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# Short-term exposure to desert dust and sandstorms and all-cause and cause-specific mortality and morbidity: A systematic review and meta-analysis☆

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ABSTRACT

*Background:* Desert dust and sandstorms raise concerns about their adverse effects on human health. Over the last decade, special attention has been given to mineral dust particles from desert sand. However, evidence from previous literature reviews has yielded inconclusive results regarding their health effects. We aim to systematically synthesize evidence on the short-term health effects of desert dust exposure from major dust source areas.
*Methods:* The bibliographic search was conducted using the MEDLINE (PubMed), Scopus, and Web of Science databases to investigate the health effects of short-term exposure to desert dust in human populations, using time series or case-crossover study designs. Study selection and reporting followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We evaluated the risk of bias (RoB) for individual studies and the certainty of evidence (CoE) for environmental exposures, as developed by a group of experts convened by the World Health Organization (WHO). Publication bias was examined using funnel plots and Begg's asymmetry test.
*Results:* A total of 71 studies were included in the review, covering data from 1993 to 2024. Most studies focused on Asian and African desert dust, with fewer studies from Arabian, American, and Australian regions. We found a significant increase in the risk for all-cause mortality (Relative Risk, RR = 1.0121, 95 %CI = [1.0045, 1.0199]). In addition, the mortality risk associated with particulate matter less than 10 μm (PM10) was slightly higher on dust days compared to non-dust days, while for particulate matter less than 2.5 μm (PM2.5), the risk was higher on non-dust days. We also observed a significant increase in the risk for cardiovascular mortality (RR = 1.0252, 95 % CI = [1.0100, 1.0407]) during dust days compared to non-dust days, but not for respiratory mortality (RR = 1.0001, 95 % CI = [0.9773, 1.0277]). The risk also increased for cardiovascular (RR = 1.0094, 95 % CI = [1.0014, 1.0174]) and respiratory morbidity (RR = 1.0693, 95 % CI = [1.0188, 1.1224]).

*Abbreviations:* AQGs, WHO Air Quality Guidelines; CoE, Certainty of Evidence; GAPH-TAG, WHO Global Air Pollution and Health Technical Advisory Group; GDG, WHO Guideline Development Group; GRADE, Grading of Recommendations Assessment, Development and Evaluation; HR, Hazard Ratio; ICD-9, International Classification of Diseases, 9th Revision; ICD-10, International Classification of Diseases, 10th Revision; OR, Odds Ratio; PECOS, Population, Exposure, Comparator, Outcomes, and Studies; PM, Particulate matter; $PM_{2.5}$, Particulate matter with a diameter of 2.5 μm (μm) or less; $PM_{10}$, Particulate matter with a diameter of 10 μm (μm) or less; $PM_{2.5\text{-}10}$, Particulate matter with a diameter between 2.5 and 10 μm (μm); PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RoB, Risk of Bias; RR, Relative Risk; SPM, Suspended particulate matter; WHO, World Health Organization; 95% CI, 95% Confidence Interval.

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*Conclusion:* Exposure to desert dust and sandstorms is linked to increased risks of all-cause and cardiovascular mortality, as well as respiratory morbidity. The overall evidence quality for each exposure-outcome combination was assessed as moderate, although data limitations prevent the establishment of specific air quality thresholds for desert dust particles. This review highlights the need for targeted public health interventions in affected regions.

## 1. Introduction

Desert dust and sandstorms play a significant role in weather, climate, and atmospheric chemistry, representing severe environmental and human health hazards (de Longueville et al., 2013; Mahowald et al., 2010). Typically, desert dust refers to particulate matter (PM) emitted from the surface of arid and semi-arid regions. Desert dust significantly impacts air quality in areas close to the emission sources and over receptor regions thousands of kilometres distant (Ginoux et al., 2012; Prospero, 2002). For desert dust to be suspended and transported over long distances, it must have a relatively fine diameter, typically within the clay (<2 μm) and silt (<50 μm) size fractions. Additionally, sand refers to sediment particles ranging from 50 to 2,000 μm in size and plays a significant role in generating dust during dust storms by eroding surfaces and through the saltation of sand particles. The influence of dust episodes on air quality is a complex issue. Desert dust can increase ambient PM concentrations by supplying large loads of mineral or crustal dust. Moreover, desert dust can carry anthropogenic pollutants previously deposited in the source areas or trapped by the high-dust air masses during atmospheric transport (Mori et al., 2003; Rodríguez et al., 2011). It can also transport large quantities of microorganisms and toxic biogenic allergens (Griffin et al., 2001; Ho et al., 2005).

Toxicological studies have shown that sand dust particles can induce inflammatory lung injury and exacerbate allergen-induced nasal and pulmonary eosinophilia (Ichinose et al., 2006; Sadakane et al. 2016; Fussell and Kelly, 2021). Findings from an in vitro study also suggests that substantial quantities of suspended dust during sandstorms could interact with chemicals present on its surface, potentially increasing the bioreactivity of PM during dust episodes (Ho et al., 2019). Additionally, mineral dust surface reactions have been observed to serve as an unrecognized source of toxic organic chemicals in the atmosphere, thereby enhancing the toxicity of aerosols in urban settings (Kameda et al., 2016).

Among the previously existing reviews, two were conducted at the regional scale (Karanasiou et al., 2012 focused on Saharan dust, and Hashizume et al., 2020 on Asian dust), while another two reviews were conducted at the global scale (de Longueville et al., 2013; Zhang et al., 2016). Although these studies claimed to have systematically reviewed the literature, only Hashizume et al. (2020) defined an appropriate research question based on a well-defined Population, Exposure, Comparator, Outcomes, and Studies (PECOS) framework that allowed for a meta-analysis and assessed the risk of bias using adapted National Institute of Health framework for observational cohort and cross-sectional Studies. Moreover, none of them developed a protocol or evaluated the certainty of the evidence using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) or a similar approach. Furthermore, none of these reviews accounted for the desert dust exposure assessment methods and metrics. Depending on the dust exposure metric, whether binary or continuous, the research questions addressed by the individual studies are different, and study results need to be pooled separately according to each metric (Tobías and Stafoggia 2020).

A recent scoping review by the World Health Organization (WHO) Global Air Pollution and Health-Technical Advisory Group (GAPH-TAG) on desert dust, sandstorms, and health aimed to identify the most probable health effects of desert dust and sandstorms based on existing epidemiological literature (Lwin et al., 2023). All reviewed studies focused on the short-term health effects of desert dust, with most employing time-series or case-crossover study designs (75 %). Mortality and morbidity outcomes, such as hospital admissions, emergency room visits, and ambulance calls, were the most studied (72 %). Among these, all-cause mortality and cause-specific mortality for cardiovascular and respiratory diseases, along with morbidity for cardiovascular and respiratory diseases, were the most frequently evaluated outcomes (86 %) (Lwin et al., 2023). This scoping review provided valuable insights to refine the PECOS framework and update the protocol for this systematic review (Tobias et al., 2019).

