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Quantifying Health Benefits of Stricter PM Standards: A Comparison of EU and WHO Annual Guidelines

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ABSTRACT

Inhalation of particulate matter (PM) is associated with respiratory, cardiovascular, and systemic health effects. In 2019, global outdoor PM exposure caused over 4.2 million premature deaths, according to the World Health Organization (WHO, 2024). Reducing PM exposure is therefore essential. This study compares outdoor European Union (EU) air quality standards (Directive 2008/50/EC) with outdoor WHO guidelines, focusing on mean annual concentrations of $PM_{2.5}$ and PM_{10} and their associated health impacts (WHO, 2021). These impacts were quantified using Disability-Adjusted Life Years (DALYs) per 100,000 people. Findings show that EU standards for mean annual $PM_{2.5}$ (20 µg/m³) and PM_{10} (40 µg/m³) are substantially higher than WHO recommendations (5 µg/m³ and 15 µg/m³, respectively), resulting in significant health impacts. Estimated burdens under current EU standards are 1,390 (95% CI: 1,377–1,403) and 1,990 (95% CI: 1,978–2,003) DALYs per 100,000 people annually for $PM_{2.5}$ and PM_{10}, compared to 350 (95% CI: 345–355) and 740 (95% CI: 735–745) DALYs under WHO guidelines. In March 2024, the EU proposed updating its standards to more closely align with WHO goals, including reducing $PM_{2.5}$ to 10 µg/m³ by 2030, still double the WHO guideline. As outdoor PM significantly influences indoor concentrations through ventilation and infiltration, and people spend most of their time indoors, this study also evaluates the influence of outdoor concentration on indoor exposure via case studies of a hospital waiting room and a three-bedroom apartment. Results show that, in absence of strong indoor sources, outdoor PM concentrations significantly impact indoor air quality (IAQ) through ventilation and building infiltration, leading to indoor concentrations that nearly match those outdoors. These findings emphasize the critical need for strict outdoor air quality standards and effective ventilation strategies to maintain safe indoor environments. Overall, this analysis supports the substantial public health benefits of aligning EU standards with WHO guidelines to reduce the disease burden associated with PM exposure.

INTRODUCTION

Air quality has been a major public health concern since industrialization and urbanization in the 18th century, which increased pollutant emissions and significantly contributed to the global burden of disease (Morantes et al., 2023). Despite national and regional efforts to reduce emissions, by the early 21st century, air pollution remained a leading health issue (Fowler et al., 2020). In response, the World Health Organization (WHO) introduced its first global outdoor air quality guidelines in 1987 (Huang, 2022).

Among all pollutants, particulate matter (PM) is the most harmful to human health (Sang et al., 2022). It includes all solid and liquid particles suspended in the air with particle diameters smaller than 10 µm (3.94×10^{-4} in.). According to the WHO (2024) exposure to outdoor air pollution by fine PM caused over 4.2 million premature deaths globally per year in 2019, contributing to health outcomes such as cardiovascular and respiratory diseases, preterm labor, miscarriages, and asthma (Kim et al., 2015; Mukherjee & Agrawal, 2017; Neas, 2000). It is also responsible for more than 80 million disability-adjusted life

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years (DALYs) each year, reflecting a significant decline in population health and quality of life. (Lu et al., 2023).

To manage PM exposure, numerous national and international outdoor air quality standards have been introduced. The WHO regularly updates its health-based guidelines, most recently in 2021, setting limits based on daily and annual outdoor averages (WHO, 2021). The European Union also sets legally binding outdoor IAQ standards, with the current 2008 directive under revision to better align with WHO recommendations (Fowler et al., 2020).

However, no safe threshold for PM exposure has been identified, underscoring the need for metrics that reflect health impacts more accurately (Marks, 2022). As a result, burden-of-disease metrics such as Disability-Adjusted Life Years (DALYs) have gained prominence (Morantes et al., 2023). DALYs, introduced by Murray (1994), combine years of life lost and years lived with disability to quantify disease burden, and have been used by the WHO to inform guidelines since 2005. (WHO, 2009.; C. J. Murray, 1994; C. J. L. Murray & Acharya, 1997).

