International Journal of Hygiene and Environmental Health 277 (2026) 114867

Contents lists available at ScienceDirect

International Journal of Hygiene and Environmental Health

journal homepage: www.elsevier.com/locate/ijheh

Development and evaluation of a risk-based air quality index for Germany

Katherine Ogurtsova [a,*], Myriam Tobollik [b], Tomke Zschachlitz [b], Wolfgang Straff [b], Florian Pfäfflin [c], Antonia Fritz [c], Volker Diegmann [c], Barbara Hoffmann [a]

[a] Institute of Occupational, Social and Environmental Medicine, Centre for Health and Society, Medical Faculty and University Hospital Düsseldorf, Heinrich Heine University Düsseldorf, Germany

[b] Section Environmental Medicine and Health Effects Assessment, German Environment Agency, Germany

[c] IVU Umwelt GmbH, Germany

A B S T R A C T

Objectives: We developed and evaluated a risk-based Air Quality Index (AQI) for Germany that harmonizes pollutant categories on risk equivalence, incorporates hourly concentrations, and improves health-relevant communication.

Methods: We identified pollutant-outcome pairs with causal or likely causal evidence, extracted effect estimates from systematic reviews and meta-analyses, and transformed daily mean effects into hourly effect estimates using German monitoring data. Equivalence coefficients were derived via Monte Carlo simulations and standardized to $PM_{2.5}$ as the reference pollutant. $PM_{2.5}$ thresholds were anchored in WHO Air Quality Guideline 2021 and the EU information threshold; risk-equivalent thresholds for PM_{10}, NO_2, O_3, and SO_2 were generated accordingly. An additional module was developed to account for concurrent elevation of multiple pollutants. The index was empirically evaluated using hourly data from German monitoring stations for 2019 and 2022, and the results were compared with the previous AQI. In sensitivity analyses, we assessed the effects of incorporating updated evidence and excluding asthma-related outcomes.

Results: Application of the risk-based AQI resulted in a marked shift from "very good" to "good" and "moderate" categories in comparison with the previous AQI, particularly for $PM_{2.5}$ and O_3, reflecting stricter concentration thresholds. "Poor" classifications increased modestly, while "very poor" remained rare. The multi-pollutant episodes module affected less than 1% of hours.

Conclusion: Overall, the risk-based AQI represents a significant step toward health-based communication of air quality in Germany. By integrating scientific evidence into its design and providing tailored guidance, it enhances preventive public health protection. Its implementation may improve risk awareness and support behavioural changes that reduce exposure.

1. Introduction

Air pollution remains one of the leading environmental risk factors affecting global public health (Boogaard et al., 2019; GBD 2023 Disease and Injury and Risk Factor Collaborators, 2025). Short-term increases in concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and sulfur dioxide (SO_2) have been consistently associated with respiratory and cardiovascular morbidity, increased hospital admissions, and premature mortality (Chen and Hoek, 2020; Huangfu and Atkinson, 2020; O'Brien et al., 2023; Orellano et al., 2020, 2021; Zheng et al., 2021). In response to emerging epidemiological evidence, the World Health Organization (WHO) published updated Air Quality Guidelines (AQG) in 2021, substantially lowering recommended annual and daily concentration thresholds (guideline values) for $PM_{2.5}$, PM_{10}, NO_2, and O_3 (WHO global air quality guidelines, 2021). Following the publication of these new guideline values, the European Commission revised its Directive on ambient air quality and cleaner air for Europe (AAQD) in 2024. Besides substantially lower limit values for annual and daily pollutant concentrations, member states are required to provide the public with timely, comprehensible information on current air quality and associated health risks, using air quality indices (AQI) (European Parliament. Council of the European Union, 2024), 2024). AQIs serve as communication tools for translating pollutant measurements into simplified, easily understandable categories, often coupled with health-related behavioural advice (Buonocore et al., 2021). By enabling individuals to make informed decisions about their daily activities, AQIs play a substantial role in public health protection and mitigation of the risk of pollutant-related acute health problems. Worldwide, numerous national, regional and global AQIs exist. Their basic methodology varies considerably, reflecting variations in data use (measured or modelled), pollutant mixtures, health priorities, and communication strategies across countries and regions (Cromar and Lazrak, 2023). This diversity underscores the challenge of ensuring comparability and clarity in risk communication across regions.

The primary objective of any AQI is to effectively inform the public

* Corresponding author.
E-mail address: Katherine.Ogurtsova@hhu.de (K. Ogurtsova).

https://doi.org/10.1016/j.ijheh.2026.114867
Received 28 February 2026; Received in revised form 1 July 2026; Accepted 15 July 2026
Available online 28 July 2026

Abbreviations:

AAQD	Directive on ambient air quality and cleaner air for Europe
AQG	Air Quality Guidelines
AQI	Air Quality Index
COPD	Chronic Obstructive Pulmonary Disease
EEA	European Environment Agency
ER	Emergency Room
HRAPIE	Health Risks of Air Pollution in Europe
NO_2	Nitrogen Dioxide
O_3	Ozone
PM	Particulate Matter
SO_2	Sulfur Dioxide
UBA	Umweltbundesamt (German Environment Agency)
WHO	World Health Organization

and especially vulnerable subpopulations by providing a reliable tool for understanding air quality and enabling informed behavioural adjustments. However, most current AQIs exhibit methodological and conceptual limitations that constrain their comparability and health relevance. These include heterogeneous approaches that emphasize different principles, such as pollutant aggregation based on a worst-pollutant rule (Environment and Climate Change Canada (ECCC), n.d.) or risk-based weighting models (Huang et al., 2022), inconsistent averaging times, and reliance on regulatory thresholds rather than health-based standards. Additio\nally, most AQIs neglect cumulative health effects of multiple pollutant exposures, handle missing or modelled data inconsistently, and vary in spatial representativeness—from single monitoring stations to national interpolated maps—introducing further challenges. Communication practices differ widely, with different scales, colour schemes, and insufficiently tailored health advice, particularly with regard to vulnerable populations. Limited transparency and accessibility of methodological documentation further impede independent evaluation and public trust. Collectively, these shortcomings compromise the validity, comparability, acceptance, and public health utility of AQIs.

In Germany, the Umweltbundesamt (UBA, German Environmental Agency) has provided a national multi-pollutant AQI since 2019. This index was primarily based on the WHO AQG 2005 (World Health Organization (WHO), 2005), which have become outdated in light of recent scientific findings and the resulting update of the WHO AQG in 2021 (World Health Organization (WHO), 2021). The 2021 update of the WHO AQG therefore necessitated a revision of UBA AQI to align with current health-based evidence. Furthermore, compliance with the revised EU AAQD 2024 required enhancements such as hourly updates, inclusion of SO_2 concentrations, and tailored behavioural recommendations for both the general population and vulnerable groups.

Finally, one basic challenge of constructing a multi-pollutant AQI is how to incorporate the different toxicities of the included pollutants. A risk-based AQI with risk-equivalent categories ensures that each index level reflects the same health risk, no matter which pollutant causes it. Such equivalence of risk across pollutants enhances index validity, transparency, and may improve public understanding.

Building on prior experience with the UBA's earlier AQI and incorporating the latest epidemiological evidence, this study aimed to develop an updated, risk-based AQI anchored in the WHO AQG 2021 and taking into account the revised EU AAQD 2024. The revised index preserves continuity with the existing UBA AQI framework—maintaining five categories, the established colour scheme, and the worst-pollutant rule—while introducing significant improvements in health evidence, hourly resolution, risk-equivalence of categories, and targeted behavioural guidance. This paper presents the methodological development and empirical evaluation of the risk-based UBA AQI.

2. Methods

2.1. Prior approach

Several methodological aspects of the previous UBA AQI have remained unchanged in the risk-based UBA AQI (Straff et al., 2021). The previous UBA AQI combined pollutant-specific indices (NO_2, O_3, PM_{10}, later $PM_{2.5}$) into a five-category system (“very good” to “very poor”) with a fixed colour scheme and was communicated via the UBA website and the “Luftqualität” application (Umweltbundesamt, n.d.). A detailed description of the construction, categories, resolution, and communication of the previous UBA AQI is provided in the literature (Straff et al., 2021), and the characteristics that remained unchanged are not described in detail here.

2.2. Concept of UBA AQI 2025

The most important changes in the risk-based UBA AQI are the equivalent risk approach, the consistent application of hourly concentrations, and the anchoring of categories in WHO AQG 2021 recommendations and EU AAQD 2024 warning threshold. First, the concept of equivalent risks in the context of an AQI refers to aligning the index categories across different pollutants so that a given category reflects a comparable level of health risk, regardless of which pollutant is dominating the air quality. In contrast, many AQIs are constructed with pollutant-specific categories using concentration thresholds that may not correspond to the same health risk for each pollutant (for example if regulatory limit values are used for these pollutant concentration thresholds). These pollutant-specific categories are then combined into an overall AQI. There are different ways to combine pollutant-specific categories. If they are combined in a way that the worst category determines the overall AQI category (worst-pollutant rule), the overall AQI will have different health implications depending on which pollutant determined the category. The equivalent risk approach harmonizes these thresholds by linking them to epidemiological evidence, such as relative risks or excess mortality/morbidity associated with each pollutant at defined levels. This ensures that an AQI category (e.g., “moderate” or “very poor”) represents a comparable level of health risk, regardless of the pollutant driving the index, thereby improving the clarity of public communication, as well as transparency and comparability across indices.

We developed this risk-based AQI for Germany by adapting the methodologies established for the Canadian (Stieb et al., 2008) and Dutch air quality indices (Dusseldorp et al., 2014) that were based on older WHO AQGs and did not incorporate the newest evidence. Our index is based on hourly concentrations and incorporates five pollutants mandated by EU legislation: $PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2 (European Parliament. Council of the European Union, 2024), with five assessment categories ranging from “very good” to “very poor” designed to reflect comparable health risks across pollutants. A major change compared to the previous index is the consistent use of hourly concentration data, which has become accessible at every routine state-run monitoring station only during the last decade. Another major change is the use of the WHO AQG 2021, which provides much stricter recommendations than the prior WHO AQG 2005.

The derivation of the risk-based UBA AQI contained the following steps:

1 Selection of pollutant-specific exposure-outcome pairs (causality, public health relevance).
2. Effect estimation: Literature search of epidemiological reviews on health effects for the specified exposure-outcome pairs and data

extraction. Quality assessment of the reviews and calculation of effect estimates for the specified exposure-outcome pairs.
3. Transformation of daily to hourly effect estimate values.
4. Risk standardization and equivalence coefficients.
5. Definition of assessment categories for $PM_{2.5}$ using the WHO AQG 2021.
6. Index construction: Calculation of risk-equivalent assessment categories for the other pollutants.

After these steps, health recommendations were developed and the newly developed AQI was applied exemplarily to real monitoring data and compared with the existing index.