This study aims to summarize the evidence on the primary effects of desert dust and sandstorms on cause-specific mortality and morbidity outcomes, while considering appropriate study designs and major dust source regions. The conclusions from this systematic review are intended to enhance the understanding of the short-term health effects of desert dust.

## 2. Methods

### 2.1. Protocol and registration

The systematic review protocol was developed according to discussions at the 3rd Meeting of the WHO Global Platform on Air Quality and Health (Madrid, Spain, March 2017) – a predecessor of the GAPH-TAG. The protocol for this study was registered in PROSPERO (CRD42018091809) and published elsewhere (Tobias et al., 2019). Later, the study protocol was amended according to the findings from the scoping review conducted by members of the WHO GAPH-TAG on desert dust, sandstorms and health (Lwin et al., 2023) (Table A.1, Supplementary Data, Appendix). The reporting of this systematic review complies with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Page et al., 2021). The PRISMA checklist for this study can be found in Table A.2 (Supplementary Data, Appendix).

### 2.2. Research question

A summary of the PECOS question (Morgan et al., 2018) is presented below:

Population: Among human population, what is the effect of

Exposure: Short-term exposure to desert dust versus

Comparator: Non-exposure or exposure to lower (or the lowest) levels of desert dust on

Outcomes: All-cause mortality and cause-specific mortality due to cardiovascular and respiratory diseases, and morbidity due to cardiovascular and respiratory diseases.

Studies: Ecological time-series or case-crossover studies.

### 2.3. Study eligibility criteria

Table 1 lists the eligibility criteria for the studies, in relation to the population, exposure, comparator, outcome and study type elements.

Where data from the same study population, with complete geographical and temporal overlap, was reported in multiple publications, only the largest and the most complete study was included to avoid double counting. Moreover, multi-city studies were preferred over single-city studies. When multiple lag estimates were reported in the studies, we followed the framework proposed by Atkinson et al. (2014) to maintain consistency with previously published systematic reviews

**Table 1**
Eligibility criteria.

| | |
|---|---|
| **Population** | Inclusion: Human population of all ages from developed and developing countries living in areas exposed to desert dust in both urban and rural settings. We have not imposed geographical restrictions. Exclusion: Studies analyzing populations with complete geographical and temporal overlap, in order to avoid double-counting of participants. |
| **Exposure** | Inclusion: We considered short-term exposure, from the same day of the exposure up to one week after exposure to desert dust characterized using a binary metric, distinguishing days affected by dust events and days not affected by dust events, or using a continuous metric, quantifying the amount of desert dust in daily PM concentrations. Desert dust exposure can be measured by source apportionment, component analysis, particle size and composition, use of weather data and back trajectories, or any other suitable method. Exclusion: Long-term exposure to desert dust. |
| **Comparator** | Inclusion: The exposure to desert dust should be compared with non-exposure to desert dust (binary metric) or exposure to lower concentrations of desert dust (continuous metric) within the same population. |
| **Outcome** | Inclusion: Mortality for all-natural causes (International Classification of Diseases 9th revision (ICD-9): 001–799, International Classification of Diseases 10th revision (ICD-10): codes A00–R99) and cause-specific for all cardiovascular (ICD-9: 390–459, ICD-10: I00-I99) and respiratory diseases (ICD-9: 460–519, ICD-10: J00-J99), and morbidity from hospital admissions and visits, emergency room visits, and ambulance calls for all cardiovascular and respiratory diseases. Exclusion: Other causes of mortality and morbidity. |
| **Study type** | Inclusion: We included epidemiological studies in human populations using ecological time-series and case-crossover study designs. Exclusion: Any other individual epidemiological design examining long-term association and qualitative studies. |

used in the update of the WHO AQGs (Lee et al. 2020; Orellano et al., 2020, 2021; Zheng et al., 2021). We extracted all the lag estimates reported in each study. For the meta-analysis, we selected the most frequently used lag across all included studies (lag 0 in this systematic review). While single lags were included, cumulative or distributed lags were not considered.

### 2.4. Study search and selection

We searched the literature for studies matching the study eligibility criteria in the Medical Literature Analysis and Retrieval System Online (MEDLINE) via PubMed, Scopus via Elsevier, and the Web of Science. The search strategy was developed in collaboration with a health sciences librarian specializing in systematic search procedures, retrieving eligible published studies up to 1st December 2024. The search strategies applied to each bibliographic database are reported in Table A.3 (Supplementary Data, Appendix). Two reviewers independently screened the titles and abstracts. All studies were classified for inclusion or exclusion based on the eligibility criteria listed in Table 1 and checked for duplicates. Full-text articles were retrieved if the study's relevance was unclear from the title and abstract, and the relevant studies were further confirmed for inclusion through full-text review. A third reviewer was available to resolve discrepancies between reviewers.

### 2.5. Risk of bias assessment

We used the domain-based risk of bias (RoB) tool to assess the quality of evidence across studies for associations between specific air pollutants and adverse health outcomes. This tool was developed by a group of experts convened by the WHO in the context of the 2021 update of the air quality guidelines (AQGs). A detailed description of this tool can be found on the WHO/Europe website (World Health Organization, 2020a). Briefly, the RoB tool includes domains with one or more subdomains on confounding, selection bias, exposure assessment, outcome measurement, missing data, and selective reporting. Each domain and subdomain could be judged as having low, moderate, or high RoB.

### 2.6. Data synthesis and statistical analysis

The relative risk (RR) was used as the standard effect measure of association across studies. The odds ratio, if reported, was considered equivalent to RR, as stated in the protocol. Meta-analysis input data was estimated and reported as RR. When reporting the effects of any particulate matter (PM) fraction, the RR was standardized for an increment of 10 $\mu g/m^3$. The measure of association from individual studies was summarized using random-effects meta-analysis (DerSimonian and Laird, 1986). We conducted a meta-analysis for mortality and morbidity outcomes when at least three studies were available to ensure the reliability of the pooled estimate on a specific health outcome (Borenstein et al., 2009).