A persistent gap remains between the health-based WHO guidelines and the more flexible regulatory EU standards shaped by political and economic considerations. This discrepancy can have substantial implications for population health. This study compares WHO guideline values and EU legal standards in terms of average concentrations and associated DALYs to quantify this health gap. It also considers the forthcoming revision of the EU directive. Given that people spend approximately 90% of their time indoors and outdoors concentrations have a large influence on indoor concentrations due to ventilation and infiltration, the study includes two case studies demonstrating how outdoor air quality standards affect indoor air quality (IAQ) and, by extension, public health. These findings emphasize the need for mandatory air quality regulations that more closely reflect actual health burdens associated with PM exposure.

METHODOLOGY

To assess the differences between the outdoor air quality guideline values set by the World Health Organization (WHO) and the outdoor air quality standards established by the European Union (EU), average concentration values from both frameworks are compared. Additionally, the Disability-Adjusted Life Years (DALYs) metric is employed to quantify the health impacts associated with these concentrations and two case studies are reviewed.

Regulations

The first step in this comparison is to assess the current limit values set by the WHO and the European Union. Limit values are set for yearly and daily average outdoor concentrations of $PM_{2.5}$ (<2.5 µm or 9.8×10^{-6} in) and PM_{10} (<10 µm or 3.94×10^{-4} in). These values can be compared directly. Additionally, the expected new target value for the annual mean outdoor $PM_{2.5}$ concentration by 2030, as outlined in the European Green Deal, can be compared to these values.

DALYs

Secondly, the corresponding burden of disease for each of these annual or daily outdoor limit values can be calculated using the Disability-Adjusted Life Years (DALYs) metric for a projected population exposed to these concentrations, under the assumption that population exposure aligns with the respective guideline limits. This calculation yields the number of healthy life years lost per 100,000 individuals when subjected to the specified concentration for one year, providing an alternative method to compare EU and WHO values in terms of public health.

The total number of DALYs per 100,000 individuals is calculated using research by Guyot et al. (2024), employing Eq. (1) to accumulate DALYs for one year and Eq. (2) to determine the burden of disease over a specific timeframe. This research uses a time-resolved calculation method for DALYs, based on work by De Jonge & Laverge (2022).

$$DALYs(t) = \int_{t_0}^{t} \frac{DALYs}{time}(t) \quad (1)$$

$$\frac{DALYs}{time}(t) = EF_{median} * IR(t) \quad (2)$$

In Eq.(2) EF_{median} is the effect factor in DALY/kg (DALY/lb), which represents the harmfulness of a specific contaminant. The values used were calculated based on epidemiological research by Morantes (2024) and are presented in

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Table 1, including their 95% confidence intervals to reflect uncertainty. The effect factor for PM_{10} is significantly lower than that of $PM_{2.5}$, corresponding to the growing body of research stating that smaller particles are more harmful to public health as they are able to penetrate deeper into the body and affect more organs (Kim et al., 2015).

Table 1. Effect Factors for Particulate Matter (Morantes et al., 2024)

Category	EF median [DALY/kg]	95% CI EF [DALY/kg]	EF median [DALY/lb]	95% CI EF [DALY/lb]
$PM_{2.5}$	*118.61*	*117.95 – 119.32*	*53.80*	*53.48 – 54.13*
PM_{10}	*85.08*	*84.81 – 85.33*	*38.58*	*38.46 – 38.69*

IR(t) represents the intake rate of contaminants in kg/s (lb/s) and is calculated using Eq.(3). Within this equation, $V_{br}(t)$ corresponds to the breathing rate over time, which is assumed to be 16m³/day (0.392 ft³/min). $C_{exp}(t)$ denotes the exposure concentration profile in µg/m³ (µg/ft³).

$$IR(t) = V_{br}(t) * C_{exp}(t) \quad (3)$$

Case studies

Finally, indoor concentrations are evaluated in two case studies (one residential and one non-residential) based on real-world conditions, recognizing that people spend most of their time indoors. These case studies assess IAQ in relation to both EU and WHO outdoor air quality guidelines, considering pollutant concentrations and associated disease burden. Since no global IAQ standards currently exist, and in the absence of significant indoor sources, indoor PM levels generally tend to closely reflect outdoor concentrations due to ventilation and infiltration. The aim is to understand how differing outdoor air quality standards influence indoor air quality and subsequent health risks. The first case study uses sensor measurements to determine the PM concentrations, while the second relates to a simulated environment.