2.2.1. Selection of exposure-outcome pairs

The index is based on evidence of short-term effects, as these capture immediate health responses to daily variations in air pollution and are crucial for timely public communication and action to mitigate risks. We selected health outcomes based on established causal or likely causal relationships with air pollutants, focusing on outcomes with substantial public health relevance according to the latest integrated scientific analyses by the US Environmental Protection Agency (U.S. Environmental Protection Agency, 2019, 2017, 2016, 2013) and WHO AQG 2021 (World Health Organization (WHO), 2021). We placed particular emphasis on morbidity outcomes, such as hospital admissions and emergency room (ER) visits, that are generally more frequent than mortality. The selected short-term outcomes were hospital admissions for cardiovascular diseases, hospital admissions for respiratory diseases, ER visits or hospital admissions for asthma, and all-cause mortality (U.S. Environmental Protection Agency, 2019, 2017, 2016, 2013). Patients with asthma are a particularly important target group for the UBA AQI because they are especially vulnerable to short-term air pollution peaks and therefore need timely and actionable health-protection information. Since asthma-related hospital admissions are also included within the broader category of respiratory hospital admissions, we additionally conducted a sensitivity analysis excluding asthma from the outcome list to assess its influence on the final index.

An association of a pollutant with an outcome was classified as causal or likely causal when it was assigned this classification in the relevant U.S. Environmental Protection Agency Integrated Science Assessment (cellular, animal, human, epidemiological), with confounding and random error sufficiently excluded (Dominici and Zigler, 2017; Glass et al., 2013). The final list of identified causal exposure-outcomes pairs is presented in the results section.

2.2.2. Effect estimation

We conducted literature searches in MEDLINE via PubMed and Google Scholar, combining database searches with the snowball searching, to identify epidemiological reviews and meta-analyses examining short-term effects for the selected exposure-outcome pairs. Searches had no temporal or geographical restrictions, while languages were limited to English and German. For O_3, we prioritized studies from temperate climate regions comparable to Germany due to concentration differences across geographical regions. For the other pollutants, no geographical restrictions were applied.

Effect estimates were extracted as percentage increases in cases per $10\ \mu g/m^3$ pollutant concentration increase. When systematic reviews and meta-analyses were available, they were used as primary evidence sources. The most recent reviews that included a meta-analysis were preferred. If a review did not include a meta-analysis, pooled estimates were calculated manually based on the individual studies included in the review. Moreover, we evaluated whether the reviews and meta-analyses included a formal quality assessment of the evidence considered. Reviews with a formal quality assessment were preferred.

2.2.3. Transformation of daily to hourly effect estimate values

Since epidemiological studies on short-term effects on the selected health outcomes primarily report effects for 24-h (8-h for O_3) mean concentrations while the index requires hourly resolution, we developed transformation factors, following an approach described in Stieb et al. (2008) and Dusseldorp et al. (2014). Using German measurement data from 2019 to 2022 across 439 and 433 monitoring stations respectively, for NO_2, SO_2, PM_{10}, and $PM_{2.5}$, transformation factors were derived as the yearly average of daily quotients between the 1-h maximum and the 24-h mean, based on days with at least 18 valid hourly values (Equation (1)). For O_3, transformation factors were calculated as the yearly average of daily quotients between the 1-h maximum and the daily maximum 8-h mean, determined from rolling 8-h averages with sufficient data coverage according to Federal Immission Protection Ordinance (BImSchV) (Bundesrepublik Deutschland, 2010) (Equation (2)).

The 24-h effect estimates from the previous step were then divided by these transformation factors to derive hourly effect estimates (Equations (3) and (4)) to obtain effect estimates applicable to hourly concentrations.

Calculation of the transformation factor for pollutant X ($PM_{2.5}$, PM_{10}, NO_2, SO_2)

$$\text{Transformation factor pollutant X} = \frac{\text{1-hour daily maximum for air pollutant X}}{\text{24-hour mean for air pollutant X}} \tag{1}$$

Calculation of the transformation factor for O_3

$$\text{Transformation factor } O_3 = \frac{\text{1-hour daily maximum for } O_3}{\text{8-hour mean for } O_3} \tag{2}$$

Calculation of the 1-h effect estimate for pollutant X ($PM_{2.5}$, PM_{10}, NO_2, SO_2)

$$\text{1-hour effect estimate pollutant X} = \frac{\text{24-hour effect estimate}}{\text{transformation factor}} \tag{3}$$

Calculation of the 1-h effect estimate for O_3

$$\text{1-hour effect estimate } O_3 = \frac{\text{8-hour effect estimate } O_3}{\text{transformation factor } O_3} \tag{4}$$

This transformation is based on several assumptions: (1) the 1-h daily maximums of air pollutant concentrations are highly correlated with the 24-h mean; (2) the increase in risk for the daily mean or the rolling 24-h mean is highly correlated with the risk associated with the daily 1-h maximum within this time period. Empirical evidence for this assumption can be found in the literature on the Canadian AQI (Stieb et al., 2008), which showed empirically that the 3-h or 1-h daily maximum effects of CO, NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 on all-cause mortality were broadly comparable to the effects of the respective 24-h mean value. This approach was also used for the Belgian and Dutch AQIs (Dusseldorp et al., 2014; irCELine, 2022).

The hourly thresholds were derived from epidemiological evidence based on daily exposure metrics by applying empirical relationships between daily concentrations and within-day peak values. Consequently, the 1-h AQI does not quantify the biological effect of a single hour of exposure, but represents the short-term risk signal associated with an hourly peak occurring within a 24-h exposure period.

Further transformation factors were examined in sensitivity analyses based on the 95th percentile (1h P95/24h), the 90th percentile (1h P90/24h) and the 70th percentile (1h P70/24h) of the hours of a day instead of the daily maximum to test which of these shows the highest correlation.

2.2.4. Risk standardization and equivalence coefficients

We standardized all pollutant hourly effect estimates to $PM_{2.5}$ as the reference pollutant. We chose $PM_{2.5}$ as the reference pollutant, because for $PM_{2.5}$, the most extensive scientific evidence base is available, it shows the strongest health effects per unit mass, and it causes the greatest disease burden in Europe (European Environment Agency, 2024a; World Health Organization (WHO), 2021). Equivalence coefficients were calculated by dividing $PM_{2.5}$ hourly effect estimates by corresponding effect estimates for the other pollutants for each health outcome (Equation (5)).

Calculation of the equivalence coefficient for pollutant X (PM_{10}, NO_2, SO_2, O_3)

$$\text{Equivalence coefficient for pollutant X and health outcome Y} = \frac{\text{1-hour effect estimate for } PM_{2.5} \text{ on Y}}{\text{1-hour effect estimate for pollutant X on Y}} \tag{5}$$

As a result, we obtained several equivalence coefficients per pollutant, depending on the number of included exposure-outcome pairs for this pollutant. However, for use in the index, a single value reflecting the relative harmfulness of each pollutant compared to $PM_{2.5}$ is necessary. To obtain this single value per pollutant and to allow accounting for statistical uncertainty, we performed Monte Carlo simulations with 10,000 iterations to generate random daily effect estimates per pollutant and per outcome, using normal distributions derived from original confidence intervals of the daily relative risk (see Table 1). Next, we transformed them to hourly effect estimates and calculated the equivalence coefficients per pollutant and per outcome as described above. This process yielded a distribution of possible equivalence coefficients per pollutant and outcome. To combine the outcome-specific distributions, we calculated the arithmetic mean of the equivalence coefficients across outcomes for each pollutant in each simulation iteration. All included health outcomes were equally weighted in this procedure to provide a balanced and transparent representation of overall health risk. This approach generated pollutant-specific distributions of equivalence coefficients, from which we derived the mean, median, and mode. The final equivalence coefficients were selected through expert judgment, considering both the characteristics of these distributions and relevant epidemiological factors, such as potential confounding between NO_2 and $PM_{2.5}$ and the high uncertainty in the estimated effects of O_3. A more detailed description of the simulation is provided in the Supplementary Materials.

Table 1
Percentage change in the outcome per 10 µg/m^3 increase with short-term pollutant exposure (24-h or 8-h means).

Pollutant	Hospital admissions for cardiovascular diseases in %	Hospital admissions for respiratory diseases in %	ER visits or hospital admissions for asthma in %	Excess all-cause mortality in %
$PM_{2.5}$ (24h)	1.0 (0.6; 1.4) [[a],[m]]	1.4 (1.0; 1.7) [[a],[m]]	2.9 (1.7; 4.1) [[a],[l]]	0.7 (0.4; 0.9) [[h]]
PM_{10} (24h)	0.7 (0.2; 1.1) [[c]]	1.6 (0.0; 3.1) [[c]]	1.0 (0.8; 1.3) [[e]]	0.4 (0.3; 0.5) [[h]]
O_3 (8h)	N/A	0.2 (−0.2; 0.5) [[fg],[j]]	0.3 (−0.7; 1.5) [[d],[k]]	0.4 (0.3; 0.5) [[h]]
NO_2 (24h)	N/A	1.8 (1.1; 2.5) [[b]]	1.4 (0.8; 2) [[d]]	0.7 (0.6; 0.9) [[h]]
SO_2 (24h)	N/A	No data	1.0 (0.1; 2) [[d]]	0.6 (0.5; 0.7) [[i]]

Notes: As the effect estimates were reported in the results of the relevant studies using varying degrees of precision, the precision was standardized by rounding all estimates to the first decimal place. Estimates were rounded to one decimal place for presentation. N/A – not applicable because the evidence for an association is not considered at least likely causal. "No data" - eligible association but no suitable estimate identified.

[a] Ru et al. (2023).
[b] WHO Regional Office for Europe (2013).
[c] Abed Al Ahad et al. (2020).
[d] Zheng et al. (2021).
[e] Zheng et al. (2015).
[f] Hůnová et al. (2013).
[g] Atkinson et al. (2014).
[h] Orellano et al. (2020).
[i] Orellano et al. (2021).
[j] Mean of estimates in Hůnová et al. (2013) and Atkinson et al. (2014) for the European region only.
[k] Northern Europe only, comprising the Greater Paris area, Amsterdam, Manchester and London.
[l] Mean of two linear relative risks of ER visits and hospital admissions for asthma.
[m] Using the linear exposure-response relationship.

2.2.5. *Definition of assessment categories for $PM_{2.5}$ using the WHO AQG 2021*

The categorization of the risk-based UBA AQI into five levels was derived from a combination of scientific evidence and normative guidance, given the absence of biologically justified cut-off values for pollutants with mostly linear exposure-response relationships. For all pollutants considered, even small increases in concentration are associated with measurable health risks, making category thresholds inevitably somewhat arbitrary. To anchor the classification in verifiable data, the WHO AQG 2021 and the EU AAQD (European Parliament. Council of the European Union, 2024) were used as reference points.