Independent meta-analyses were conducted separately depending on how exposure to desert dust was measured in each study (Tobias and Stafoggia, 2020). Desert dust exposure can be assessed using two primary approaches. The *binary metric* classifies days as either impacted by a dust event (dust days) or not (non-dust days). In epidemiological studies, it is typically used as a risk factor, comparing the occurrence of health outcomes on dust days versus non-dust days. However, some studies have also employed this metric as an effect modifier, examining whether the association between daily total PM concentrations and health outcomes differs on dust days compared to non-dust days. The *continuous metric* quantifies the amount of dust in the air from desert sources contributing to daily PM concentrations (Querol et al., 2019). It enables us to evaluate whether health outcomes are associated with the specific fraction of PM originating from desert dust sources.

Subgroup analyses were conducted by age group, whenever data became available in the individual studies, and by the desert origin of dust exposure, as the composition of dust particles is indeed different due to the geological and climatic conditions of each desert (Querol et al., 2019). We further conducted a sensitivity analysis for each combination of desert exposure and health outcome by excluding the studies with a high RoB in any of the domains of the RoB tool.

Statistical heterogeneity of the effect estimates between studies included in the meta-analysis was assessed using the Cochran Q test for heterogeneity and the I2 statistic (Higgins and Thompson, 2002). Publication bias was evaluated when at least ten studies were included in the meta-analysis using funnel plots and Begg's asymmetry test (Begg and Mazumdar, 1994). All analyses were conducted using Stata Statistical Software, release 17 (Stata Corp, College Station, TX, 2021).

### 2.7. Certainty of evidence

The certainty of evidence (CoE) was assessed using an adaptation of the grading of recommendations assessment, development, and evaluation (GRADE) approach for air quality and health studies, developed by a group of experts convened by the WHO in the context of the 2021 AQGs update (Morgan et al., 2016; World Health Organization, 2020b). Briefly, this approach implies that observational studies are always at risk of unmeasured confounding. Therefore, the level of evidence started with moderate CoE and was potentially downgraded according to the domains of limitations in studies, indirectness, inconsistency, imprecision, and publication bias. Subsequently, the domains of large effect size, confounding, and concentration–response gradient were examined, allowing for the upgrading of the CoE if appropriate. Some domains of this tool were evaluated using results of the RoB, heterogeneity, and publication bias, as previously described in the methodology.

Domains used to downgrade the level of evidence.

*Limitations in studies*: The evidence was downgraded if there were statistical differences between studies showing high versus moderate or low RoB in the sensitivity analysis. If the sensitivity analysis for RoB showed a considerable influence on the pooled effect-size, the conclusions were based on the high-quality studies only, and the evidence was

not downgraded.

*Indirectness*: The evidence was not downgraded based on this domain, as the PECOS question in the included studies always reflected the PECOS systematic review.

*Inconsistency*: The evidence was downgraded if severe heterogeneity was detected, when the prediction interval of the random-effects meta-analysis included unity and was more than twice the meta-analytical confidence interval.

*Imprecision*: The evidence was downgraded if the health events (deaths and hospitalizations) used when calculating the pooled effect size was below 100,000. This number is lower than the value proposed in the adapted GRADE approach (World Health Organization 2020b), because that value was calculated for RR in long-term studies. We defined our own cut-off point for short-term studies, using data from two selected multi-city studies (Lee at al., 2014; Stafoggia et al., 2016), in which significant positive effect sizes were found considering approximately 100,000 health events or less. The rationale behind this reasoning is that if the number of events is sufficient for a given study to derive significant effect sizes, the same number will be adequate for meta-analysis.

*Publication bias*: The evidence was downgraded if publication bias was detected by visual inspection of the funnel plots or through the Begg's test.

Domains used to upgrade the level of evidence:

*Large effect size:* The magnitude of the effect size was assessed by calculating the *E-value* ($E-value = RR + \sqrt{RR \times (RR-1)}$). The E-value quantifies the minimum strength of association as RR that an unmeasured confounder must have to negate the observed exposure-outcome association. The evidence was upgraded if the *E-value* was substantially larger than the anticipated effect of a significant unmeasured confounder.

*Confounding:* The evidence was not upgraded using this domain, as several potential confounders could shift the RR in both directions.

*Concentration-response gradient*: The evidence was upgraded if a concentration–response association was observed, either linearly or non-linearly.

Finally, the overall CoE was rated as high, indicating that further research is unlikely to change confidence in the effect size estimate; moderate, indicating that further research is likely to have a substantial impact on the confidence in the effect size estimate; low, suggesting that further research is very likely to have a substantial impact on the confidence in the effect size estimate; or very low, meaning that the effect