Case study 1. This case study concerns a small public waiting area in a hospital in Belgium. The waiting room is located on the second floor of the oncology department, which frequently serves vulnerable individuals who significantly benefit from good air quality, as PM has been shown to have a greater impact on these groups (Kim et al., 2015). The room is relatively small and accommodates approximately 12 people, including patients and family members. A small window facing north-west can be opened, though it is only done so at night due to safety concerns. The door remains open during consultation hours. A floor plan of the waiting room is shown in Figure 1a.

a) b)

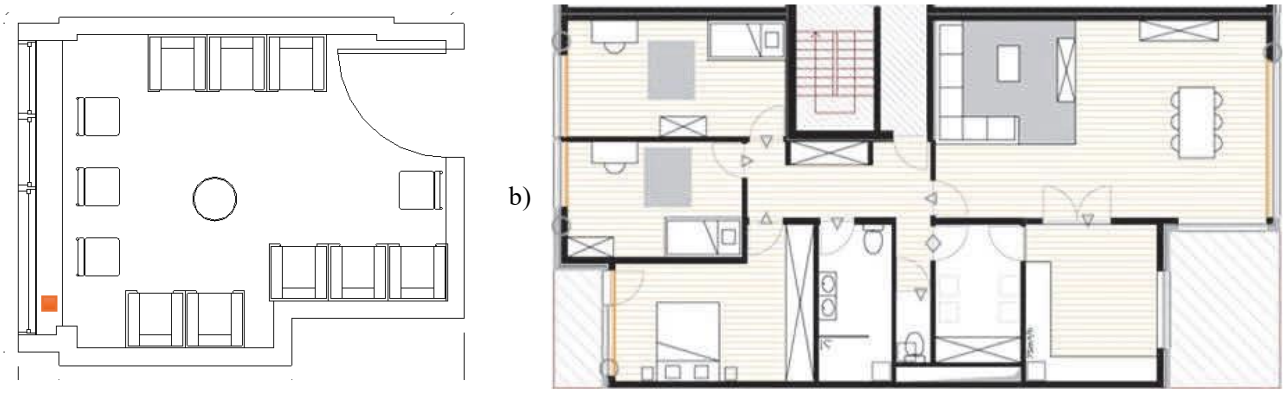

Figure 1 (a) Floor plan of the waiting room on the second floor of the hospital, with indicated location of the sensor. (b) Floor plan of the modelled three-bedroom apartment (De Jonge, 2023).

IAQ in the hospital is regulated by a mechanical ventilation system with both local exhaust and supply. No specific

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information on the building's pressurization status was available. The system is equipped with a Camfil filter (most likely an ePM1 50% or ePM2.5 65% class) that is regularly replaced. The hospital is situated near a major traffic area, making problematic outdoor PM concentrations migrating to the indoors likely. During a three-week period, from 9 to 22 March, a commercial air quality sensor was placed in the space to measure IAQ. The sensor was positioned on the window sill at the breathing height of the patients.

Case study 2. This case concerns a multi-zone model developed by De Jonge (2023) using the Modelica language, which was adapted by Corneillie et al. (2025) to include particulate matter. The model represents a three-bedroom apartment with a living area of approximately 120 m² (1292.7 ft²). The floor plan of the apartment can be seen in Figure 1b.

The apartment is equipped with a continuous Mechanical Ventilation with Heat Recovery (MVHR) system. In the model, outdoor concentrations for Vilvoorde are used. Here, the average annual concentrations for $PM_{2.5}$ and PM_{10} were 9.6 µg/m³ (5.99×10^{-7} gr/ft³) and 18.5 µg/m³ (1.15×10^{-6} gr/ft³), respectively. Four scenarios regarding ventilation are assessed in this research (Corneillie et al., 2025). Windows are opened according to the research of Verbruggen et al. (2021) to simulate a realistic indoor concentration relative to outdoor levels.

