nitrogen dioxide (NO_2), formaldehyde (HCHO), radon, and ozone (O_3). They are CoCs because, together, they account for over 99% of total median harm in dwellings and so can then be used to regulate their IAQ. One way to do this is to set a harm budget, the distribution of harm that is expected in an acceptable reference scenario (Morantes et al. 2024).

National regulatory bodies, environmental agencies, and global health organizations regularly establish indoor and outdoor air quality standards and guidelines for various contaminants. These entities typically rely on exposure limit values (ELVs) to protect public health, defining the maximum permissible concentration experienced over a given exposure period. However, ELVs for the same contaminants may vary significantly across different organizations for identical exposure periods (Abdul-Wahab et al. 2015; Morantes et al. 2016; Salis et al. 2017). Such disparities in ELVs implicitly reflect varying assessments of contaminant harm influenced by policy considerations, policymaker judgments, and differences in available contaminant data, rather than representing consistent hazard levels. The derivation of guidelines and standards also varies, some as the consequence of practical experience, others from comprehensive reviews and expert consensus on the health effects of contaminants. Most standards are established through toxicological and epidemiological health impact assessments (Borsboom et al. 2016).

The concept of the harm budget (Morantes et al. 2024) can be refined further to incorporate the ELVs of contaminants along with their corresponding HIs. This refined approach, termed the Regulated Harm Budget (RHB), enables the determination of the magnitude of harm associated with each contaminant's ELV. Essentially, the RHB represents the total allowed harm from all regulated contaminants, implicitly established by a regulatory body. This approach also draws inspiration from the IAQ equivalence principle proposed by Sherman, Walker, and Logue (2012).

We assess the degree of protection from chronic harm by using exposure limit values (ELVs) of member countries of the Air Infiltration and Ventilation Centre (AIVC) for indoor environments. The method is described in Section 2. The results are presented in Section 3 and are discussed in Section 4.

2 METHOD

2.1 Estimating Chronic Harm

All-cause chronic population *harm* (DALY/person/year) from the inhalation of a specific airborne contaminant (indicated by the subscript i) is a function of a harm intensity, HI_i, (DALY/μg/m^3/person/year) and a concentration, C_i.

$$Harm_i = HI_i \cdot C_i \quad (1)$$

Generally, the contaminant concentrations are reported in units of μg/m^3, but some have others, such as Bq/m^3 for radon, and CFU/m^3 for mold spores. The reported statistic should be an annual median given the expected log-normality of any distribution of contaminant measurements (Ott 1990). Harm intensities for a total of 110 contaminants are considered here: 45 indoor contaminants commonly found in dwellings are given in Morantes et al. (2024) and 65 other indoor contaminants (data not published).

The harm intensities are specific to individual contaminants and can be applied in any environment. However, a limitation persists: when the concentration surpasses a maximum median threshold, higher estimates of harm are obtained compared to a non-linear approach. In the case of epidemiology-based HIs, Table 1 gives appropriate concentration thresholds for a linear approach to HI, considering a 10% mean absolute percentage error overestimation as the limit (Morantes et al. 2024). Conversely, for toxicology-based HIs, no such limit is indicated, as this approach demonstrates applicability across a full range of concentrations (Fantke et al. 2017).

Table 1: Appropriate concentration thresholds for a linear HIi approach

Contaminant (i)	Concentration Regime (µg/m^3)	Mean Absolute Percentage Error (%)
Acrolein	(0 – 2.7)	10 (95% C.I. 9–20)
Benzene	(0 – 890)	10 (95% C.I. 8–10)
Formaldehyde	(0 – 33)	10 (95% C.I. 10–10)
Mold	(0 – 3750)	10 (95% C.I. 9–10)
Nitrogen dioxide	(0 – 225)	10 (95% C.I. 10–10)
Ozone	(0 – 495)	10 (95% C.I. 10–10)
PM_{10}	(0 – 108)	10 (95% C.I. 10–10)
$PM_{2.5}$	(0 – 50)	10 (95% C.I. 10–10)
Radon	(0 – 425)	9 (95% C.I. 8–10)
Sulphur dioxide	(0 – 66)	10 (95% C.I. 9–10)

2.2 Estimating Regulated Harm Budgets (RHB)

The total harm estimated using all contaminant ELVs specified by a regulatory body constitutes a Regulated Harm Budget (RHB). However, not all contaminants specified have a high HI and/or are only found at low concentrations, and so are not particularly harmful. The CoCs identified by Morantes et al. (2024) are harmful and so the analysis is restricted to these.

Accordingly, a RHB for any regulatory body is defined as

$$RHB = \sum_{i=1}^{N_{CoCs}} HI_i \cdot \hat{C}_i \qquad (2)$$

Here, N_{CoC} represents the total number of Contaminants of Concern for which ELVs are specified by a regulatory body, and $\hat{C}$ denotes the long-term concentration threshold specified by a regulatory body in a relevant standard or guideline.