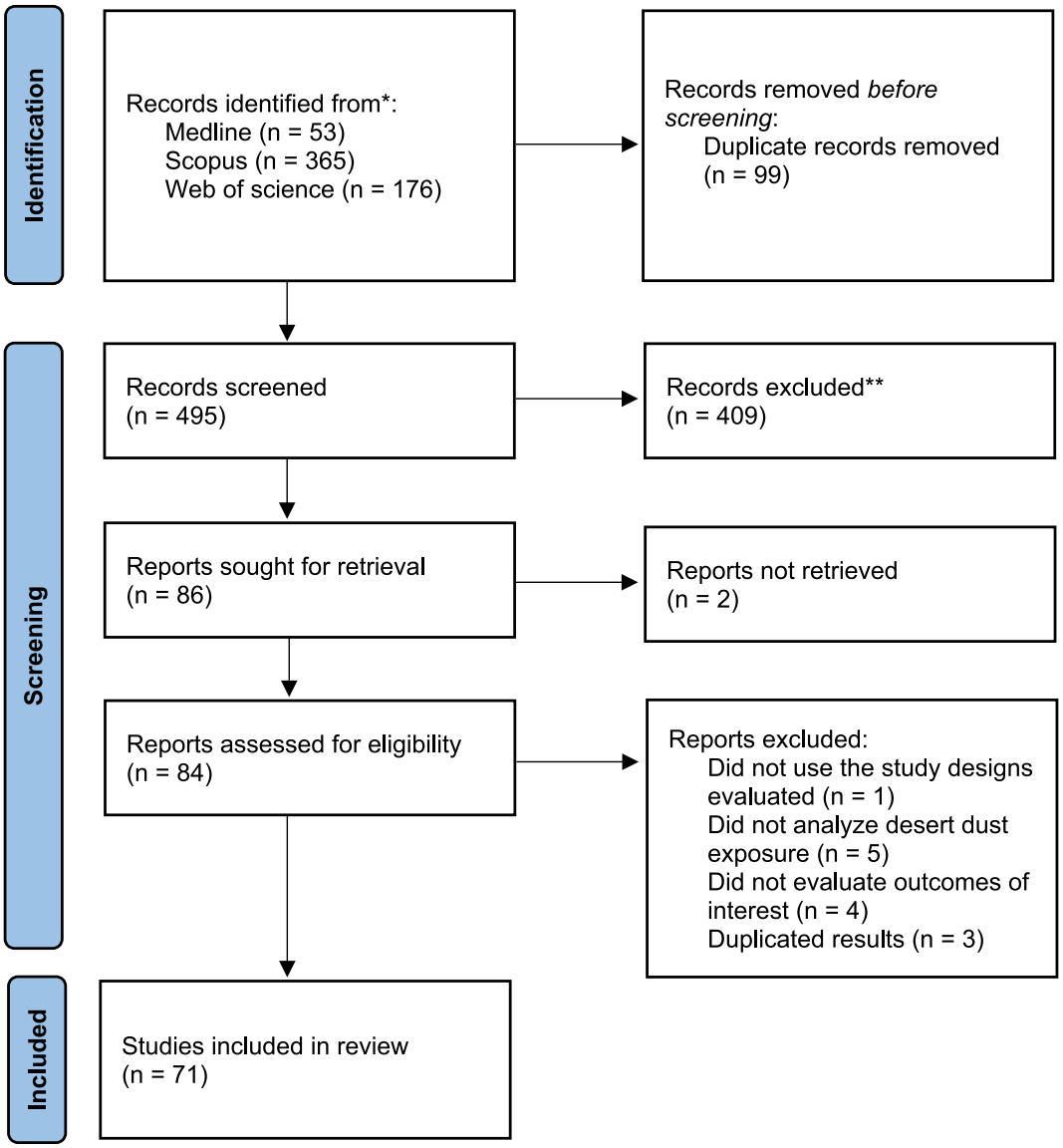


**Fig. 1.** PRISMA flowchart of assessment of eligible studies.

size is highly uncertain (World Health Organization, 2020b).

## 3. Results

### 3.1. Studies included

The search through electronic databases yielded 592 studies. After removing duplicates, 495 studies were screened by title and abstract. From these, 86 studies were selected for retrieval, but 2 could not be accessed. Therefore, 84 studies were ultimately assessed for eligibility and selected for a full-text assessment. We finally included 71 studies in the systematic review (Fig. 1).

The included studies analyzed time-series data spanning from 1993 to 2024, focusing on the association between desert dust exposure and various health outcomes. Of these, 34 studies examined all-cause mortality, 28 cardiovascular mortality, 25 studies respiratory mortality, 18 studies cardiovascular morbidity, and 29 studies respiratory morbidity. Most studies focused on Asian dust originating from the Gobi and Taklamakan deserts in western China and Mongolia (n = 33). African dust storms from the Sahara Desert (n = 24) were studied in regions far beyond the source, mostly in Southern Mediterranean countries but also a few in the Caribbean. Fewer studies examined dust from the Arabian Desert (n = 8), while other studies focused on local deserts in Australia (n = 3) and America (n = 3) (Fig. A.1, Supplementary Data, Appendix). Ten articles presented results from multi-location studies, whereas the remaining studies focused on single locations.

Detailed information from the included studies is provided in Table A.4 (Supplementary Data, Appendix).

### 3.2. Risk of bias

In two out of six domains, selection bias and selective reporting, the RoB was found to be low or moderate (Fig. 2). In the confounding, exposure assessment, outcome measurement domains, a non-negligible proportion of articles were found to have high RoB. The confounding domain showed 12.7 % of the studies with a high RoB. The main reason for the high RoB was the lack of proper adjustment for critical confounders in the time-series design (i.e., long-term trend and seasonality, and weather variables). The exposure assessment domain showed 7 % with high RoB, mainly because those studies did not report the method used to assess desert dust exposure. The outcome assessment domain showed 2.8 % with high RoB, due to the studies that did not use the ICD or another known standard for cause-specific mortality. Finally, the missing data domain showed 29.5 % with high RoB. The reasons for the high RoB were related to the lack of information on the number of missing values in the exposure data, the absence of information regarding imputation methods, or when the number of missing data for the exposure was higher than 5 %.

We also explored the RoB distribution across domains within each exposure-outcome combination, which was relatively homogeneous, indicating a consistent pattern of RoB.

The RoB reporting per item and domain in the individual studies, along with the rationale to justify each judgment, is available in Table A.5 (Supplementary Data, Appendix).

### 3.3. Meta-analysis

Table 2 reports the meta-analytical estimates of the associations between desert dust, as a binary exposure, and the study outcomes. Results are expressed as RR of the health outcomes on dust compared to non-dust days. The forest plots for these meta-analyses are shown in Fig. A.2 (Supplementary Data, Appendix). The mortality risk increased significantly by 1.12 % on dust days (RR = 1.0121, 95 % CI = [1.0045, 1.0199], n = 26, $I^2$ = 26.1 %) compared to non-dust days.

However, in five studies the binary desert dust exposure was used as an effect modifier, evaluating whether the association between all-cause

**Table 2**
Summary of meta-analytical estimates for the risk of mortality and morbidity outcomes for dust days compared to non-dust days.

| Outcome | N | RR | (95 % CI) | | p-value | $I^2$ (%) |
|---|---|---|---|---|---|---|
| **Mortality** | | | | | | |
| *All-cause* | 26 | 1.0121 | (1.0045 | , 1.0199) | 0.0019 | 26.1 |
| *Cardiovascular* | 22 | 1.0252 | (1.0100 | , 1.0407) | 0.0011 | 21.0 |
| *Respiratory* | 20 | 1.0001 | (0.9773 | , 1.0277) | 0.9918 | 28.3 |
| **Morbidity** | | | | | | |
| *Cardiovascular* | 4 | 1.0094 | (1.0014 | , 1.0174) | 0.0204 | 0.0 |
| *Respiratory* | 9 | 1.0693 | (1.0188 | , 1.1224) | 0.0067 | 81.9 |

RR, Relative Risk for dust days compared to non-dust days; N, number of effect sizes included in the meta-analysis.