RESULTS

Averaging outdoor values

The European Union introduced its first mandatory PM standards in 1999, establishing limits for PM_{10} (particles <10 µm [3.94×10^{-4} in.]). With the adoption of the Ambient Air Quality Directive in 2008, annual average limits for $PM_{2.5}$ (particles <2.5 µm [9.84×10^{-5} in.]) were also defined (Priemus & Schutte-Postma, 2009). This annual limit for $PM_{2.5}$ was revised in 2020 from 25 µg/m³ (1.56×10^{-6} gr/ft³) to 20 µg/m³ (1.25×10^{-3} gr/ft³).

The WHO began issuing outdoor air quality guidelines in 1987, initially focusing on total suspended particles (TSP). In 2005, these were updated to include particle-size-specific limits for $PM_{2.5}$ and PM_{10}. The most recent revision, in 2021, significantly lowered the recommended $PM_{2.5}$ concentrations in response to growing evidence of adverse health effects (Huang, 2022).

The current annual and daily outdoor guideline values for both PM categories are summarized in Table 2. Note that daily limit values may be exceeded for a maximum of three to four days per year.

Table 2. Comparison between Outdoor Guideline Values of WHO and Limit Values of EU

Category	Averaging Period	WHO (2021) [µg/m³ (gr/ft³)]	EU Directive 2008/50/EC [µg/m³ (gr/ft³)]
$PM_{2.5}$	*24 hours*	*15 (9.35×10^{-4})*	-
	1 year	*5 (3.12×10^{-4})*	*20 (1.25×10^{-3})*
PM_{10}	*24 hours*	*45 (2.81×10^{-3})*	*50 (3.12×10^{-3})*
	1 year	*15 (9.35×10^{-4})*	*40 (2.49×10^{-3})*

The discrepancy between the two frameworks is immediately evident. The revised 2020 EU annual outdoor limit for $PM_{2.5}$, set at 20 µg/m³ (1.25×10^{-3} gr/ft³), is four times higher than the WHO outdoor guideline of 5 µg/m³ (3.12×10^{-4} gr/ft³). For PM_{10}, the daily average limit is relatively close (50 µg/m³ [3.12×10^{-3} gr/ft³] EU vs. 45 µg/m³ [2.81×10^{-3} gr/ft³] WHO), but the annual limit set by the EU is more than double that of the WHO (40 µg/m³ [2.49×10^{-3} gr/ft³] vs. 15 µg/m³ [9.35×10^{-4} gr/ft³]). This disparity likely translates into substantial differences in population exposure and related health outcomes. The fact that legally binding EU standards are significantly less stringent than WHO guidelines may have considerable negative implications for public health. Moreover, the absence of a daily limit for $PM_{2.5}$ in the EU directive diminishes the perceived urgency of regulating this more harmful pollutant relative to PM_{10}.

In 2024, the European Union announced plans to revise its directive under the framework of the European Green Deal. The proposed update, slated for implementation in 2030, would reduce the annual $PM_{2.5}$ limit to 10 µg/m³ (6.24×10^{-7} gr/ft³). While this represents a notable improvement, it still falls short of the WHO guideline by a factor of two, leaving room for continued public health risks.

DALYs

The resulting number of Disability-Adjusted Life Years (DALYs) can be calculated for each outdoor limit concentration and corresponding averaging period. While this represents a simplification, since ambient pollutant

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concentrations in real-world conditions rarely remain constant at their respective limit values, it aligns with the approach taken in the formulation of outdoor air quality standards. These values therefore represent the maximum potential health burden, in terms of DALYs, attributable to long-term exposure at guideline-compliant pollutant levels. The calculated DALYs corresponding to these exposure limits are summarized in Table 3.

Table 3. Number of DALYs per 100,000 individuals associated with exposure at standard limit values.