The threshold between the categories "very good" and "good" for the $PM_{2.5}$ anchor pollutant was set at the WHO AQG 2021 annual mean of 5 µg/m^3. This value represents a level below that the certainty of the developing serious chronic health outcomes is very low, thus justifies its role as the upper bound of the best category. The division between "good" and "moderate" was based on the WHO 24-h mean guideline of 15 µg/m^3 $PM_{2.5}$, which, according to WHO, ensures a low risk of acute effects from short-term exposure. To determine the boundary between "moderate" and "poor," this 24-h mean of 15 µg/m^3 was converted into a corresponding hourly mean using the empirical transformation factor 2 (1.82 derived in the previous step (section 2.2.3) was rounded to obtain a readily communicable threshold), yielding a 1-h daily maximum of 30 µg/m^3. Concentrations between 15 and 30 µg/m^3 have been associated with an elevated risk of serious health impacts, such as all-cause non-accidental mortality and cause-specific mortality, providing a rationale for classifying exposures in this range as moderate and concentrations above this range as "poor." Finally, the threshold between "poor" and "very poor" was aligned with the information threshold of the EU AAQD 2024, set at 50 µg/m^3 $PM_{2.5}$ for the 24-h mean (Table 3).

Category thresholds for other pollutants were calculated by multiplying $PM_{2.5}$ thresholds by their respective equivalence coefficients, ensuring risk-equivalent categories across all pollutants. The thresholds were rounded to the nearest whole number.

An optional module was developed to account for periods in which multiple pollutants simultaneously reach elevated concentrations (Liu and Peng, 2018; Mainka and Żak, 2022; Mauderly et al., 2010; Song et al., 2025). However, the module still uses the single-pollutant risk functions. It employs a rule set that escalates AQI categories when several pollutants are elevated and where epidemiological evidence supports increased effects due to simultaneous elevated concentrations of two or more pollutants. Specifically, if at least two pollutants fall within the "moderate" category and both concentrations are in the upper half of this range, the overall index is elevated to "poor." Similarly, if at least two pollutants are classified as "poor" and both concentrations are in the upper half of that range, the overall index is shifted to "very poor." These multipollutant episode upward reclassification rules apply to relevant pollutant pairs, namely $PM_{2.5}$ or PM_{10} with NO_2, O_3, or SO_2, as well as the combinations of O_3 with NO_2 or SO_2. Effects between $PM_{2.5}$ and PM_{10} were excluded.

2.2.6. *Index construction*

For risk communication, individual pollutant assessments are combined using a worst-pollutant rule, where the overall AQI category corresponds to the poorest performing pollutant at each monitoring station. For stations with incomplete pollutant coverage, the index is based on pollutants available for a particular station. In this case, the index is visually represented as a partially filled circle to indicate

Table 2
1-h effect estimate (additional cases in per cent) and equivalence coefficients per 10 μg/m^3 concentration increase as well as statistical parameters of the simulated equivalence coefficients (n = 10,000).

Pollutant	1-h effect estimate (additional cases in per cent) and equivalence coefficients per pollutant and outcome per 10 μg/m^3 concentration increase					Statistical parameters of the simulated equivalence coefficients (n = 10,000)						
	Parameter	Hospital admissions for cardiovascular diseases in %	Hospital admissions for respiratory diseases in %	ER visits or hospital admissions for asthma in %	Excess all-cause mortality in %	Mean	Median	Mode	95% uncertainty range	Point estimate[a]	Adjusted equivalence coefficients	Arguments
$PM_{2.5}$	1-h effect estimate (%)	0.55	0.77	1.59	0.38	-	-	-	-	-	-	-
	Equivalence coefficient	1.00	1.00	1.00	1.00							
PM_{10}	1-h effect estimate (%)	0.38	0.88	0.55	0.22	1.58	1.84	1.74	[1.19, 3.42]	1.75	1.80	The rounded median was chosen.
	Equivalence coefficient	1.43	0.88	2.91	1.75							
O_3	1-h effect estimate (%)	N/A	0.18	0.27	0.36	−3.27	1.19	1.49	[-19.86; 20.84]	3.81	4.80	The broad uncertainty range, as well as the priority of morbidity over mortality (the equivalence coefficients were 4.33 for hospital admissions for all respiratory diseases and 5.98 for the subgroup of asthmatic diseases). Also, the chosen value matches the highest index threshold for O_3 to the alert threshold of the EU Ambient Air Quality Directive.
	Equivalence coefficient	-	4.33	5.98	1.08							
NO_2	1-h effect estimate (%)	N/A	0.90	0.70	0.35	1.47	1.43	1.38	[1.01, 2.12]	1.4	2.00	NO_2 and $PM_{2.5}$ often come from the same sources and are correlated, which may lead to overestimation of NO_2 effects. Higher value was chosen a higher that means lower assumed toxicity per concentration unit.
	Equivalence coefficient	-	0.96	2.26	1.09							
SO_2	1-h effect estimate (%)	N/A	No data	0.47	0.28	2.94	2.34	2.00	[-1.15, 10.15]	2.38	2.00	Right-skewed distribution. The modal value was chosen.
	Equivalence coefficient	-	-	3.39	1.36							

[a] Calculated directly from the point effect estimates without accounting for statistical uncertainty.

Table 3
Reference points in the category classification for an anchor pollutant $PM_{2.5}$.

Threshold between categories	Concentration	Source of Threshold Value	Justification
"very good" to "good"	5 μg/m^3	5 μg/m^3 is the $PM_{2.5}$ annual mean value of the WHO Air Quality Guidelines 2021.	The annual AQG value of 5 μg/m^3 was selected as a normative anchor. It should not be interpreted as a biological threshold below which adverse effects are absent. When the value of 5 μg/m^3 is met, the certainty of short-term effects and of developing chronic health effects is very low.
"good" to "moderate"	15 μg/m^3	15 μg/m^3 is the $PM_{2.5}$ 24-h mean value of the WHO Air Quality Guidelines 2021.	Normative choice to provide a transparent link between the $PM_{2.5}$ category boundaries and the WHO AQGs while retaining the overall risk-equivalence framework of the index. When the value of 15 μg/m^3 is met over the full day, the certainty of short-term effects is very low. Above 15 μg/m^3 over one day, the certainty of acute and chronic health effects increases. The value is not interpreted as a threshold for acute health effects.
"moderate" to "poor"	30 μg/m^3	Conversion of the $PM_{2.5}$ 24-h mean value (15 μg/m^3) into an hourly value using a transformation factor of 2.	Above 30 μg/m^3 over 1 h, the certainty of serious, acute health effects increases.
"poor" to "very poor"	50 μg/m^3	50 μg/m^3 is the $PM_{2.5}$ information threshold of the EU AAQD 2024.	The information threshold is a level beyond which there is a risk to human health from brief exposure for particularly sensitive population and vulnerable groups and for which immediate and appropriate information is necessary. Above the legal information threshold, the public must be informed due to the increased risk of short-term health effects. Unlike the 15 μg/m^3 AQG value, the 50 μg/m^3 information threshold was retained directly to preserve alignment with the legally defined communication threshold rather than to derive a risk-equivalent hourly concentration.

potential underestimation of air quality conditions and communicate data limitations to users (Umweltbundesamt, n.d.).

2.3. Health recommendation development

We developed differentiated behavioural recommendations targeting both the general population and vulnerable subgroups, including elderly individuals, children, pregnant women, and patients with pre-existing cardiovascular or respiratory conditions. Since the assessment categories for individual pollutants reflect comparable increases in risk for short-term health effects, pollutant-specific behavioural recommendations were deemed unnecessary. The index is designed to support short-term behavioural adjustments and therefore focuses primarily on short-term health impacts. Recommendations emphasized limiting outdoor physical exertion during periods of poor air quality while balancing the established health benefits of physical activity. Additional guidance addressed emission reduction strategies through modified transport choices and residential heating practices.

2.4. Empirical evaluation and implementation

The newly developed UBA AQI was applied exemplarily to real monitoring data and compared with the existing index. Hourly monitoring data from the German air quality network, encompassing 439 stations in 2019 and 433 stations in 2022, were processed to compute both the new risk-based AQI and previous UBA AQI. The comparison focused on the distribution of index categories and the pollutants driving the overall index values. Furthermore, sensitivity checks illustrated how varying pollutant mixtures influence the aggregated index. This comparative application provided an empirical basis for assessing the plausibility of the category distributions and the practical implications of the revised methodology.

2.5. Sensitivity analysis incorporating updated evidence

Since the development and publication of the index, new evidence has become available, including updated guidance on concentration–response functions for health risk assessment of air pollution in the WHO European Region, as presented in the Health Risks of Air Pollution in Europe II (HRAPIE II) (World Health Organization (WHO). Regional Office for Europe, 2025). We therefore conducted a sensitivity analysis in which the index was recalculated using these updated effect estimates. In addition, to account for the potential non-linearity of the ozone concentration–response function, we introduced a lower exposure bound for O_3 (45 μg/m^3) based on evidence from various studies of nonlinear exposure-response functions (Jia et al., 2026; Ma et al., 2023; Vicedo-Cabrera et al., 2020; Zheng et al., 2021), including the study with similar climate conditions (Klompmaker et al., 2021). We then compared the resulting distributions of equivalence coefficients between the original and updated versions of the index, as well as the frequencies of AQI categories in the empirical data. This analysis aims to demonstrate the adaptability of the index to emerging scientific evidence and to provide an opportunity to assess the robustness of the proposed risk-based framework while opening a clear pathway for future updates as new evidence becomes available.

3. Results

The extended description of the methodology and the results can be found in the final report of the project (Pfäfflin et al., 2025) and its technical description (Pfäfflin et al., 2026).

3.1. Selection of exposure-outcome pairs

We identified the following exposure-outcome pairs with classified as causal or likely causal. Short-term increases in particulate matter

($PM_{2.5}$ and PM_{10}) were causally linked to non-accidental mortality, cardiovascular mortality, and adverse cardiovascular outcomes such as high blood pressure, cardiac arrhythmia, and related emergencies. They were also associated with respiratory effects, including exacerbation of existing disease, increased symptoms or medication use in patients with asthma or chronic obstructive pulmonary disease (COPD), respiratory emergencies, and mortality due to respiratory diseases. For NO_2 and SO_2, short-term exposure has been shown to cause mortality from respiratory diseases as well as emergencies related to asthma and COPD. O_3 was causally associated with respiratory diseases and emergencies due to asthma and COPD. However, the evidence for causal effects of short-term increases in O_3, NO_2, or SO_2 on all-cause mortality or on cardiovascular outcomes and related emergencies is currently insufficient according to US Environmental Protection Agency (U.S. Environmental Protection Agency, 2019; 2017, 2016, 2013) classifications, although the WHO AQG 2021 reviews indicate high certainty for some of these associations.

3.2. Effect estimation

The data sources from which the effect estimates for the defined exposure-outcome pairs were derived and all effect estimates used are listed in Table 1.

We evaluated whether the reviews and meta-analyses included a formal quality assessment of the evidence considered. Formal quality assessment of evidence is a relatively recent development, with modern tools such as Grading of Recommendations Assessment, Development and Evaluation (GRADE) or Risk of Bias of Office of Health Assessment and Translation (OHAT) being used to systematically evaluate the evidence base. More recent papers, such as those by Zheng et al., 2021; Zheng et al., 2021; Orellano et al., 2020; Orellano et al., 2020; Orellano et al. 2021; Orellano et al., 2021), use specific risk-of-bias tools to assess internal validity. Older studies often use less formalised, narrative approaches. The application of the newer methods rarely identified serious quality issues; in most cases, the quality of the evidence was high. In contrast, other studies, such as those by Abed Al Ahad et al. (Abed Al Ahad et al., 2020) and Hůnová et al. (2013), performed no systematic assessment of the risk of bias. Because these reviews did not include a systematic assessment, the risk of bias in their evidence base remains uncertain. However, it appears unlikely, as applied methods were similar to more recent studies, which were evaluated with a systematic tool.