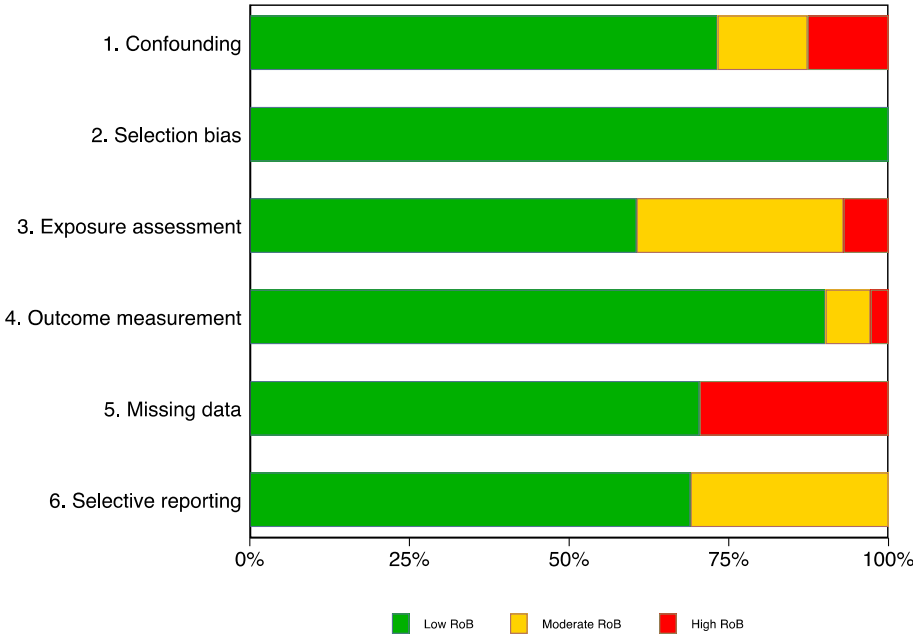


**Fig. 2.** Summary of the risk of bias assessment.

mortality and daily concentrations of PM differs between dust days and non-dust days (Fig. A.4, Supplementary Data, Appendix). A 10 μg/m$^3$ increase in $PM_{10}$ was associated with a 0.9 % mortality risk during dust days (RR = 1.0119, 95 % CI [0.9981, 1.0201], $I^2$ = 89.6 %) and 0.74 % on non-dust days (RR = 1.0074, 95 % CI [1.0029, 1.0120], $I^2$ = 36.7 %). No increase in mortality risk was observed for a 10 μg/m$^3$ increase in $PM_{2.5}$ on dust days (RR = 0.9888, 95 % CI [0.9737, 1.0042], $I^2$ = 24.1 %), while the risk was larger on non-dust days (RR = 1.0067, 95 % CI [0.9917, 1.0219], $I^2$ = 71.1 %).

Moreover, the mortality risk for cardiovascular diseases increased significantly by 2.52 % on dust days (RR = 1.0252, 95 % CI = [1.0100, 1.0407], n = 22, $I^2$ = 21 %) compared to non-dust days. In contrast, the mortality risk for respiratory causes did not show a significant increase (RR = 1.0001, 95 % CI = [0.9773, 1.0277], n = 20, $I^2$ = 28.3 %).

For morbidity outcomes, the risk increased significantly by 0.94 % for cardiovascular diseases (RR = 1.0094, 95 % CI = [1.0014, 1.0174], n = 4, $I^2$ = 0 %) and by 6.93 % for respiratory diseases (RR = 1.0693, 95 % CI = [1.0188, 1.1224], n = 9, $I^2$ = 78.0 %).

### 3.4. Subgroup and sensitivity analyses

We performed subgroup analyses by age group for the mortality outcomes (Fig. A.4, Supplementary Data, Appendix). We did not find a substantial difference in the risk of all-cause mortality between populations older than 65/75 years (RR = 1.0105, 95 % CI = [0.9979, 1.0233], n = 17, $I^2$ = 42.6 %) and those younger than 65/75 years (RR = 1.0094, 95 % CI = [0.9987, 1.0203], n = 18, $I^2$ = 0 %). However, the risk of cardiovascular mortality was significantly higher in the older population (RR = 1.0255, 95 % CI = [0.9859, 1.0666], n = 5, $I^2$ = 41.7 %) compared to the younger (RR = 0.9742, 95 % CI = [0.9334, 1.0167], n = 4, $I^2$ = 0 %). Similarly, the risk of respiratory mortality was higher in the older population (RR = 1.0430, 95 % CI = [0.9058, 1.2010], n = 3, $I^2$ = 68.1 %) than in the younger (RR = 1.010, 95 % CI = [0.8270, 1.2359], n = 3, $I^2$ = 40.6 %).

Moreover, we also conducted subgroup analyses by the origin of the desert source for the mortality outcomes (Fig. A.7, Supplementary Data, Appendix). We found a similar risk of all-cause mortality in Asian (RR = 1.0122, 95 % CI = [1.0019, 1.02226], n = 16, $I^2$ = 34 %) and African dust studies (RR = 1.0185, 95 % CI = [0.9861, 1.0520], n = 3, $I^2$ = 40.9 %), while the risk was lower in Arabian studies (RR = 1.0042, 95 % CI = [0.9855, 1.0233], n = 3, $I^2$ = 49.2 %). For cardiovascular mortality, the risk was higher in studies on Asian dust (RR = 1.0312, 95 % CI [1.0140, 1.04898], n = 15, $I^2$ = 20.8 %); however, fewer than three studies were available for African and Arabian dust. For respiratory mortality, no significant risk was observed in studies on Asian dust (RR = 0.9950, 95 % CI [0.9620, 1.0292], n = 13, $I^2$ = 32.8 %), and the number of studies for African and Arabian dust was also fewer than three.

The sensitivity analysis for mortality and morbidity outcomes, excluding studies with a high risk of bias (RoB) in any domain of the RoB tool, did not reveal differences between pooled risk estimates based on only low/moderate RoB studies and those including all studies (Table A.7, Supplementary Data, Appendix).