There is limited evidence of chronic synergistic effects at the concentrations expected in buildings and so the RHB in Equation (2) is calculated additively, following conventional risk assessment practice and the Concentration Addition principle (Morantes et al. 2024).

2.3 Sources of Data

We use the online guidelines database of the International Society of Indoor Air Quality and Climate (ISIAQ) STC34 Indoor Environmental Quality (IEQ), compiled by Dimitroulopoulou et al. (2023). It contains 844 entries, which we reduce to 746 by excluding non-contaminants, such as water,

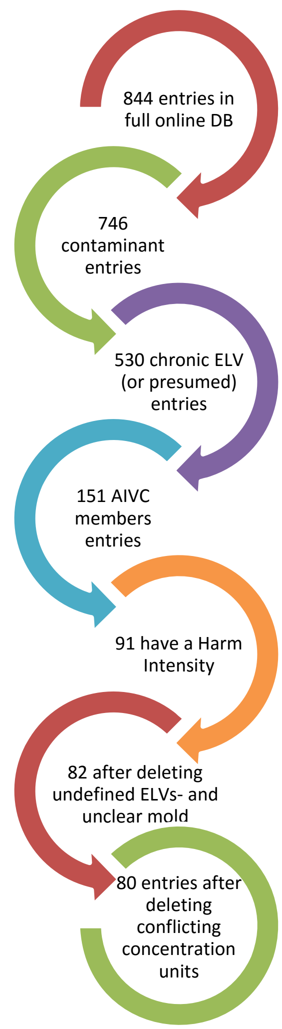

Figure 1. Data analysis workflow.

air temperature, relative humidity, and PM ratios. Entries are categorized based on averaging times, denoted as chronic (>24h, annual), acute (<24h), and no data. Entries without exposure periods were retained by assuming applicability across all timeframes. Removing acute entries left 530 entries. Restricting the dataset to member countries of the Air Infiltration and Ventilation Centre (AIVC) left 151 entries. Considering only contaminants with a harm intensity (including Total Volatile Organic Compounds, TVOCs) left 91 entries. Removing entries with undefined ELVs, indicated by statements such as "as low as possible", reduced the dataset to 85 entries. Two more entries for airborne mold were removed because some of the information was unclear, and to ensure consistency, entries with conflicting concentration units (pCi/L) were excluded, although they will be converted in future work. This gave a final dataset of 80 entries for assessment; see Figure 1.

3 RESULTS AND DISCUSSION

3.1 Regulated Harm Budgets

To ensure a fair comparison between different RHBs, it is essential that they consider the same set of contaminants. So far, CoCs have only been identified in dwellings using a harm-based approach, but there is a need to extend the analysis to other common indoor environments, such as offices, schools, or shops, where the types and concentrations of contaminants may differ from dwellings.

Table 2 presents RHBs for countries where identical CoCs are regulated. It shows that Spain is the only country to have ELVs for all three CoCs, and so this RHB cannot be compared directly against the others. The magnitude of its RHB is a median of 2400 DALYs/10^5 person/year, and so if all buildings in Spain were compliant then the RHB indicates the maximum median population harm from exposure to HCHO, NO_2 and $PM_{2.5}$.

China, Spain, and Norway have ELVs for the chronic exposure to both NO_2 and $PM_{2.5}$. The USA and Spain are the only countries with ELVs for HCHO and $PM_{2.5}$. ELVs for HCHO and NO_2 are specified by Sweden, Spain, France, and the UK. The ELVs for $PM_{2.5}$ typically result in a greater regulated harm when compared to other contaminants. This confirms the disparity in the allowable harm for different contaminant and highlights the need for consistent hazard levels.

Table 2: Regulated harm budgets for selected contaminants, by country. Highest to lowest median harm. DALYs/10^5 person/year.

Contaminants	Country	Regulated Harm Budget	Geometric Standard Deviation
HCHO, NO_2, $PM_{2.5}$	Spain	2400	1.3
NO_2, $PM_{2.5}$	China	3600	1.2
	Spain	2400	1.3
	Norway	1500	1.2
HCHO, $PM_{2.5}$	USA	2200	1.2
	Spain	1200	1.2
HCHO, NO_2	Sweden	7300	1.5
	Spain	1100	1.7
	France	570	1.8
	UK	280	1.6