3.3. Transformation of daily to hourly effect estimate values

The quantified transformation factors for the different percentiles and the years 2019 and 2022 are shown in Supplementary Table 1. The underlying data comprise measurements from Germany in 2019 and 2022. We examined the variability of the equivalence coefficients across different percentiles for each pollutant (data not shown). The additional transformation factors (e.g. 99th percentile/24-h mean) showed lower values for all pollutants. Therefore, we decided to use the 1-h maximum. Regarding the two years, differences between the two years were small for all pollutants. The final transformation factors, calculated as the averages for 2019 and 2022, were 1.82 for $PM_{2.5}$, 1.83 for PM_{10}, 1.13 for O_3, 1.99 for NO_2, and 2.13 for SO_2 (Supplementary Table 1).

3.4. Risk standardization and equivalence coefficients

For $PM_{2.5}$, each 10 $\mu g/m^3$ increase in the 1-h maximum level was linked to increases across all outcomes, including a 0.55% rise in cardiovascular hospital admissions, 0.77% in respiratory hospital admissions, 1.59% in asthma-related ER visits or admissions, and 0.38% in excess all-cause mortality. PM_{10} showed increases ranging from 0.22% to 0.88% across outcomes (Table 2). For O_3, NO_2, and SO_2, effects were limited to outcomes with causal evidence, most consistently for respiratory and asthma-related ER visits and for mortality. Cardiovascular effects were not estimated for these pollutants due to missing evidence.

The equivalence coefficients, using $PM_{2.5}$ as the reference pollutant with a coefficient of 1.00 across all health outcomes, indicate the relative concentration increase (per 10 $\mu g/m^3$) of each pollutant required to produce the same health effect as a 10 $\mu g/m^3$ increase in $PM_{2.5}$. For example, PM_{10} requires a 14.3 $\mu g/m^3$ increase (coefficient 1.43) to have the same effect on cardiovascular hospital admissions, but shows a lower coefficient (0.88) for respiratory hospital admissions and a substantially higher coefficient (2.91) for asthma-related ER visits. O_3 exhibits a coefficient of 4.33 for respiratory hospital admissions and 5.98 for asthma-related ER visits, indicating that a larger increase in O_3 concentration is required to produce an effect equivalent to that of a 10 $\mu g/m^3$ increase in $PM_{2.5}$, while SO_2 shows a coefficient of 3.39 for asthma and 1.36 for excess all-cause mortality. For NO_2 the highest coefficient was 2.26 for asthma-related ER visits, followed by excess all-cause mortality with 1.09 and respiratory hospital admissions of 0.96 (Table 2).

Table 2 summarizes statistical parameters derived from 10,000 simulations of equivalence coefficients for selected pollutants. For each pollutant, the mean, median, mode, and 95% uncertainty range are presented, reflecting variability in the estimated health impact relative to $PM_{2.5}$. Because some simulated estimates crossed zero, ratio-based equivalence coefficients could become negative or extremely large. Consequently, the resulting distributions, particularly their means, were unstable for pollutants with imprecise effect estimates. Median, mode, point estimates, and epidemiological plausibility were therefore considered jointly. Notably, O_3 shows a wide uncertainty range (−19.86; 20.84), indicating high variability and uncertainty in its effect estimates, while SO_2 exhibits the highest mean coefficient (2.94) with a substantial upper bound. The final coefficients were selected by considering the simulated distributions, point estimates, epidemiological plausibility, and practical AQI requirements, and range from 1.80 for PM_{10} to 4.80 for O_3, indicating that larger concentration increases of these pollutants are required to produce an effect equivalent to that of $PM_{2.5}$. The finally chosen equivalence coefficients are 2.00 for NO_2, 4.80 for O_3, 1.80 for PM_{10} and 2.00 for SO_2. The argumentation for the selection is given in Table 2.

3.5. Index construction

The category thresholds for the other pollutants were determined using the equivalence coefficients and the thresholds for $PM_{2.5}$. Table 4 provides the concentration thresholds of all pollutants used to assign AQI categories.

3.6. Health recommendation development

Based on the defined category thresholds of UBA AQI (Table 4), health-related behavioural recommendations were formulated at the index level rather than for individual pollutants (Table 5). The recommendations were designed to be concise, comprehensible, and practically feasible, with clear differentiation between the general population and vulnerable groups, such as individuals with pre-existing conditions, children, the elderly, and pregnant women. Assessments relied on the most recent hourly pollutant concentrations to enable timely behavioural adjustments and mitigate the risk of acute health effects. Vulnerable groups were advised to monitor symptoms and modify physical activity at lower AQI categories as compared to the general population, ensuring earlier protection where vulnerability is greater.

3.7. Empirical evaluation and implementation

We applied the risk-based UBA AQI to hourly data from 439 stations (2019) and 433 stations (2022). Compared to the previous UBA AQI, the new index resulted in a shift toward less favourable categories (Fig. 1).

Table 4
Risk-based UBA AQI, including category thresholds and equivalence coefficients.

Index	Hourly mean values in μg/m³									
	NO_2		PM_{10}		$PM_{2.5}$		O_3		SO_2	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Very poor	101		91		**51**		241		101	
Poor	61	100	55	90	**31**	**50**	145	240	61	100
Moderate	31	60	28	54	**16**	**30**	73	144	31	60
Good	11	30	10	27	**6**	**15**	25	72	11	30
Very good	0	10	0	9	**0**	**5**	0	24	0	10
Equivalence coefficient	2.00		1.80		1.00		4.80		2.00	

While "good" remained the most frequent classification, "very good" decreased sharply. The frequency of the "very good" category dropped from 31.7% to 4.6% in 2019 and from 35.8% to 5% in 2022 (Supplementary Table 3). The "moderate" category, previously the third most frequent (16.0% in 2019; 10.0% in 2022), increased markedly, rising to 38.5% and 35.5%. This category particularly increased for $PM_{2.5}$ and O_3, reflecting the stricter WHO guidelines ($PM_{2.5}$ from 2.1% to 7.9% and O_3 from 1.6% to 15.0% in 2019) (Fig. 1). The "poor" category, which was rarely assigned in the previous UBA AQI (3.1% in 2019; 2.1% in 2022), also showed an increase in frequency (5.6% and 2.8%). The "very poor" category remained extremely rare in all versions, though a slight increase was observed (from 0.1% in 2019 and 0.0% in 2022 to 0.5% and 0.2% respectively).

Pollutant-specific patterns are also evident: NO_2 determined the overall AQI category in more than 70% of observations at traffic stations. O_3 was frequently responsible in rural background stations and contributed substantially across urban and industrial stations. $PM_{2.5}$ drove the index more frequently, i.e. was the "worst pollutant", than PM_{10} at all types of stations.

The multipollutant episodes module led to an upward adjustment of the AQI category—either from "moderate" to "poor" or from "poor" to "very poor"—under four tested definitions that differ in how much of the category range is considered (top 25%, 50%, 75%, or the full category). For both 2019 and 2022, multipollutant episode-triggered changes are rare across all variants (Supplementary Table 2). When applying the finally chosen definition (top 50% of the category), the module raised the category in only 0.74% and 0.67% of all hours for the "moderate" to "poor" transition, and 0.05% and 0.03% of hours for the "poor" to "very poor" transition, in 2019 and 2022 respectively.

3.8. Sensitivity analysis

The risk estimates recommended in the HRAPIE II project were used in a sensitivity analysis. Specifically, for all-cause mortality, the RRs were 1.0068 (95% CI: 1.0059–1.0077) for $PM_{2.5}$, 1.0046 (95% CI: 1.0036–1.0057) for NO_2, and 1.0018 (95% CI: 1.0012–1.0024) for O_3. For hospital admissions, the RR was 1.009 (95% CI: 1.0026–1.0153) for $PM_{2.5}$ and CVD admissions, 1.0057 (95% CI: 1.0033–1.0082) for NO_2 and respiratory admissions, and 1.0075 (95% CI: 1.003–1.012) for O_3 and respiratory admissions. Compared with the main analysis, the evidence from HRAPIE II yielded slightly lower mortality estimates for O_3 and NO_2, lower $PM_{2.5}$-related CVD admissions, substantially lower NO_2-related respiratory admissions, and higher O_3-related respiratory admissions.

Furthermore, hospitalisation due to asthma was excluded, to test for its impact on the results. For each sensitivity analysis the equivalence

Table 5
Proposed behavioural recommendations for the risk-based UBA AQI.[b]

Index	Risk	Health-related behaviour		Other behavioural recommendations[a]
	General information	General public	Particularly vulnerable groups	
Very poor	The current air quality is very poor. Health issues may arise. Individuals with pre-existing lung and cardiovascular diseases, children and the elderly are most at risk, but even healthy people may experience health effects.	Postpone physically demanding activities or relocate them to places with better air quality. If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	Avoid physical exertion outdoors. Postpone physically demanding activities or relocate them to places with better air quality. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	You can help to ensure that air pollution stops rising and starts falling by leaving your car at home. Use public transport and walk or cycle shorter distances. Share journeys/carpool instead of driving alone. Do not burn wood in stoves or fireplaces and refrain from lighting any kind of fire outdoors. Do not use any equipment with combustion engines for hobbies or garden work.
Poor	The current air quality is poor. Health issues may arise. Individuals with pre-existing lung and cardiovascular diseases, children and the elderly are most at risk.	If you exercise outdoors, you should choose an area with better air quality (e.g. low traffic). If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	Postpone physically demanding activities or relocate them to places with better air quality. Alternatively, reduce the level of your physical exertion. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	
Moderate	The current air quality is moderate. Particularly vulnerable people may experience health problems. Individuals with pre-existing lung and cardiovascular diseases are most at risk.	Enjoy your usual outdoor activities.	If you exercise outdoors, you should choose an area with better air quality (e.g. low traffic) and pay attention to possible health effects. If you repeatedly experience health effects such as coughing or shortness of breath, you should reduce your physical activity and review your medication with your doctor.	You can help to ensure that air pollution does not rise or starts falling by leaving your car at home. Use public transport and walk or cycle shorter distances. Form carpool instead of driving alone. If possible, do not use any equipment with combustion engines for hobbies or garden work.
Good	The current level of air pollution is low. Short-term health problems due to air pollution are unlikely. However, effects on chronic diseases cannot be ruled out in the event of long-term exposure at this level.	Enjoy your outdoor activities.	Enjoy your outdoor activities.	You can help keep the air pollution low by leaving your car at home, using public transport and walking or cycling shorter distances. Form carpool instead of driving alone. If possible, do not use any equipment with combustion engines for hobbies or garden work.
Very good	The current level of air pollution is very low. No health problems are expected to be caused by air pollutants.	Enjoy your outdoor activities.	Enjoy your outdoor activities.	