### 3.5. Publication bias assessment

Publication bias was assessed in studies examining mortality

**Table 3**
Certainty of evidence profile for each exposure-outcome combination.

| Exposure – Outcome | Limitations in studies | Indirectness | Inconsistency | Imprecision | Publication bias | Large effect size | Confounding | Concentration-response gradient | Certainty of evidence |
|---|---|---|---|---|---|---|---|---|---|
| | Downgrade | | | | | Upgrade | | | |
| All-cause mortality | (0) No differences between high versus low/ moderate RoB | (0) All studies were consistent with the PECOS | (0) 80 % prediction interval includes null effect, but is not twice the confidence interval | (0) Large number of mortality counts | (0) Publication bias not detected | (0) Insufficient data to assess the impact of unmeasured variables | (0) Unknown direction of effect of other confounding | (0) Significant positive association, but CRF not evaluated because exposure with a binary metric | Moderate |
| Cardiovascular mortality | (0) No differences between high versus low/ moderate RoB | (0) All studies were consistent with the PECOS | (0) 80 % prediction interval did not include unity | (0) Large number of mortality counts | (0) Publication bias not detected | (0) Insufficient data to assess the impact of unmeasured variables | (0) Unknown direction of effect of other confounding | (0) Significant positive association, but CRF not evaluated because exposure with a binary metric | Moderate |
| Respiratory mortality | ((0) No differences between high versus low/ moderate RoB | (0) All studies were consistent with the PECOS | (0) 80 % prediction interval includes null effect, but is not twice the confidence interval | (0) Large number of mortality counts | (0) Publication bias not detected | (0) Insufficient data to assess the impact of unmeasured variables | (0) Unknown direction of effect of other confounding | (0) Significant positive association, but CRF not evaluated because exposure with a binary metric | Moderate |
| Cardiovascular morbidity | ((0) No differences between high versus low/ moderate RoB | (0) All studies were consistent with the PECOS | (0) 80 % prediction interval did not include unity | (0) Large number of morbidity counts | (0) Publication bias not evaluated | (0) Insufficient data to assess the impact of unmeasured variables | (0) Unknown direction of effect of other confounding | (0) Significant positive association, but CRF not evaluated because exposure with a binary metric | Moderate |
| Respiratory morbidity | (0) No differences between high versus low/ moderate RoB | (0) All studies were consistent with the PECOS | (0) 80 % prediction interval includes null effect, but is not twice the confidence interval | (0) Large number of morbidity counts | (0) Publication bias not evaluated | (0) Insufficient data to assess the impact of unmeasured variables | (0) Unknown direction of effect of other confounding | (0) Significant positive association, but CRF not evaluated because exposure with a binary metric | Moderate |

Certainty of evidence, stating from moderate certainty; () between brackets is the downgrading/upgrading in that domain; CRF: Concentration-response function.

outcomes. The funnel plots did not show clear evidence of asymmetry, and this finding was further supported by Begg's test (Fig. A.9, Supplementary Data, Appendix). However, since the number of studies examining morbidity outcomes was fewer than ten, assessing publication bias was not feasible.

### 3.6. Certainty of the evidence assessment

The CoE produced neither downgrades nor upgrades applied to any specific domain (Table 3).

No differences were found in the pooled risk estimates when comparing studies with low/moderate risk of bias (RoB) versus those with high RoB. All studies were consistent with the PECOS framework for all dust exposure-health outcome combinations. Publication bias was not detected in the exposure-outcome combinations that included more than ten studies. Although significant positive short-term associations were observed between desert dust and health outcomes, the binary metric for desert dust exposure did not allow for the assessment of concentration–response functions.

## 4. Discussion

This systematic review and meta-analysis of global time-series and case-crossover studies provides comprehensive evidence on the short-term health effects of desert dust and sandstorms on all-cause and cause-specific mortality and morbidity. Unlike earlier reviews, this systematic review accounts for desert source regions and exposure metrics, evaluates risk of bias (RoB), and applies the GRADE framework, offering a more rigorous assessment of the evidence base.

Our findings suggest that exposure to desert dust is associated with an immediate increase in the risk of all-cause and cardiovascular mortality, but not respiratory mortality, on dust days compared to non-dust days. Additionally, respiratory morbidity is linked to immediate exposure to desert dust events, whereas the risk of cardiovascular morbidity is somewhat lower. These findings are consistent with those of a previous systematic review and meta-analysis conducted for Asian dust (Hashizume et al., 2020). However, the studies assessing desert dust exposure with a binary metric that classifies days as either impacted by a dust event or not, comparing health outcomes on dust days to non-dust days, while informative, do not allow us to estimate concentration–response functions, as they consider all dust events uniformly without quantifying the dust load (Tobias and Stafoggia, 2020). Moreover, a few studies in this systematic review used the binary desert dust exposure as an effect modifier, evaluating whether the association between PM concentrations and daily all-cause mortality differs between dust and non-dust days. The meta-analysis results indicate a slightly higher mortality risk for $PM_{10}$ on dust days compared to non-dust days. In contrast, the mortality risk for $PM_{2.5}$ was larger on non-dust days. A previous systematic review on ambient dust PM pollution also reported an increased risk of all-cause mortality associated with $PM_{10}$ exposure during dust days (Pouri et al., 2024). However, it did not compare the mortality risk during non-dust days, failing to explore the potential modifying role of desert dust on the PM-mortality association. Although the assumption is that PM composition may vary between these days, the total $PM_{10}$ comprises a combination of natural and anthropogenic sources, even during dust days (Querol et al. 2019). As a result, it becomes challenging to attribute health effects solely to one source or the other by merely categorizing days based on the presence of a dust episode (Tobias and Stafoggia, 2020). To address this issue, some studies adopted a different approach by analyzing PM's fine and coarse fractions separately. Unfortunately, we could not perform the meta-analysis for the coarse fraction ($PM_{2.5\text{-}10}$) due to the lack of studies. The use of desert dust as a continuous exposure metric could enable the estimation of independent effects for desert dust and non-desert PM sources, as well as facilitate the estimation of concentration–response functions (Querol et al., 2019). However, very few studies in this systematic review quantified desert dust as a continuous exposure, limiting the ability to perform meta-analysis.

Heterogeneity between studies was generally low for all mortality outcomes, enhancing the reliability of the results. Moreover, subgroup analyses suggest that the risk of cardiovascular and respiratory mortality was significantly higher in the older population. This may be attributed to the higher prevalence of heart and lung diseases among the elderly compared to younger age groups. (Shin et al., 2022). Additionally, studies conducted in receptor areas influenced by Asian or African dust exhibited higher risk for all-cause mortality compared to those influenced by Arabian dust. Differences in the geological and chemical composition of dust particles from various source regions may explain these variations (Querol et al. 2019). Although heterogeneity for cardiovascular morbidity was low, substantial heterogeneity was observed for respiratory morbidity. Subgroup analysis could not be performed due to the limited number of studies. The large heterogeneity observed for respiratory morbidity may be attributed to the diverse nature of the included outcomes, such as hospital admissions, clinic visits, emergency room visits, and ambulance transports. Furthermore, even when using ICD classification, respiratory morbidity encompasses a wide variety of conditions, and the variability in severity likely contributes to the observed differences across studies.

The risk of bias (RoB) in individual studies was relatively high only in the missing data domain, primarily because several studies did not report the methods used to impute missing data or specify the proportion or number of missing days for exposure. The exposure assessment and outcome assessment domains exhibited a high RoB in a few studies that did not report the methods used for dust exposure assessment or the ICD codes for the health outcomes. Other domains were relatively consistent, benefiting from the high standardization of the time-series regression design adapted from air pollution studies used to assess the short-term effects of desert dust. The confounding domain was the only one to influence the RoB in a small proportion of studies. Nevertheless, the sensitivity analysis excluding studies with a high risk of bias did not significantly alter the pooled estimates for either mortality or morbidity outcomes, further reinforcing the reliability of the results. Additionally, we found no evidence of publication bias, although this assessment was only possible for mortality outcomes. However, despite observing significant short-term associations that increase the risk of mortality and morbidity outcomes on dust days compared to non-dust days, the use of a binary metric, as stated earlier, avoided the evaluation of concentration–response functions.