Category	Exposure period	WHO (2021)	WHO (2021)	EU directive 2008/50/EC	EU directive 2008/50/EC
		[µg/m³ (gr/ft³)]	DALYs/ 100,000	[µg/m³ (gr/ft³)]	DALYs/ 100,000
$PM_{2.5}$	*24 hours*	*15 (9.35 × 10⁻⁴)*	*2.83*	-	-
	1 year	*5 (3.12 × 10⁻⁴)*	*345*	*20 (1.25 × 10⁻³)*	*1,378.07*
PM_{10}	*24 hours*	*45 (2.81 × 10⁻³)*	*6.13*	*50 (3.12 × 10⁻³)*	*6.81*
	1 year	*15 (9.35 × 10⁻⁴)*	*745*	*40 (2.49 × 10⁻³)*	*1,987.69*

The results reveal a substantial difference between the outdoor air quality guidelines established by the World Health Organization (WHO) and the regulatory limits set by the European Union (EU). For $PM_{2.5}$, the annual DALY burden under the EU limit is approximately four times higher than that under the WHO guideline. Likewise, for PM_{10}, the annual exposure under the EU limit is nearly three times greater than under the WHO recommendation.

In contrast, DALY estimates for short-term (24-hour) PM_{10} exposure show only modest variation, reflecting the relatively close concentrations set by both standards. These results underscore the critical public health consequences of adopting stricter ambient air quality standards. Aligning EU limits with WHO guidelines could significantly reduce the disease burden attributable to long-term ambient particulate matter exposure.

CASE STUDIES

As people spend the majority of their time indoors, IAQ plays a critical role in determining overall health outcomes. This section explores how outdoor air pollution influences indoor exposure through two case studies. Since air pollution levels fluctuate over time, these case studies use real-world PM concentration data rather than constant profiles, ensuring more realistic assessments. Both case studies are set in Belgian climate conditions and are evaluated in relation to the outdoor air quality guidelines of the WHO and the legal outdoor limits of the EU. The goal is to examine how differing outdoor PM levels affect IAQ, and to assess the implications of using different regulatory benchmarks to interpret indoor exposure risks.

Hospital waiting room

In the first case study, a hospital waiting room was monitored during an IAQ measurement campaign. Concentrations of $PM_{2.5}$ and PM_{10} were recorded at ten-minute intervals, and used to construct an exposure profile. From this dataset, both the average annual and the highest daily average indoor concentration were derived. Importantly, these calculations only account for the period during which the space was open to the public (approximately 07:00 to 19:00), as the ventilation system is programmed for occupancy only during these hours. The measured concentrations are presented in Table 4.

Table 4. Average concentrations of $PM_{2.5}$ and PM_{10}

Category	Average annual concentration [µg/m³ (gr/ft³)]	Highest daily average [µg/m³ (gr/ft³)]
$PM_{2.5}$	*3.5 (2.18 × 10⁻⁴)*	*4.4 (2.74 × 10⁻⁴)*
PM_{10}	-	*9.0 (5.61 × 10⁻⁴)*

When compared with the outdoor limit values in Table 3, these indoor concentrations are significantly lower than all EU thresholds, over five times lower for $PM_{2.5}$ and nine times lower for PM_{10}, creating the impression of exceptional air quality. However, comparing these results to the WHO guideline values paints a more nuanced picture. The hospital room's indoor $PM_{2.5}$ levels still comply comfortably with WHO outdoor standards, though the margin is less dramatic. In the case of PM_{10}, while the annual indoor average is more than sufficient, the difference with the WHO guideline is reduced to approximately threefold instead of ninefold. While the EU air quality directive includes a limit value for the outdoor daily average

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concentration of PM_{10}, it does not set a maximum daily average for $PM_{2.5}$, which limits comparative interpretation.

Additionally, the daily average indoor PM_{10} concentration remains well below the maximum thresholds set by both the WHO and EU outdoor standards. This superior IAQ is attributed to a highly effective, well-maintained mechanical ventilation system, and the absence of open windows during occupied hours, which minimizes infiltration of outdoor pollutants. As such, the impact of outdoor air quality on this indoor environment is substantially reduced, but still provides an important comparative framework.