[a] The advice for "Other behavioral recommendations" was largely adopted from the Swiss air quality index and the WHO recommendations for the design of air quality indices (Cercl'Air, 2020).
[b] The general information and the health-related behaviour advice differ slightly from the information given on the UBA website and in the app.

coefficients were calculated as in the main analysis, including the Monte Carlo simulation.

3.8.1. Effect of hospitalisations for asthma

Excluding asthma hospitalisations from the outcome set shifted the coefficient distributions towards one for all pollutants. The changes were particularly marked for SO_2 and NO_2 and were also evident for PM_{10}, making their estimated toxicity more comparable to that of $PM_{2.5}$ (Supplementary Fig. 1 and Supplementary Table 4). In particular, the median of the NO_2 equivalence coefficient distribution decreased substantially under the original UBA AQI framework, from 1.42 to 0.99, indicating that asthma hospitalisations contributed importantly to the estimated NO_2-related health burden. Under the new evidence framework, however, the NO_2 median changed only slightly, from 2.17 to 2.05. Although the distribution of O_3 equivalence coefficients remained highly uncertain, asthma exclusion also resulted in slightly lower median values.

3.8.2. Inclusion of HRAPIE II evidence

Compared with the UBA AQI presented above, the inclusion of the new evidence from HRAPIE II resulted in higher estimated equivalence coefficient medians for NO_2 and O_3, while PM_{10} and SO_2 medians changed only marginally. The increase was particularly pronounced for NO_2, with median estimates rising from 1.43 to 2.17 in the baseline scenario. O_3 estimates also increased and became more consistent (Supplementary Fig. 1 and Supplementary Table 4).

The distributions for PM_{10} and SO_2 changed only marginally, and their finalised coefficients were not changed. In contrast, the NO_2 median increased substantially, although the previously selected final coefficient of 2.0 remained compatible with the updated evidence. For O_3, the previously selected equalizing coefficient of 4.8 appeared disproportionately high relatively to the updated point estimate of 3.09. Consequently, a different approach was adopted for ozone by applying a lower exposure bound of 45 μg/m^3 instead of 0, and an equivalence coefficient of 3 (Supplementary Table 5). This resulted in an O_3 threshold of 60 μg/m^3 between categories "very good" and "good". This choice was also supported by the substantial uncertainty associated with ozone concentrations below 60 μg/m^3 and by the exposure range underlying the recommended risk estimates (Supplementary Table 6). Applying the O_3 equivalence coefficient directly would have resulted in a threshold concentration of 15 μg/m^3 O_3 between "very good" and "good" categories that unlikely produces health effects comparable to those associated with a $PM_{2.5}$ concentration of 5 μg/m^3.

As a result of changes in the definition of the O_3 categories, the AQI based on the new evidence showed higher frequencies in the "very good" category than the risk-based UBA AQI: 11.6% versus 4.6% in 2019 and 12.7% versus 5.0% in 2022 (Supplementary Table 6). In contrast, the frequency of the "good" category increased only slightly under the

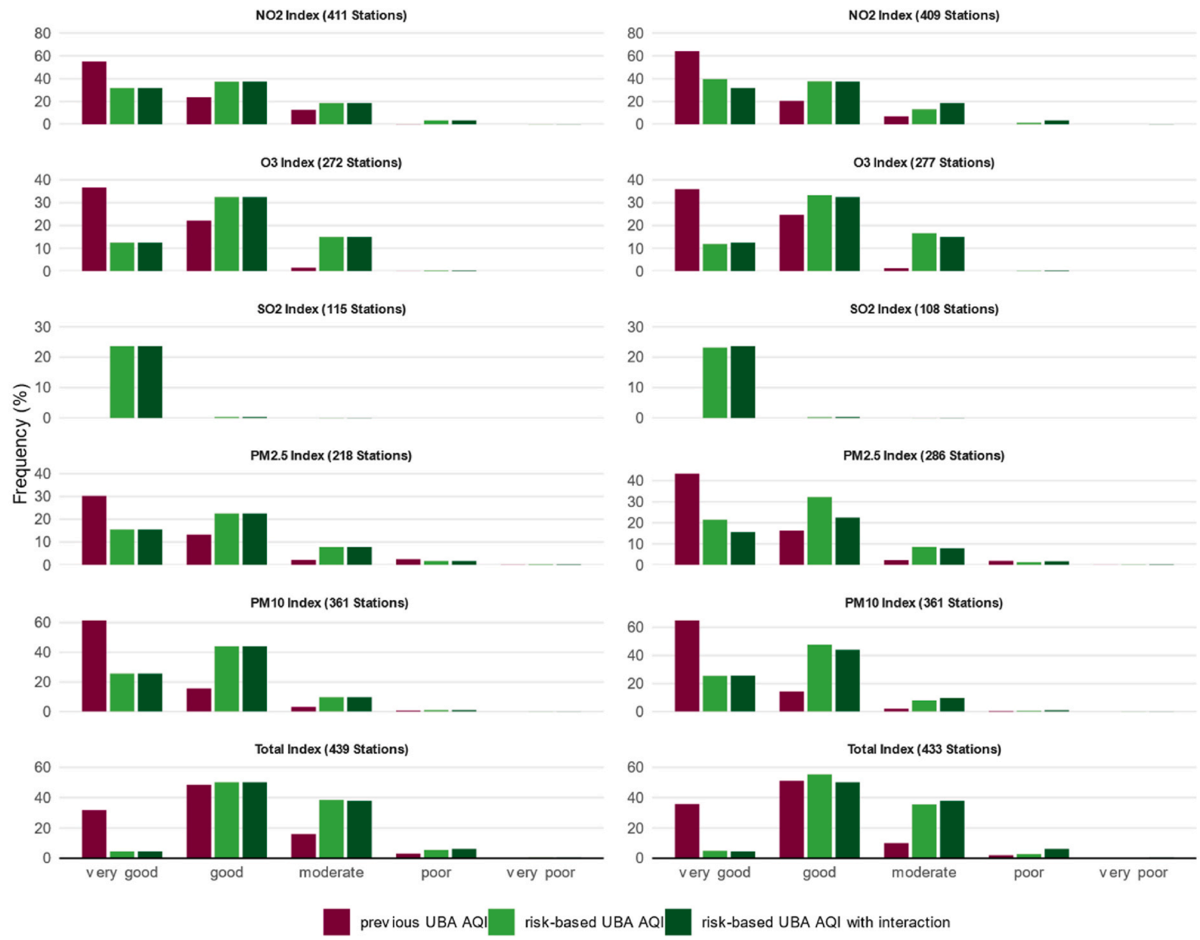

Fig. 1. Frequency distribution of the AQI categories of the three index variants examined in 2019 (left) and 2022 (right) for NO_2, O_3, SO_2, $PM_{2.5}$ and PM_{10} and the AQI.

new-evidence index. The frequency of the "moderate" category decreased, whereas the frequencies of the "poor" and "very poor" categories increased.

4. Discussion

We proposed a new risk-based UBA AQI that uses epidemiological evidence to harmonize health risks across pollutants, ensuring that transitions between air quality categories correspond to comparable increases in health risk across pollutants, averaged over different health outcomes. Overall, adoption of the new index leads to a moderate shift towards less favourable categories, with $PM_{2.5}$ playing a more dominant role in determining the overall AQI category than in the previous index and O_3 increasing in importance for determining the overall index in rural monitoring stations.

One of the main challenges in designing an AQI is to provide users with a truly helpful tool. An index that frequently indicates only "good" air quality may fail to prompt awareness of existing health risks, while one that predominantly shows "poor" air quality can lead to warning fatigue or inaction. Moreover, it cannot be ruled out that some individuals may feel alarmed by behavioural recommendations and unnecessarily restrict their physical or other activities. The old UBA AQI was developed with these issues in mind. The risk-based AQI for Germany was developed using the best evidence available at the time of its development. Unlike conventional AQIs with regulatory standards for category thresholds, this index ensures that each category represents a comparable increase in health risk, independent of pollutant. By standardizing to $PM_{2.5}$ and using equivalence coefficients, the UBA AQI provides a coherent, risk-equivalent scale across pollutants.

The UBA AQI was evaluated using two years of measurement data. We were concerned that the introduction of a stricter assessment of the air quality in highly polluted regions may lead to a predominance of "poor" air-quality classifications, potentially contributing to warning fatigue among the affected populations (Chen et al., 2018; Saberian et al., 2017; World Health Organization (WHO), 2021). In such contexts, frequent and persistent alerts can reduce risk salience and diminish behavioural responsiveness over time, particularly if warnings are perceived as unavoidable or lacking actionable alternatives (Mirabelli et al., 2020; Potter et al., 2021). In this regard, regionally adapted or spatially disaggregated AQIs may help mitigate warning fatigue by reflecting local pollution patterns more accurately, enabling targeted messaging, and prioritizing alerts where short-term risk reductions are most feasible (Bagkis et al., 2025; Chandra and Lee, 2025; Wang et al., 2023). Indeed, the WHO recommends to construct and apply indices in smaller geographical units (World Health Organization (WHO) Regional Office for Europe, 2026). The evaluation of the risk-based UBA AQI showed that application of the new AQI, while substantially reducing the frequency of "very good" classifications, increases in "moderate" and "poor" categories were only moderate. These increases reflect the adoption of the stricter WHO AQG 2021 levels and highlight that health-relevant exposures are more common than previously communicated. A further geographical differentiation into separate indices within Germany was not deemed necessary, because the observed distribution is unlikely to result in frequent persistent warnings or warning fatigue.

Recommendations in the new index are specified for the general population and for vulnerable subgroups. The basic principle is to raise awareness for potential health issues with increasing index value, starting with earlier warnings for vulnerable people. The users are recommended to move physical activity to areas or times with lower concentrations and low traffic, without discouraging them from physical activity in general. Although ozone may be lower close to traffic because of chemical titration, traffic locations can have higher concentrations of other harmful pollutants and should not be recommended for exercise. However, it should be noted that the proposed behavioural recommendations are not identical to those ultimately implemented in the app and the UBA portal.

The recommendations sought to strike a balance between health protection and the continued promotion of active mobility, recognising its central role in public health and sustainability (Tainio et al., 2016). In addition to personal protective advice, guidance was provided on low-emission behaviours, particularly in transport and heating, with the dual aim of reducing individual exposure and raising awareness of contributions to improved urban air quality. The recommendations were tailored to each AQI category. For instance, under "poor" conditions, the general population was advised to limit strenuous outdoor activity in polluted areas, while vulnerable groups were instructed to postpone such activity altogether. Under "very poor" conditions, both groups were recommended to refrain from outdoor exertion entirely. Furthermore, additional behavioural recommendations are provided, such as reducing car usage, to help mitigate air pollution and link it to individual behaviour (Table 5). Nevertheless, we are aware that personal influence on current air pollution is limited.