The strengths of this systematic review comprise an inclusion criterion that encompasses various desert dust exposure assessment methods and metrics, while accounting for major dust source regions and populations in both source regions and receptor areas. We also applied a rigorous assessment of RoB and CoE using tools specifically adapted for air quality and health studies. These tools were developed by a group of experts convened by the WHO as part of the 2021 update to the Air Quality Guidelines (Morgan et al., 2016; World Health Organization, 2020b). The CoE remained consistent throughout the assessment process, with neither downgrades nor upgrades applied to any specific element. The overall quality of the evidence for each exposure-outcome combination evaluated was assessed as moderate certainty. While a clear association exists between desert dust exposure and the health outcomes reviewed, further research is needed to strengthen the evidence base. Nonetheless, there are some limitations that should be considered. First, most of the studies included in this systematic review were conducted in dust-affected locations, with limited studies from source regions. Only one study was conducted in West Africa, despite the proximity of the Sahara, and studies in the Middle East were limited to Iran and Kuwait. To address this gap, more resources should be allocated to research in these regions, preferably through multi-country collaborative projects (Tobias et al., 2024). Second, the main core of the evidence was derived from studies using a binary metric for desert dust exposure, with only a few studies employing a continuous metric to

investigate the health effects of desert dust PM composition. As a result, concentration–response functions for desert dust exposure could not be established. Third, we found considerable variation in how results were reported across studies involving different populations and age groups. Similarly, the choice of the number of lags evaluated and the lag structures (e.g., single lags versus averaged lags) made comparisons challenging. This variation is a common limitation in air pollution time-series studies (Kim and Lee, 2019). However, in this systematic review, most of the studies reporting single-lag estimates focused on the immediate effects of desert dust exposure on the same day (i.e., lag 0). Developing a standardized protocol to ensure consistent definitions and reporting procedures would help enhance the reliability and comparability of epidemiological time-series studies (Tobias and Stafoggia, 2020).

The findings of this study supported the update of the WHO Global Air Quality Guidelines, coordinated by the WHO Regional Office for Europe and the European Centre for Environment and Health. While limitations in the available data prevented the establishment of specific AQGs levels for particles originating from desert dust, the results of this systematic review underscore the need for targeted public health interventions in regions frequently affected by desert dust events. This is especially important given that the frequency and intensity of desert dust and sandstorms have increased in recent decades due to land use and land cover changes, as well as climate-related factors in many dryland areas (Shukla et al., 2019).

## 5. Conclusion

This systematic review and meta-analysis provides evidence on the short-term health effects of desert dust exposure, revealing significant associations with increased risks of all-cause and cardiovascular mortality, as well as respiratory morbidity. Although current exposure metrics and limited source-region studies may hinder full attribution and impede concentration–response analyses, the existing body of evidence supports targeted public health interventions in desert dust-affected areas. Future research should prioritize continuous exposure metrics for a better understanding of desert dust PM composition, broader geographic coverage in source regions, and investigation of the long-term effects to strengthen air quality guidelines and address the challenges of desert dust exposure in the current climate change scenario.

## CRediT authorship contribution statement

**Aurelio Tobías:** Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Xavier Querol:** Writing – review & editing. **Marta Roqué:** Writing – review & editing, Validation, Methodology. **Kaung Suu Lwin:** Writing – review & editing, Data curation. **Lei Yuan:** Data curation. **Sophearen Ith:** Data curation. **Htay Zin Wai:** Data curation. **Paul Lester Chua:** Methodology, Data curation. **Iván Solá:** Methodology. **Matteo Renzi:** Data curation. **Massimo Stafoggia:** Writing – review & editing, Methodology, Data curation. **Masahiro Hashizume:** Writing – review & editing, Validation.

## Declaration of competing interest

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

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## Appendix A. Supplementary material

Supplementary Data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109277.

## Data availability

Data will be made available on request.

## References

Begg, C.B., Mazumdar, M., 1994. Operating characteristics of a rank correlation test for publication bias. Biometrics 50.
Borenstein, M.; Hedges, L.; Higgins, J.; Rothstein, H. (eds.) Introduction to Meta Analysis. Chichester, West Sussex, UK: John Wiley & Sons; 2009.
de Longueville, F., Ozer, P., Doumbia, S., Henry, S., 2013. Desert dust impacts on human health: an alarming worldwide reality and a need for studies in West Africa. Int. J. Biometeorol. 57, 1–19.
DerSimonian, R., Laird, N., 1986. Meta-analysis in clinical trials. Control Clin. Trials 7, 177–188.
Fussell, J.C., Kelly, F.J., 2021. Mechanisms underlying the health effects of desert sand dust. Environ. Int. 157, 106790.
Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., Zhao, M., 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on modis deep blue aerosol products. Rev. Geophys. 50, 1–36.
Griffin, D.W., Garrison, V.H., Herman, J.R., Shinn, E.A., 2001. African desert dust in the Caribbean atmosphere:Microbiology and public health. Aerobiologia 17, 203–213.
Hashizume, M., Kim, Y., Ng, C.F.S., Chung, Y., Madaniyazi, L., Bell, M.L., Guo, Y.L., Kan, H., Honda, Y., Yi, S.M., Kim, H., Nishiwaki, Y., 2020. Health effects of Asian dust: a systematic review and meta-analysis. Environ. Health Perspect. 128, 66001.
Higgins, J.P., Thompson, S.G., 2002. Quantifying heterogeneity in a meta-analysis. Stat. Med. 21, 1539–1558.
Ho, H.-M., Rao, C.Y., Hsu, H.-H., Chiu, Y.-H., Liu, C.-M., Chao, H.J., 2005. Characteristics and determinants of ambient fungal spores in Hualien. Taiwan. Atmos. Environ. 39, 5839–5850.
Ho, K.-F., Wu, K.-C., Niu, X., Wu, Y., Zhu, C.-S., Wu, F., Cao, J.-J., Shen, Z.-X., Hsiao, T.-C., Chuang, K.-J., Chuang, H.-C., 2019. Contributions of local pollution emissions to particle bioreactivity in downwind cities in China during Asian dust periods. Environ. Pollut. 245, 675–683.
Ichinose, T., Sadakane, K., Takano, H., Yanagisawa, R., Nishikawa, M., Mori, I., Kawazato, H., Yasuda, A., Hiyoshi, K., Shibamoto, T., 2006. Enhancement of mite allergen-induced eosinophil infiltration in the murine airway and local cytokine/chemokine expression by asian sand dust. J. Toxicol. Environ. Health a. 69, 1571–1585.
Kameda, T., Azumi, E., Fukushima, A., Tang, N., Matsuki, A., Kamiya, Y., Toriba, A., Hayakawa, K., 2016. Mineral dust aerosols promote the formation of toxic nitropolycyclic aromatic compounds. Sci. Rep. 6, 24427.
Kim, H., Lee, J.-T., 2019. On inferences about lag effects using lag models in air pollution time-series studies. Environ. Res. 171, 134–144.
Lee, K.K., Spath, N., Miller, M.R., Mill, N.L., Shah, A.S.V., 2020. Short-term exposure to carbon monoxide and myocardial infarction: A systematic review and meta-analysis. Environ. Int. 143, 105901.
Lwin, K.S., Tobias, A., Chua, P.L., Yuan, L., Thawonmas, R., Ith, S., Htay, Z.W., Yu, L.S., Yamasaki, L., Roque, M., Querol, X., Fussell, J.C., Nadeau, K.C., Stafoggia, M., Saliba, N.A., Sheng Ng, C.F., Hashizume, M., 2023. Effects of desert dust and sandstorms on human health: a scoping review. Geohealth 7, e2022GH000728.
Mahowald, N.M., Kloster, S., Engelstaedter, S., Moore, J.K., Mukhopadhyay, S., McConnell, J.R., Albani, S., Doney, S.C., Bhattacharya, A., Curran, M.A.J., Flanner, M.G., Hoffman, F.M., Lawrence, D.M., Lindsay, K., Mayewski, P.A., Neff, J.,