To further contextualize the air quality, the associated DALYs per 100,000 individuals were calculated for each pollutant. These are summarized in Table 5. The results mirror the concentration data: DALYs corresponding to the hospital waiting room concentrations are significantly lower than those estimated for outdoor EU limit values. While the differences are smaller when compared to WHO outdoor guidelines, the indoor environment still performs well within acceptable thresholds, especially for $PM_{2.5}$. This suggests that in such controlled indoor environments, outdoor concentrations are not the primary determinant of exposure, particularly when natural ventilation is avoided and mechanical systems are optimized.

Table 5. Number of DALYs/100 000 for $PM_{2.5}$ and PM_{10}

Category	WHO guidelines	EU standards	Hospital waiting room
$PM_{2.5}$	*345*	*1,378.07*	*243*
PM_{10}	*745*	*1,987.69*	*218.5*

Apartment unit

In a second case study, indoor concentrations of $PM_{2.5}$ and PM_{10} were assessed in a simulated apartment unit, under four distinct ventilation and filtration scenarios based on the methodology outlined by Corneillie et al. (2025): (1) No window airing, (2) Window airing, (3) HEPA filtration, (4) Window airing & HEPA filtration. These scenarios reflect different degrees of outdoor air influence, either through building envelope infiltration, mechanical ventilation systems, or direct exchange via open windows. The average indoor concentrations for $PM_{2.5}$ and PM_{10} in each scenario are presented in Table 6. It is noteworthy that none of the PM_{10} 24-hour concentrations exceeded outdoor EU limit values.

Table 6. Average concentrations in the apartment for $PM_{2.5}$ and PM_{10}

Category	(1) No Window Airing	(2) Window Airing	(3) HEPA	(4) HEPA & Window
	[µg/m³ (gr/ft³)]	[µg/m³ (gr/ft³)]	[µg/m³ (gr/ft³)]	[µg/m³ (gr/ft³)]
$PM_{2.5}$	*9.03 (5.63×10^{-4})*	*8.90 (5.55×10^{-4})*	*0.20 (1.25×10^{-5})*	*2.90 (1.81×10^{-4})*
PM_{10}	*17.6 (1.10×10^{-3})*	*17.5 (1.09×10^{-3})*	*0.30 (1.87×10^{-5})*	*7.20 (4.49×10^{-4})*

The results in Table 6 clearly illustrate the impact of outdoor air on indoor particulate concentrations. In the first scenario, where only infiltration through the building envelope occurs, indoor $PM_{2.5}$ and PM_{10} concentrations remain below the outdoor EU air quality limits. This reflects compliance with EU standards. However, the small difference from the outdoor concentration for $PM_{2.5}$ and PM_{10}, 9.6 µg/m³ (5.99×10^{-7} gr/ft³) and 18.5 µg/m³ (1.15×10^{-6} gr/ft³) respectively, indicates only little obstruction was exercised by the building envelope. In addition, when compared with the WHO outdoor guideline values, both $PM_{2.5}$ and PM_{10} annual indoor average concentrations exceed outdoor WHO recommendations, with a notable exceedance in $PM_{2.5}$ levels. Introducing window airing results in very similar concentrations, suggesting that occasional window opening does not drastically alter IAQ when no filtration is present.

The effect of HEPA filtration is immediate and substantial. In scenario 3, indoor concentrations of both $PM_{2.5}$ and PM_{10} drop dramatically, well below WHO outdoor guideline values. However, reintroducing window airing in scenario 4 compromises this benefit, though the concentrations still remain under the defined limits. This is due to scheduled window openings rather than constant ventilation, which partially undermines the performance of the filtration system. Further insights are provided by Figure 2, which illustrates the $PM_{2.5}$ concentration profiles in the bedroom over representative summer and winter days, both with/ without HEPA filtration. In this particular room, the window remains open continuously during summer and is briefly opened between 08:00 and 09:00 during winter. The figure clearly demonstrates that indoor $PM_{2.5}$ concentrations closely mirror outdoor levels when the window is open. Moreover, the efficacy of HEPA filtration is significantly compromised when outdoor air enters the space directly through open windows, bypassing the filtration system.