Currently, most citizens in the EU have access to two different indices – the AQI developed by the European Environment Agency (EEA) and a national AQI. While a European AQI is useful for supranational comparisons, a national approach is also supported by WHO recommendations. Risk communication should remain flexible enough to reflect differences between countries in air pollution mixtures, baseline concentrations, outdoor activity patterns, and risk preferences. Accordingly, country-specific health messaging that reflects the national context should be continued *(*Cromar and Lazrak, 2023*)*. In addition to these official AQIs, there are other, partly commercial AQIs available as well. The simultaneous use of two or more different indices with different messaging may lead to confusion and distrust in the population. Further research is needed to assess whether a harmonized AQI for the entire EU would be more beneficial than the current approach, in which individual countries, such as Germany, maintain their own national indices.

4.1. Limitations

Nevertheless, several limitations remain. The risk-equivalent scaling requires complex calculations and depends heavily on the availability and robustness of epidemiological effect estimates, which are incomplete for some pollutants and health outcomes.

The transformation of daily to hourly risk estimates relies on empirical concentration ratios rather than direct epidemiological evidence, introducing uncertainty. The index is intended for near-real-time risk communication and behavioural guidance; however, the associated risk should be interpreted as the risk represented by an hourly peak within a daily exposure pattern, not as the biological effect of exactly 1 h of exposure. For O_3, for example, broad confidence intervals in effect estimates introduce substantial uncertainty. Additionally, some pollutant–outcome associations (e.g., O_3 and asthma admissions in temperate climates) are supported only by limited data. On the other hand, the relative ease of updating equivalence factors as new epidemiological evidence becomes available makes the index adaptable, not necessarily robust, for long-term application in public health practice. However, updates to the index should be planned carefully and not performed too frequently, as doing so could reduce the credibility of the AQI among users and thus the public acceptance of the AQI.

The worst-pollutant rule, though simple and consistent with previous practice, may underrepresent multi-pollutant health risks despite the optional multipollutant episodes module. In practice, the worst-pollutant (maximum sub-index) rule leads to situations in which several pollutants are simultaneously elevated: when, for example, $PM_{2.5}$ and O_3 are each "moderate," the reported index remains driven by only one component, even though health risks plausibly reflect additive (and sometimes correlated) contributions of the mixture. This limitation is frequently noted in the literature, where the conventional AQI is described as being unable to capture additive/combined effects across pollutants and thus potentially underrepresenting health-relevant risk during multi-exposure periods (Chen et al., 2023; Stieb et al., 2008). Beyond conceptual concerns, reviews emphasize that multipollutant metrics are methodologically heterogeneous (choice of pollutants, weighting, time windows, and model form), and that strong correlations among pollutants complicate estimation and interpretation (Oakes et al., 2014). Furthermore, in some cases two-pollutant estimates led to paradoxical results and interpretation challenges (Castro et al., 2023). However, the evidence base is still uneven across regions, pollutant mixtures, and endpoints, so multipollutant episode modules are often not backed by a robust, broadly validated epidemiological evidence that would justify replacing the worst-pollutant rule (To et al., 2012).

The UBA AQI relies on 1-h average concentrations rather than a 24-h moving average because short measurement averaging intervals are more responsive to rapid changes in air quality, allowing timelier public communication, and align with existing EU alert thresholds. This shorter averaging time makes the index more actionable for hourly health recommendations. The calculation of the hourly risk equivalent requires several assumptions: first, daily 1-h maximum value in 24-h period is highly correlated with 24-h mean (Gutiérrez-Avila et al., 2025; Samoli et al., 2006; Stieb et al., 2008); second, the health effect relative risks for 24-h mean are highly correlated with the relative ratios based on 1-h maximum concentrations as shown in empirical data (Gutiérrez-Avila et al., 2025; Samoli et al., 2006; World Health Organisation and Regional Office for Europe, 2013). At the same time, the 1-h effect estimate must not be interpreted as a relative risk for a 1-h exposure period as it does not refer to the biological effect of a 1-h exposure period but to the 1-h maximum of a 24-h period.

An AQI is always a simplification of complex environmental and health data. For particulate matter, particularly $PM_{2.5}$, no clear threshold has been identified. For O_3 and other gaseous pollutants, the shape of the concentration–response relationship at low concentrations is less certain. The WHO reaffirmed this in its most recent AQG, emphasizing that both mortality and morbidity risks increase continuously with rising pollutant concentrations. Consequently, the definition of AQI categories inevitably involves a degree of arbitrariness—for example, determining the concentration threshold below which air quality can still be classified as "very good." While the long-term WHO guideline values were used as reference points in developing the index, more recent studies suggest that health effects may already occur at concentrations below 5 $\mu g/m^3$ for $PM_{2.5}$ (Weichenthal et al., 2022).

Even though we use the WHO AQG values to anchor the $PM_{2.5}$ bands, the AQGs are not intended to define bands for an AQI. Exceeding an AQG value indicates an increased risk of adverse health effects, but the guidelines themselves are not designed as categorical thresholds. Mortality evidence played an important role in deriving several WHO AQGs, although the guideline process considered a broader range of health outcomes. In our index, we account for morbidity risks and explicitly consider vulnerable groups, such as people with asthma. Our approach focuses on short-term health outcomes, such as hospital admissions due to cardiovascular disease or asthma attacks. We recognize that applying a risk-based approach consistently across all pollutants leads to bands that do not fully align with the WHO AQGs, which may create communication challenges. Nevertheless, we chose this approach to ensure methodological consistency across pollutants.

The calculation of equivalence coefficients is also subject to several limitations. The coefficients depend on the availability and quality of epidemiological evidence, which differs between pollutants and health outcomes. For some pollutant–outcome combinations, effect estimates are based on a larger and more consistent evidence base, whereas for others the uncertainty is greater. In addition, translating effect estimates from different exposure metrics and time windows into hourly AQI categories requires assumptions, for example regarding the relationship between daily and hourly concentrations. Therefore, the resulting equivalence coefficients should not be interpreted as fixed biological constants, but rather as pragmatic, evidence-informed parameters for harmonizing the AQI structure. Furthermore, Monte Carlo simulations were performed to account for the statistical uncertainty associated with the risk estimates. However, because the level of uncertainty differed substantially between pollutants, for example, $PM_{2.5}$ estimates were characterized by relatively narrow confidence intervals, whereas O_3 estimates showed considerably wider confidence intervals, the resulting coefficient distributions were used as an additional source of information rather than as a strict decision rule. The simulations were intended to characterize the robustness and uncertainty of the coefficients, while the final coefficient selection also considered expert judgement and practical aspects of AQI communication.

Furthermore, risk standardization necessarily simplifies complex exposure–response relationships. It assumes that relative risks can be compared across pollutants and outcomes in a common framework, although the underlying mechanisms, affected populations, exposure patterns, and exposure–response functions may differ. The final coefficients therefore combine quantitative evidence with expert judgment to ensure scientific plausibility, consistency with existing standards, and practical applicability for public communication. Future updates of the AQI should re-evaluate these coefficients as new epidemiological evidence becomes available and should assess the sensitivity of AQI categorization to alternative coefficient choices.

Some characteristics of the risk-based UBA AQI remained unchanged compared to the prior UBA AQI from 2019: the AQI is based on data from fixed monitoring stations. However, these stations are sometimes located several kilometres away from an individual's actual location and therefore do not accurately reflect personal exposure. This limitation cannot be resolved by an index that is based only on concentrations obtained from fixed monitoring stations and remains a significant constraint in assessing individual health risks. Solutions include spatial interpolation between stations or the use of hourly "real-time" modelling results covering the entire country, which could be incorporated in further improved versions of the index.

4.2. Strengths

There are several strengths of the index developed here. First, the construction of the index relies on high-quality epidemiological syntheses. Second, the transformation of effect estimates to hourly resolution improves timeliness, enabling the population to adapt their behaviour if necessary. Third, the index explicitly includes vulnerable groups in recommendations. Fourth, in this approach the index categories are anchored in both WHO AQG 2021 and EU alert thresholds. Fifth, the index is dominated by air pollution effects on morbidity due to larger relative contribution of morbidity endpoints to the risk-based equivalence coefficients, reflecting more common outcomes than the more traditionally used mortality effects. Sixth, the applied method is transparent and reproducible.

A strength of the risk-standardization approach is that it provides a transparent and epidemiologically grounded basis for comparing pollutants with different units, concentration ranges, and health-risk profiles within one common AQI framework. By deriving equivalence coefficients, the index categories are aligned according to comparable expected health risks rather than only pollutant-specific regulatory thresholds. This improves internal consistency of the AQI and supports clearer communication of health concern across pollutants.

Two institutions played a key role in the development of the index in different ways: on the one hand, the WHO, through its scientific documents on AQIs; and on the other hand, the EU, via the EU AAQD 2024, which establishes legal requirements. By incorporating both perspectives, the index gains strength as a robust and comprehensive tool.

For example, the WHO Regional Office for Europe suggested that local authorities adopt health-based, multipollutant indices offering tailored messaging for specific groups to keep safety alerts effective and avoid warning fatigue (Cromar and Lazrak, 2023). Following this recommendation, we developed the present version of an AQI specifically designed for Germany. At the same time, the EEA introduced a revised harmonized AQI for Europe that also covers Germany (European Environment Agency, 2024b). While both the EEA AQI and the UBA AQI for Germany rely on the same exposure data from national monitoring networks, their methodologies differ substantially. The EEA AQI focuses primarily on mortality, applies WHO guideline values directly for lower index categories for all pollutants and therefore does not take a purely risk-based approach. It includes an additional category ("extremely poor") and uses a broader concentration range, covering situations all over Europe. In contrast, the UBA AQI was specifically tailored to the German context. It incorporates narrower concentration intervals to reflect typical national air pollution levels, emphasizes both morbidity and mortality, and applies a risk-equivalent classification approach based on recent epidemiological findings. For the German index, morbidity outcomes were prioritized because they are generally more frequent, their estimates may in some settings be obtained with greater precision than mortality estimates. Particularly, patients with asthma represent one of the most important target groups for the UBA AQI, as they are vulnerable to short-term air pollution peaks and therefore have the greatest need for timely, actionable health-protection information.

Furthermore, the behavioural recommendations are informed by national public health expertise and designed to support early action to mitigate risk, especially for vulnerable groups.

Another strength of the developed UBA AQI is that it meets the principal AQI-related requirements of the EU AAQD 2024, published during the process of index development. The Directive mandates that member states provide an AQI offering hourly updates on at least SO_2, NO_2, PM_{10}, $PM_{2.5}$, and O_3. Furthermore, the AQI should, to the extent possible, be comparable across all member states and adhere to the WHO AQG 2021, which serve as the foundation for the AQI. It must also incorporate health impact information, with specific details tailored to sensitive populations and vulnerable groups, as is also reflected in the UBA AQI.

4.3. Further development

In the future, several further developments of the index seem beneficial. As most indices and their recommendations have not been tested for correct understanding and implementation. The language used in the index and accompanying recommendations should be tested for clarity and accessibility, as some individuals may struggle to understand the AQI and the suggested behavioural recommendations (Pinakidou, 2025). Additionally, it is important to evaluate whether the index effectively induces appropriate behavioural changes in relevant population groups and ultimately contributes to a measurable reduction in morbidity and mortality. Increased awareness does not necessarily translate into behavioural change (Pinakidou, 2025), and in some cases, the index may even have unintended negative consequences, such as discouraging people from engaging in outdoor physical activity and social interaction, both of which are important for overall health.