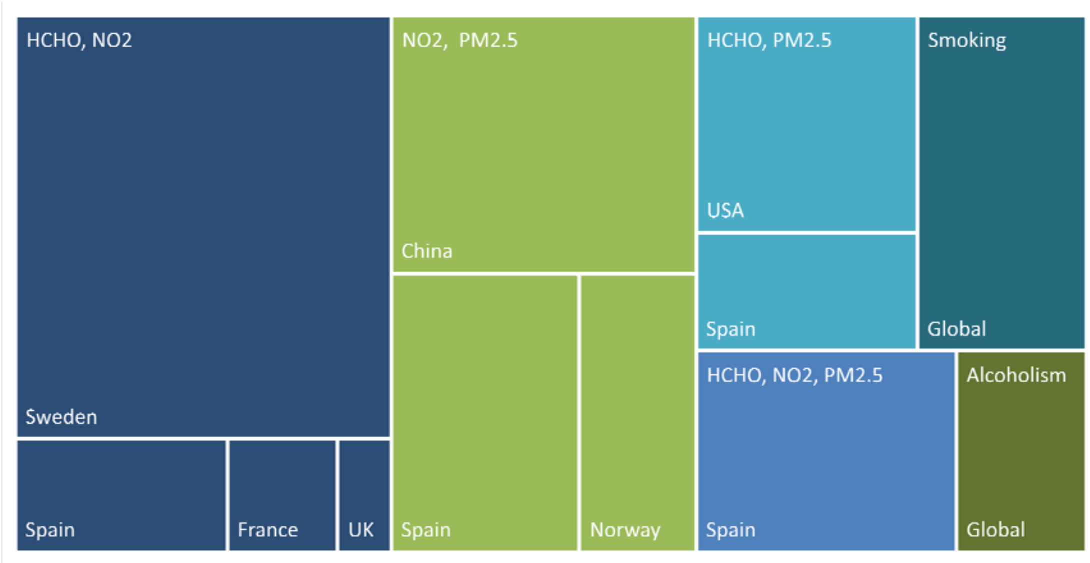

Figure 2. Median regulated harm budgets and other known risks treemap.

To contextualize the data in Table 2, the RHBs are compared against the harm caused by other daily hazards typically deemed unacceptable by the general population, such as the global burden attributed to alcoholism (1200 DALYs/10^5 person/year) and smoking (2600 DALYs/10^5 person/year) (IHME 2019). Figure 2 illustrates the median RHBs using a tree-map and shows that Spain's three-CoC RHB is equivalent to the burden of disease from smoking. The RHBs for most AIVC countries, however, exceed the harm values for smoking and alcoholism. There are already interventions in place in most countries to reduce population harm from them, and so these results suggest that appropriate interventions should be applied to mitigate against the harm from indoor air contaminants too and reduce it to an acceptable level.

3.2 Regulating IAQ

The results show the regulated harm budget (RHB) for the AIVC countries vary a lot, even when the same set of CoCs are considered. Those contaminants do not contribute equally to the budget. To ensure that they do, contaminants must be expected to be both present and at harmful concentrations. Conversely, it is inadvisable to include contaminants expected to cause little harm as the measurement, and control of those contaminants is not cost effective. CoCs for dwellings have been identified by Morantes et al. (2024); see Section 1. In that study, harm from 44 contaminants prevalent in dwellings was calculated at (median) 2,200 DALYs/10^5 person/year.

For typical occupancies, countries should determine a harm budget from those CoCs and allow trade-offs between them. ELVs can be used in special situations where other contaminants are expected at unusually high concentrations.

This work serves as an initial evaluation of RHBs using ELVs rather than a definitive benchmark. More research is needed on guideline development and resulting health impacts, as there is considerable uncertainty in this arena. Nonetheless, this approach provides a starting point for assessing the protectiveness of indoor air quality regulations.

Future work will evaluate RHBs for all countries in the ISIAQ database, for different regulatory bodies in the same country (ASHRAE and the Environmental Protection Agency), and for the World Health Organization. Additionally, an exploration of calculating harm intensities for contaminants not included in the current analysis will be conducted, effectively expanding the scope and depth of the study.

While our study provides insights into the assessment of regulated harm from indoor air contaminants, it is important to acknowledge certain limitations. Firstly, the ELVs for chronic exposures extracted from the database were assumed to be applicable without thorough validation. Therefore, future research should focus on ensuring the consistency and accuracy of these ELVs to enhance the reliability of our findings.

4 CONCLUSIONS

There is significant variability in the regulated harm levels from exposure limit values set by different regulatory bodies for the same indoor air contaminants, highlighting inconsistencies in the level of public health protection provided.

We show a regulated harm budget, representing the total allowed harm from all regulated contaminants implicitly established by a regulatory body. Among the AIVC countries considered, Spain is the only nation with recommended chronic limit values for three key contaminants of concern ($PM_{2.5}$, NO_2, and formaldehyde), with an RHB of 2400 DALYs/10^5 person/year.

The regulated harm budgets for most AIVC countries exceed the harm values associated with smoking and alcoholism, suggesting that appropriate interventions should be applied to mitigate the harm from indoor air contaminants.

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