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In terms of health impacts, the Disability-Adjusted Life Years (DALYs) per 100,000 individuals were calculated for each of the four scenarios, based on exposure in the kitchen over the course of one year. In Scenario 1, the total DALYs due to $PM_{2.5}$ exposure amount to 1,270. In Scenario 2, DALYs decrease slightly to 1,100. This minor difference is partially due to air exchange between rooms with varying window schedules, which introduces complexity in interpreting the exposure profile.

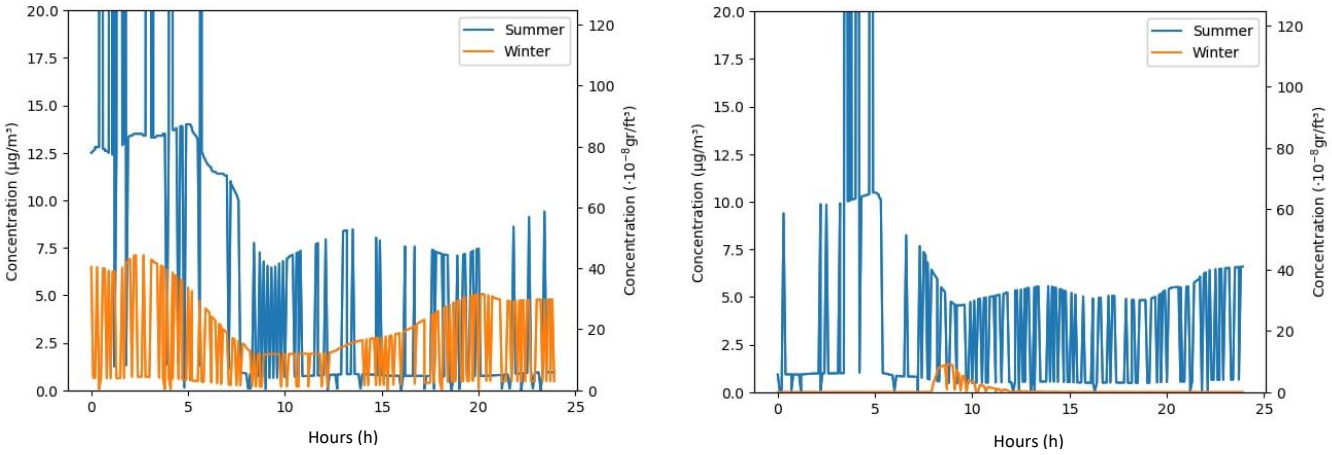

Figure 2 $PM_{2.5}$ concentration in the bedroom with window airing for one day during summer and during winter (a) without filter and (b) with HEPA filter.

The introduction of a HEPA filter (Scenario 3) results in a substantial reduction in health burden, with DALYs dropping to just 77. This indicates the high effectiveness of mechanical filtration in improving IAQ. However, in Scenario 4, where HEPA filtration is combined with window airing, DALYs increase again to 503, due to unfiltered outdoor air entering the space, which undermines the effectiveness of the filtration system.

For PM_{10}, similar trends are observed. DALYs remain very similar between Scenarios 1 and 2, indicating limited impact of window airing in the absence of filtration. When HEPA filtration is applied (Scenario 3), DALYs for PM_{10} drop significantly from 1,674 to 115. However, when window airing is reintroduced in Scenario 4, DALYs increase sharply again to 824, highlighting the sensitivity of IAQ improvements to unfiltered outdoor air exchange. Compared to guideline values, the DALY outcomes align with conclusions drawn from average concentration comparisons. All simulated scenarios yield lower DALYs than the EU outdoor air quality limits; however, they remain significantly higher than the outdoor concentration targets set by the WHO, except in the case of HEPA filtration without window airing, which meets the WHO benchmark. Nevertheless, this idealized condition may not be realistic in typical residential settings where some degree of window opening is common. A summary of DALY values for these scenarios, compared to the benchmark values, is provided in Table 7.