Future digital risk-communication tools could also integrate other acute environmental hazards such as heat, pollen, and extreme weather events. These factors could be communicated collectively through a single digital platform, such as an app, providing an integrated summary of the combined effects of different environmental conditions on human health. For example, heat, air pollution, and pollen all impact the cardiovascular and respiratory systems, with potential synergistic effects that may exacerbate health outcomes (Anenberg et al., 2020; Rai et al., 2023).

4.4. Conclusion

Overall, the risk-based UBA AQI represents a significant step toward health-based communication of air quality in Germany. By integrating scientific evidence into its design and providing tailored guidance, it enhances preventive public health protection. Its implementation is expected to improve risk awareness and has the potential to support behavioural changes aimed at reducing exposure and emissions.

Ethics

Ethical approval was not required for this study, as it relied exclusively on aggregated, non-identifiable environmental data and involved no human participants.

Funding

The project was funded by the Federal Ministry for Environment, Climate Action, Nature Conservation and Nuclear Safety and supervised by the German Environment Agency (FKZ 3722 61 202 0).

CRediT authorship contribution statement

Katherine Ogurtsova: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Myriam Tobollik:** Conceptualization, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Tomke Zschachlitz:** Project administration, Resources, Writing – review & editing. **Wolfgang Straff:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Florian Pfäfflin:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Resources, Supervision, Writing – review & editing. **Antonia Fritz:** Data curation, Formal analysis, Writing – review & editing. **Volker Diegmann:** Conceptualization, Supervision, Writing – review & editing. **Barbara Hoffmann:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

Declaration of competing financial interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Myriam Tobollik, Tomke Zschachlitz, and Wolfgang Straff are employed at the German Environment Agency (Umweltbundesamt).

Acknowledgements

We would like to thank Anja Behrens, Ute Dauert, Susann Kessinger and Stefan Feigenspan for their invaluable support in the development of the index, as well as for their continuous feedback. We acknowledge the use of DeepL (version 26.1.1.19426) for language and grammar checks in the preparation of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2026.114867.

References

Abed Al Ahad, M., Sullivan, F., Demšar, U., Melhem, M., Kulu, H., 2020. The effect of air-pollution and weather exposure on mortality and hospital admission and implications for further research: a systematic scoping review. PLoS One 15, e0241415. https://doi.org/10.1371/journal.pone.0241415.

Anenberg, S.C., Haines, S., Wang, E., Nassikas, N., Kinney, P.L., 2020. Synergistic health effects of air pollution, temperature, and pollen exposure: a systematic review of epidemiological evidence. Environ. Health 19. https://doi.org/10.1186/S12940-020-00681-Z.

Atkinson, R.W., Mills, I.C., Walton, H.A., Kang, S., Anderson, H.R., 2014. Systematic Review and Quantitative meta-analysis of the Evidence for Associations Between Chronic and short-term Exposure to Outdoor Air Pollutants and Health, pp. 1–141.

Bagkis, E., Hassani, A., Schneider, P., DeSouza, P., Shetty, S., Kassandros, T., Salamalikis, V., Castell, N., Karatzas, K., Ahlawat, A., Khan, J., 2025. Evolving trends in application of low-cost air quality sensor networks: challenges and future directions. Climate and Atmospheric Sci. 2025 8 (1), 335. https://doi.org/10.1038/s41612-025-01216-4.

Boogaard, H., Walker, K., Cohen, A.J., 2019. Air pollution: the emergence of a major global health risk factor. Int. Health 11, 417–421. https://doi.org/10.1093/INTHEALTH/IHZ078.

Bundesrepublik Deutschland, 2010. Neununddreißigste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung über Luftqualitätsstandards und Emissionshöchstmengen – 39. BImSchV). Bundesgesetzblatt. Bundesministerium der Justiz, Berlin.

Buonocore, J.J., Robinson, L.A., Hammitt, J.K., O'Keeffe, L., 2021. Estimating the potential health benefits of air quality warnings. Risk Anal. 41, 645–660. https://doi.org/10.1111/RISA.13640.

Castro, A., Künzli, N., de Hoogh, K., Kappeler, R., Kutlar Joss, M., Vienneau, D., Röösli, M., 2023. Mortality attributable to ambient fine particulate matter and nitrogen dioxide in Switzerland in 2019: use of two-pollutant effect estimates. Environ. Res. 231, 116029. https://doi.org/10.1016/J.ENVRES.2023.116029.

Cercl'Air, 2020. Kurzzeit-Luftbelastungs-Index (KBI): Gesamtschweizerisches Index-System zur vereinfachten Kommunikation der Kurzzeit-Luftbelastung unter Berücksichtigung der gesundheitlichen Auswirkungen, Empfehlung. Cercl`Air, Schweizerische Gesellschaft der Lufthygiene-Fachleute, Schweiz.

Chandra, S.V.S.N., Lee, J.K.W., 2025. A systematic review of heat health warning systems: enhancing the framework towards effective health outcomes. Curr. Environ. Health Rep. 12, 31. https://doi.org/10.1007/S40572-025-00496-5.

Chen, H., Li, Q., Kaufman, J.S., Wang, J., Copes, R., Su, Y., Benmarhnia, T., 2018. Effect of air quality alerts on human health: a regression discontinuity analysis in Toronto, Canada. Lancet Planet. Health 2, e2–e3. https://doi.org/10.1016/S2542-5196(17)30185-7.

Chen, M.J., Leon Guo, Y., Lin, P., Chiang, H.C., Chen, P.C., Chen, Y.C., 2023. Air quality health index (AQHI) based on multiple air pollutants and mortality risks in Taiwan: construction and validation. Environ. Res. 231, 116214. https://doi.org/10.1016/J.ENVRES.2023.116214.

Chen, J., Hoek, G., 2020. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. Environ. Int. 143. https://doi.org/10.1016/j.envint.2020.105974.

Cromar, K., Lazrak, N., 2023. Risk Communication of Ambient Air Pollution in the WHO European Region: Review of Air Quality Indexes and Lessons Learned. World Health Organization, Copenhagen.

Dominici, F., Zigler, C., 2017. Best practices for gauging evidence of causality in air pollution epidemiology. Am. J. Epidemiol. 186, 1303–1309. https://doi.org/10.1093/AJE/KWX307.

Dusseldorp, A., Fischer, P.H., Dijkema, M.B.A., Strak, M.M., 2014. Luchtkwaliteitsindex. Aanbevelingen voor de samenstelling en duiding. Rijksinstituut voor Volksgezondheid en Milieu. RIVM.

Environment and Climate Change Canada (ECCC), n.d. Environment and Climate Change Canada. About the Air Quality Health Index [WWW Document]. URL http://www.canada.ca/en/environment-climate-change/services/air-quality-health-index/about.html (accessed June.30.2026).

European Environment Agency, 2024a. Europe's Air Quality Status 2024, EEA Briefing. European Environment Agency, Copenhagen. https://doi.org/10.2800/5970.

European Environment Agency, 2024b. About the European air quality index [WWW Document]. URL. https://www.eea.europa.eu/themes/air/air-quality-index. (Accessed 30 June 2026).

European Parliament. Council of the European Union, 2024. Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on Ambient Air Quality and Cleaner Air for Europe (Recast). Official Journal of the European Union. Publications Office of the European Union, Luxembourg.

GBD 2023 Disease and Injury and Risk Factor Collaborators, 2025. Burden of 375 diseases and injuries, risk-attributable burden of 88 risk factors, and healthy life expectancy in 204 countries and territories, including 660 subnational locations, 1990-2023: a systematic analysis for the global burden of disease study 2023. Lancet 406, 1873–1922. https://doi.org/10.1016/S0140-6736(25)01637-X.

Glass, T.A., Goodman, S.N., Hernán, M.A., Samet, J.M., 2013. Causal inference in public health. Annu. Rev. Publ. Health 34, 61. https://doi.org/10.1146/ANNUREV-PUBLHEALTH-031811-124606.

Gutiérrez-Avila, I., Wright, R.O., Rosa, M.J., Just, A.C., 2025. Exposure to daily mean and maximum 1-hour PM2.5 concentrations and pediatric respiratory mortality in the Mexico City metropolitan area. Environ. Epidemiol. 9, e408. https://doi.org/10.1097/EE9.0000000000000408.