Rothenberg, D., Thomas, E., Thornton, P.E., Zender, C.S., 2010. Observed 20th century desert dust variability: impact on climate and biogeochemistry. Atmos. Chem. Phys. 10, 10875–10893.
Morgan, R.L., Thayer, K.A., Bero, L., Bruce, N., Falck-Ytter, Y., Ghersi, D., Guyatt, G., Hooijmans, C., Langendam, M., Mandrioli, D., Mustafa, R.A., Rehfuess, E.A., Rooney, A.A., Shea, B., Silbergeld, E.K., Sutton, P., Wolfe, M.S., Woodruff, T.J., Verbeek, J.H., Holloway, A.C., Santesso, N., Schunemann, H.J., 2016. GRADE: assessing the quality of evidence in environmental and occupational health. Environ. Int. 92–93, 611–616.
Morgan, R.L., Whaley, P., Thayer, K.A., Schunemann, H.J., 2018. Identifying the PECO: a framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. Environ. Int. 121, 1027–1031.
Mori, I., Nishikawa, M., Tanimura, T., Quan, H., 2003. Change in size distribution and chemical composition of kosa (Asian dust) aerosol during long-range transport. Atmos. Environ. 37, 4253–4263.
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, 105876.
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, 106434.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372, n71.
Pouri, N., Karimi, B., Kolivand, A., Mirhoseini, S.H., 2024. Ambient dust pollution with all-cause, cardiovascular and respiratory mortality: a systematic review and meta-analysis. Sci. Total Environ. 912, 168945.
Prospero, J.M., 2002. Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Rev. Geophys. 40, 1002.
Querol, X., Tobias, A., Perez, N., Karanasiou, A., Amato, F., Stafoggia, M., Perez Garcia-Pando, C., Ginoux, P., Forastiere, F., Gumy, S., Mudu, P., Alastuey, A., 2019. Monitoring the impact of desert dust outbreaks for air quality for health studies. Environ. Int. 130, 104867.
Rodríguez, S., Alastuey, A., Alonso-Pérez, S., Querol, X., Cuevas, E., Abreu-Afonso, J., Viana, M., Pérez, N., Pandolfi, M., De La Rosa, J., 2011. Transport of desert dust mixed with North African industrial pollutants in the subtropical Saharan Air Layer. Atmos. Chem. Phys. 11, 6663–6685.
Sadakane, K., Ichinose, T., Nishikawa, M., Takano, H., Shibamoto, T., 2016. Co-exposure to zymosan a and heat-inactivated asian sand dust exacerbates ovalbumin-induced murine lung eosinophilia. Allergy Asthma Clin. Immunol. 12, 48.
Shin, H.H., Maquiling, A., Thomson, E.M., Park, I.-W., Stieb, D.M., Dehghani, P., 2022. Sex-difference in air pollution-related acute circulatory and respiratory mortality and hospitalization. Sci. Total Environ. 806, 150515.
Shukla, P.R.; Skea, J.; Calvo Buendia, E.; Masson-Delmotte, V.; Pörtne,r H-O.; Roberts, D. C.; Zhai, P.; Slade, R.; Connors, S.; van Diemen, R.; Ferrat, M.; Haughey, E.; Luz, S.; Neogi, S.; Pathak, M.; Petzold, J.; Portugal Pereira, J.; Vyas, P.; Huntley, E.; Kissick, K.; Belkacemi, M.; Malley, M. (eds.) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC; 2019. (https://www.ipcc.ch/srccl/).
Tobias, A.; Stafoggia, M.; Gumy, S.; Malkawi, M.; Safi, H. Unraveling the short-term health effects of particulate matter air pollution in the WHO Eastern Mediterranean region: The imperative for time-series studies. East. Mediterr. Health J. 2024, in press.
Tobias, A., Karanasiou, A., Amato, F., Roque, M., Querol, X., 2019. Health effects of desert dust and sandstorms: a systematic review and meta-analysis protocol. BMJ Open 9, e029876.
Tobias, A., Stafoggia, M., 2020. Modeling desert dust exposures in epidemiologic short-term health effects studies. Epidemiology 31, 788–795.
World Health Organization Global Air Quality Guidelines Working Group on Certainty of Evidence Assessmen. Approach to assessing the certainty of evidence from systematic reviews informing WHO global air quality guidelines; 2020b. (https://ars.els-cdn.com/content/image/1-s2.0-S0160412020318316-mmc4.pdf).
World Health Organization Regional Office for Europe. Risk of bias assessment instrument for systematic reviews informing WHO global air quality guidelines; 2020a. (https://apps.who.int/iris/handle/10665/341717).
Zhang, X., Zhao, L., Tong, D., Wu, G., Dan, M., Teng, B., 2016. A systematic review of global desert dust and associated human health effects. Atmos. 7.
Zheng, X., Orellano, P., Lin, H., Jiang, M., Guan, W., 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, 106435.