Table 7. Number of DALYs/ 100,000 for each scenario

Category	$PM_{2.5}$ DALYs	95% CI $PM_{2.5}$	PM_{10} DALYs	95% CI PM_{10}
WHO (2021)	*345*	*343 – 349*	*745*	*742-749*
EU directive 2008/50/EC	*1,378*	*1,375 – 1,385*	*1,988*	*1,984-1,993*
(1) No window airing, no filter	*1,270*	*1,266 – 1,276*	*1,674*	*1,670-1,679*
(2) Window airing, no filter	*1,100*	*1,097 – 1,104*	*1,652*	*1,648-1,656*
(3) HEPA filter, no window airing	*77*	*76 – 78*	*115*	*114-117*
(4) HEPA filter & window airing	*503*	*500-507*	*824*	*821-828*

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DISCUSSION

This study reveals a clear mismatch between outdoor air quality standards: while current EU limits are officially met, the associated health burden is still three to four times higher than if WHO outdoor guidelines were followed. This creates a false sense of safety, as meeting legal thresholds does not mean health risks are low.

Reducing the EU standards to better align with WHO recommendations could greatly benefit public health. However, political feasibility may hinder such a drastic change based solely on health benefits. Additionally, the absence of a daily $PM_{2.5}$ concentration limit could result in severe acute effects, as no legal framework exists to address high short-term concentrations. Implementing a legally binding daily $PM_{2.5}$ limit would be a critical step toward protecting against short-term health risks.

Outdoor concentrations strongly influence IAQ, especially in residential settings where window airing is common. Case studies show that indoor PM levels track outdoor levels closely when windows are open, undermining the protective effect of mechanical filtration. In contrast, when windows remain closed and filtration is used, indoor PM concentrations, and associated DALYs, drop substantially, often below WHO thresholds.

The study's limitations include its limited generalizability across different regions with varying outdoor air quality, and the focus on short-term data rather than long-term exposure. The considered case studies were both in well-controlled and ventilated spaces, potentially underestimating the exposure risks in poorly ventilated spaces. The commercial sensors from case study 1 provide a lesser accuracy than laboratory grade appliances. The study is also bound by the limitations of the current legal framework, usually considering average concentrations instead of exposure profiles and only assessing $PM_{2.5}$ and PM_{10}.

Additionally, the studied environments did not contain major indoor PM sources, such as cooking, burning candles, or using biomass heaters. In homes or buildings where such sources are present, indoor concentrations would likely be much higher, making it even more difficult to achieve compliance with either EU or WHO outdoor air quality guidelines. This also highlights the compounding effect of indoor and outdoor sources: if outdoor air already results in DALY levels well above WHO benchmarks, any additional indoor emissions could push exposures into highly harmful ranges. Therefore, the absence of large indoor sources in this study should be interpreted as a best-case scenario, one where even limited outdoor PM infiltration already causes significant health burdens.

This underscores two urgent needs: stricter outdoor air quality standards to reduce baseline exposure, and specific indoor air quality policies. Evaluating DALYs across full exposure profiles and not just average concentrations could provide a more accurate view of real-world health impacts.

CONCLUSION

This study highlights the critical disparities between the European Union's outdoor air quality standards and the World Health Organization's (WHO) guidelines, concerning particulate matter ($PM_{2.5}$ and PM_{10}). While EU standards are currently met by outdoor air quality, these values are significantly higher than those recommended by the WHO, potentially leading to a false sense of security regarding public health. The results demonstrate that stricter EU standards, more closely aligned with WHO recommendations, could substantially reduce the health impacts of air pollution, as reflected in the number of Disability-Adjusted Life Years (DALYs). The case studies presented show that high IAQ can be maintained even with outdoor air that meets EU standards, provided windows remain closed. However, in residential settings where the closure of windows is not realistic, these findings emphasize the need for additional measures such as better IAQ management, stricter outdoor air quality standards and specific indoor air quality standards. As people spend most of their time at their own home, those standards can have a large influence. Public awareness campaigns could also play a pivotal role in shifting perceptions of outdoor air quality, urging the adoption of healthier habits and practices to protect both indoor and outdoor environments.

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