Hůnová, I., Malý, M., Řezáčová, J., Braniš, M., 2013. Association between ambient ozone and health outcomes in Prague. Int. Arch. Occup. Environ. Health 86, 89–97. https://doi.org/10.1007/s00420-012-0751-y.
Huang, W.Z., He, W.Y., Knibbs, L.D., Jalaludin, B., Guo, Y.M., Morawska, L., Heinrich, J., Chen, D.H., Yu, Y.J., Zeng, X.W., Yu, H.Y., Yang, B.Y., Hu, L.W., Liu, R.Q., Feng, W. R., Dong, G.H., 2022. Improved morbidity-based air quality health index development using Bayesian multi-pollutant weighted model. Environ. Res. 204, 112397. https://doi.org/10.1016/J.ENVRES.2021.112397.
Huangfu, P., Atkinson, R., 2020. Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: a systematic review and meta-analysis. Environ. Int. 144. https://doi.org/10.1016/j.envint.2020.105998.
irCELine, 2022. Proposal for a New Air Quality Index.
Jia, X., Song, B., Wang, S., Wang, Y., Bi, Y., Zheng, Y., Zuo, K., Huang, J., Sun, H., Chen, G., Ren, J., Liu, Y., 2026. Association of short-term exposure to ozone with total and cause-specific mortality: a systematic review and meta-analysis. J. Hazard. Mater. 501, 140825. https://doi.org/10.1016/J.JHAZMAT.2025.140825.
Klompmaker, J.O., Hart, J.E., James, P., Sabath, M.B., Wu, X., Zanobetti, A., Dominici, F., Laden, F., 2021. Air pollution and cardiovascular disease hospitalization – are associations modified by greenness, temperature and humidity? Environ. Int. 156, 106715. https://doi.org/10.1016/J.ENVINT.2021.106715.
Liu, J.C., Peng, R.D., 2018. Health effect of mixtures of ozone, nitrogen dioxide, and fine particulates in 85 US counties. Air Quality, Atmosphere & Health 2018 11 (3), 311–324. https://doi.org/10.1007/S11869-017-0544-2.
Ma, Y., Zhao, H., Su, Y., 2023. Ozone pollution and acute exacerbation of asthma in residents of China: an ecological study. J. Asthma Allergy 16, 951. https://doi.org/10.2147/JAA.S422476.
Mainka, A., Żak, M., 2022. Synergistic or antagonistic health effects of Long- and short-term exposure to ambient NO2 and PM2.5: a review. Int. J. Environ. Res. Publ. Health 19, 14079. https://doi.org/10.3390/IJERPH192114079.
Mauderly, J.L., Burnett, R.T., Castillejos, M., Özkaynak, H., Samet, J.M., Stieb, D.M., Vedal, S., Wyzga, R.E., 2010. Is the air pollution health research community prepared to support a multipollutant air quality management framework? Inhal. Toxicol. 22, 1–19. https://doi.org/10.3109/08958371003793846.
Mirabelli, M.C., Ebelt, S., Damon, S.A., 2020. Air quality index and air quality awareness among adults in the United States. Environ. Res. 183, 109185. https://doi.org/10.1016/J.ENVRES.2020.109185.
O'Brien, E., Masselot, P., Sera, F., Roye, D., Breitner, S., Ng, C.F.S., Coelho, M. de S.Z.S., Madureira, J., Tobias, A., Vicedo-Cabrera, A.M., Bell, M.L., Lavigne, E., Kan, H., Gasparrini, A., Carrasco, G., Chen, B.Y., Entezari, A., Guo, Y., Guo, Y.L., Hashizume, M., Holobaca, I.H., Íñiguez, C., Jaakkola, J.J.K., Kim, H., Lee, W., Li, S., Maasikmets, M., Mayvaneh, F., Nunes, B., Orru, H., Osorio, S., Ragettli, M.S., Ryti, N., Saldiva, P.H.N., Schneider, A., Schwartz, J., Tong, S., Zanobetti, A., 2023. Short-term association between sulfur dioxide and mortality: a multicountry analysis in 399 cities. Environ. Health Perspect. 131, 037002. https://doi.org/10.1289/EHP11112.
Oakes, M., Baxter, L., Long, T.C., 2014. Evaluating the application of multipollutant exposure metrics in air pollution health studies. Environ. Int. 69, 90–99. https://doi.org/10.1016/j.envint.2014.03.030.
Orellano, P., Reynoso, J., Quaranta, N., 2021. Short-term exposure to sulphur dioxide (SO2) and all-cause and respiratory mortality: a systematic review and meta-analysis. Environ. Int. 150. https://doi.org/10.1016/j.envint.2021.106434.
Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., Ciapponi, A., 2020. Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: systematic review and meta-analysis. Environ. Int. 142. https://doi.org/10.1016/j.envint.2020.105876.
Pfäfflin, F., Fritz, A., Diegmann, V., Hoffmann, B., Ogurtsova, K., 2026. Technical Documentation of the Risk-based UBA Air Quality Index. Umweltbundesamt, Berlin.
Pfäfflin, F., Fritz, A., Diegmann, V., Hoffmann, B., Ogurtsova, K., Weik, K., 2025. Überarbeitung des Luftqualitätsindex des Umweltbundesamtes nach der Herausgabe der Luftqualitätsleitlinien der WHO 2021, Umwelt & Gesundheit. Umweltbundesamt, Dessau-Roßlau. https://doi.org/10.60810/openumwelt-7990.
Pinakidou, S., 2025. People's perceptions of air pollution and their awareness of official indexes at the start of the twenty-first century: a review. Discover Environment 2025 3 (1). https://doi.org/10.1007/S44274-025-00213-X, 57.
Potter, S., Harrison, S., Kreft, P., 2021. The benefits and challenges of implementing impact-based severe weather warning systems: perspectives of weather, flood, and emergency management personnel. Weather Clim. Soc. 13, 303–314. https://doi.org/10.1175/WCAS-D-20-0110.1.
Rai, M., Stafoggia, M., de'Donato, F., Scortichini, M., Zafeiratou, S., Vazquez Fernandez, L., Zhang, S., Katsouyanni, K., Samoli, E., Rao, S., Lavigne, E., Guo, Y., Kan, H., Osorio, S., Kyselý, J., Urban, A., Orru, H., Maasikmets, M., Jaakkola, J.J.K., Ryti, N., Pascal, M., Hashizume, M., Fook Sheng Ng, C., Alahmad, B., Hurtado Diaz, M., De la Cruz Valencia, C., Nunes, B., Madureira, J., Scovronick, N., Garland, R.M., Kim, H., Lee, W., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Maria Vicedo-Cabrera, A., Ragettli, M.S., Leon Guo, Y.L., Pan, S.C., Li, S., Gasparrini, A., Sera, F., Masselot, P., Schwartz, J., Zanobetti, A., Bell, M.L., Schneider, A., Breitner, S., 2023. Heat-related cardiorespiratory mortality: effect modification by air pollution across 482 cities from 24 countries. Environ. Int. 174. https://doi.org/10.1016/j.envint.2023.107825.
Ru, M., Shindell, D., Spadaro, J.V., Lamarque, J.-F.F., Challapalli, A., Wagner, F., Kiesewetter, G., 2023. New concentration-response functions for seven morbidity endpoints associated with short-term PM2.5 exposure and their implications for health impact assessment. Environ. Int. 179, 108122. https://doi.org/10.1016/j.envint.2023.108122.
Saberian, S., Heyes, A., Rivers, N., 2017. Alerts work! air quality warnings and cycling. Resour. Energy Econ. 49, 165–185. https://doi.org/10.1016/J.RESENEECO.2017.05.004.
Samoli, E., Aga, E., Touloumi, G., Nisiotis, K., Forsberg, B., Lefranc, A., Pekkanen, J., Wojtyniak, B., Schindler, C., Niciu, E., Brunstein, R., Dodič Fikfak, M., Schwartz, J., Katsouyanni, K., 2006. Short-term effects of nitrogen dioxide on mortality: an analysis within the APHEA project. Eur. Respir. J. 27, 1129–1138. https://doi.org/10.1183/09031936.06.00143905.
Song, S.H., Tong, M., Wang, M., Li, S.F., Cheng, C.L., Xi, R., Gao, Q., Li, R., Liang, Y.M., Li, X.J., 2025. Ambient PM2.5 and O3 and their combined effects on the onset of acute cardiovascular events: a time-stratified case-crossover study in Jining, China (2015–2023). BMC Public Health 2025 25 (1), 4224. https://doi.org/10.1186/S12889-025-25166-X.
Stieb, D.M., Burnett, R.T., Smith-Doiron, M., Brion, O., Shin, H.H., Economou, V., 2008. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. J. Air Waste Manag. Assoc. 58, 435–450. https://doi.org/10.3155/1047-3289.58.3.435.
Straff, W., Tobollik, M., Mücke, H.-G.H.-G., 2021. Eine umweltmedizinische Begründung für die Bewertungsklassen und Beurteilungs-Schwellenwerte des Luftqualitätsindex (LQI) des Umweltbundesamtes. UMID, Dessau-Roßlau.
Tainio, M., de Nazelle, A.J., Götschi, T., Kahlmeier, S., Rojas-Rueda, D., Nieuwenhuijsen, M.J., de Sá, T.H., Kelly, P., Woodcock, J., 2016. Can air pollution negate the health benefits of cycling and walking? Prev. Med. (Baltim). 87, 233–236. https://doi.org/10.1016/J.YPMED.2016.02.002.
To, T., Shen, S., Atenafu, E.G., Guan, J., Mclimont, S., Stocks, B., Licskai, C., 2012. The air quality health index and asthma morbidity: a population-based study. Environ. Health Perspect. 121, 46. https://doi.org/10.1289/EHP.1104816.
Umweltbundesamt, n.d. Luftdaten [WWW Document]. Umweltbundesamt. URL https://www.umweltbundesamt.de/daten/luft/luftdaten/(accessed 6.29.26a).
Umweltbundesamt, n.d. Der Luftqualitätsindex - LQI [WWW Document]. URL https://www.umweltbundesamt.de/themen/luft/luftqualitaet/der-luftqualitaetsindex-lqi#der-luftqualittsindex-lqi-des-umweltbundesamtes (accessed 6.16.26b).
U.S. Environmental Protection Agency, 2013. Integrated Science Assessment for Ozone and Related Photochemical Oxidants. U.S. Environmental Protection Agency, Research Triangle Park, NC.
U.S. Environmental Protection Agency, 2016. Integrated Science Assessment (ISA) for Oxides of Nitrogen – Health Criteria. U.S. Environmental Protection Agency, Washington, DC.
U.S. Environmental Protection Agency, 2017. Integrated Science Assessment (ISA) for Sulfur Oxides – Health Criteria. U.S. Environmental Protection Agency, Washington, DC.
U.S. Environmental Protection Agency, 2019. Integrated Science Assessment (ISA) for Particulate Matter. U.S. Environmental Protection Agency, Washington, DC.
Vicedo-Cabrera, A.M., Sera, F., Liu, C., Armstrong, B., Milojevic, A., Guo, Y., Tong, S., Lavigne, E., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Pascal, M., Huber, V., Schneider, A., Katsouyanni, K., Samoli, E., Stafoggia, M., Scortichini, M., Hashizume, M., Honda, Y., Ng, C.F.S., Hurtado-Diaz, M., Cruz, J., Silva, S., Madureira, J., Scovronick, N., Garland, R.M., Kim, H., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Ragettli, M.S., Röösli, M., Guo, Y.L.L., Chen, B.Y., Zanobetti, A., Schwartz, J., Bell, M.L., Kan, H., Gasparrini, A., 2020. Short term association between ozone and mortality: global two stage time series study in 406 locations in 20 countries. BMJ 368, 36. https://doi.org/10.1136/BMJ.M108.
Wang, A., Mora, S., Machida, Y., deSouza, P., Paul, S., Oyinlola, O., Duarte, F., Ratti, C., 2023. Hyperlocal environmental data with a mobile platform in urban environments. Sci. Data 10, 524. https://doi.org/10.1038/S41597-023-02425-3.
Weichenthal, S., Pinault, L., Christidis, T., Burnett, R.T., Brook, J.R., Chu, Y., Crouse, D. L., Erickson, A.C., Hystad, P., Li, C., Martin, R.V., Meng, J., Pappin, A.J., Tjepkema, M., van Donkelaar, A., Weagle, C.L., Brauer, M., 2022. How low can you go? Air pollution affects mortality at very low levels. Sci. Adv. 8, 3381. https://doi.org/10.1126/sciadv.abo3381.
World Health Organisation (WHO). Regional Office for Europe, 2013. Health risks of air pollution in Europe – HRAPIE project: recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide. World Health Organization. World Health Organization, Copenhagen.
World Health Organization (WHO), 2005. WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005.
World Health Organization (WHO), 2021. WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization, Geneva.
World Health Organization (WHO). Regional Office for Europe, 2025. Health Risks of Air Pollution in Europe: HRAPIE-2 Project: Updated Guidance on concentration–response Functions for Health Risk Assessment of Air Pollution in the WHO European Region. World Health Organization, Regional Office for Europe.
World Health Organization (WHO). Regional Office for Europe, 2026. Air Quality Indexes: Key Considerations and Roadmaps for Best Practices. World Health Organization, Regional Office for Europe.
Zheng, X.Y., Ding, H., Jiang, L.N., Chen, S.W., Zheng, J.P., Qiu, M., Zhou, Y.X., Chen, Q., Guan, W.J., 2015. Association between air pollutants and asthma emergency room visits and hospital admissions in time series studies: a systematic review and meta-Analysis. PLoS One 10. https://doi.org/10.1371/journal.pone.0138146.
Zheng, X.Y., Orellano, P., Lin, H.L., Jiang, M., Guan, W.J., 2021. Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: a systematic review and meta-analysis. Environ. Int. 150. https://doi.org/10.1016/j.envint.2021.106435.